Sobre el evento

Hemos enriquecido la agenda del evento con actividades académicas, sociales y culturales para que los participantes e invitados creen oportunidades estratégicas para los empresarios del sector, y generen espacios para la creación de nuevos negocios, estimulando el crecimiento de la industria.

En la tarde del 20 de noviembre se dio grata bienvenida a todos los asistentes en uno de los auditorios más icónicos de Bogotá, el auditorio Fabio Lozano ubicado en la Universidad de Bogotá Jorge Tadeo Lozano donde se desarrolló la sesión especial de 5th Energy Day.

El día de apertura del 8° ELAEE (21 de noviembre) se llevó a cabo sesiones simultáneas y una mesa redonda donde se discutieron temas de gran impacto en electricidad, finalizando la jornada con una cena de gala.

Durante el martes 22 de noviembre se realizaron la sesión de plenaria doble, sesión de póster y sesiones simultáneas discutiendo de temas de gran impacto como lo es Energía y Cambio Climático.

El 8 Encuentro Latinoamericano de Economía de la Energía, reunió expertos en economía de la energía pertenecientes a la industria y la academia con el fin de discutir y explorar aspectos relacionados con la transición energética.

Las ponencias presentadas estuvieron enfocadas en los siguientes temas:

✓ Mercados de petróleo y gas
✓ Geopolítica de la energía
✓ Mercados eléctricos
✓ Energía y finanzas
✓ Demanda energética
✓ Estudio de países
✓ Energía y sociedad
✓ Política energética
✓ Cambio climático
✓ Innovación disruptiva y transición energética
✓ Energía y macroeconomía
✓ Gobiernos Locales
✓ Integración de sistemas
✓ Energía y transporte
✓ Integración energética regional.

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COMITÉ ACADÉMICO

El 8° ELAEE contó con un valioso comité académico que semana tras semana antes del evento, estuvo atento de los trabajos recibidos con el fin de evaluarlos.
Los miembros del comité son:

Chair: Isaac Dyner R.	
Gerardo Rabinovich	Richard Green
Ricardo Raineri	Felipe Henao
Luciano Losekann	Andrés Julián Aristizabal
Edmar de Almeida	Enrique Ángel
María Camila Ochoa	Maritza Jiménez
Laura Cárdenas	Thiago Brito
Adonis Yatchew	Veronica Gutman
Edmilson dos Santos	Carlos Jaime Franco
Hirdan Costa	Richard Hochstetler
Sebastián Zapata	Milton Herrera
Richard Green	Richard Hochstetler
José Daniel Morcillo	Laura Lotero Velez
Andrés Ochoa	

COMITÉ DE ORGANIZACIÓN

El comité de organización del 8° ELAEE está compuesto por las siguientes personas, quienes dedicaron su tiempo y esfuerzo para brindar un encuentro de gran impacto para los asistentes:

Chair: José Antonio Vargas Lleras	
Isaac Dyner	Gerardo Rabinovich
Marcela Castro	Daniel Díaz
María Camila Ochoa	Diego Vargas
Laura Cárdenas	Carlos Montoya
Maritza Jiménez	Alejandro García

PATROCINADORES

*Minciencias Colombia. *Program: Valuing Variability in the Colombian Electricity Market. Project call 852. Contract 80740-540-2020.*

CONFERENCISTAS

Lo más destacados representantes del sector energético participaron en las plenarias y conferencias. Líderes de pensamiento influyentes, especialistas y académicos, de la industria y del gobierno nacional e internacional en temas de energía y empresas de gran impacto participaron.

¡El 8° ELAEE llevo a cabo las discusiones más enriquecedoras e inspiradoras!

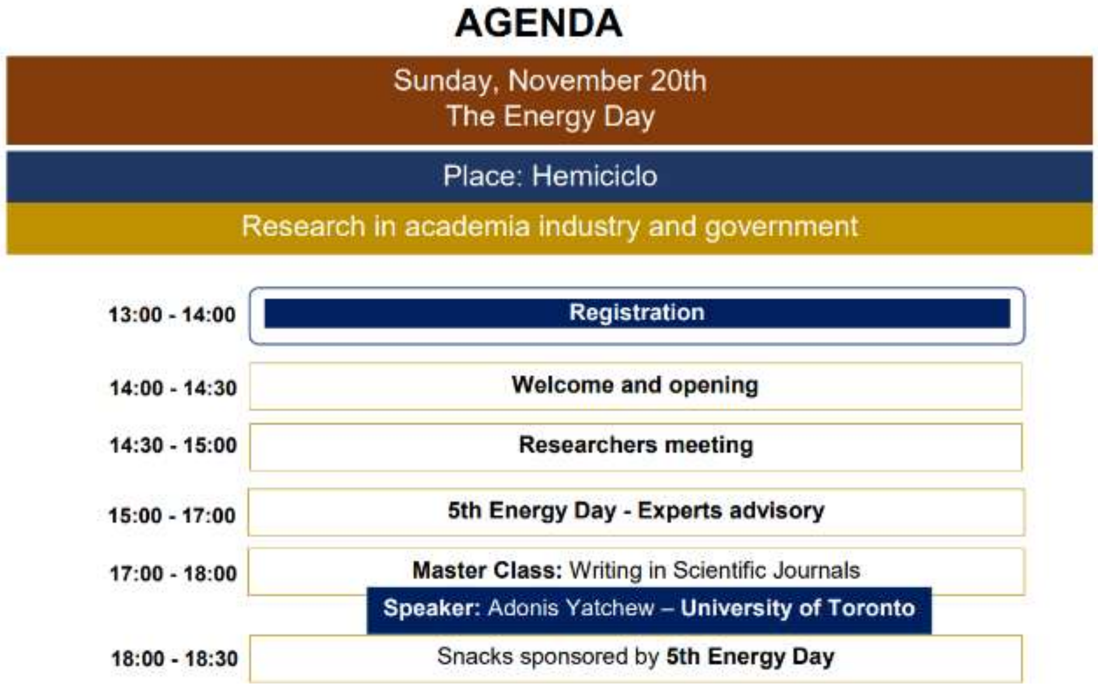
43 expertos internacionales y nacionales que pertenecen a empresas de alto impacto en el sector energético:

- Adonis Yatchew – **University of Toronto**
- Peter Hartley – **IAEE**
- Isaac Dyner – **Universidad de Bogotá Jorge Tadeo Lozano**
- Ricardo Raineri – **Exministro de Energía Chile**
- Medardo Cadena – **OLADE**
- Amylkar Acosta **– Exministro de Minas y Energía Colombia**
- Govinda R. Timilsina – **World Bank**
- Fernando Navajas – **FIEL**
- Gerardo Rabinovich **– Instituto Argentino de Energía**
- Antoine Halff – **Columbia University**
- Axel Pierru – **KAPSARC**
- Jean Eudes Moncomble **– Conseil Français de l’Energie**
- Astrid Martínez – **Fedesarrollo**
- Christophe Bonnery – **PSE (Paris School of Economics)**
- César Ramírez – **ISA**
- Robert Kleinbaum – **Mission Driven Energy**
- Camila Ochoa – **Universidad EIA**
- Yannick Perez – **IEEE**
- Pablo Ferragut – **Arpel**
- Sylvie D’Apote – **IBP**
- Luz Stella Murgas – **Naturgas**
- Edmilson Moutinho dos Santos – **Universidad de São Paulo**
- Michael Pollitt – **University of Cambridge**
- Roberto Brandao – **Universidad Federal de Río de Janeiro**
- Daniel Perczyk **– Fundación Torcuato Di Tella**
- Ruben Chaer – **ADME**
- Edmar de Almeida **– Institut of Energy PUC RIO**
- Jorge Valencia – **Experto Comisionado**
- Luciano Losekann **– Universidade Federal Fluminense UFF**
- Cristián Cárdenas – **Universidad de Florida**
- Daniel Bouille – **Bariloche Foundation**
- Michelle Hallack – **BID**
- Hamid Al Sadoon – **KAPSARC**
- Ángela Montoya – **Colombian Ambassador**
- Joisa Dutra – **FGV CERI**
- Jean Michel Glachant – **FSR**

- Olga Lucía Polania – **ASOCODIS**
- Luis Guillermo Prada – **XM Colombia**
- Francesco Bertoli – **Enel Grids**
- Andrés Guzmán – **KAPSARC**
- Walter Cont – **CAF Banco de Desarrollo de América Latina**
- Ana Carolina Chaves –**GESEL**

El 8° ELAEE contó con la participación de más de **130** personas, **62** ponencias y **6** exposiciones de póster.

AGENDA



AGENDA

Sunday, November 20th
The Energy Day

Place: Hemiciclo

Research in academia industry and government

13:00 - 14:00	Registration
14:00 - 14:30	**Welcome and opening**
14:30 - 15:00	**Researchers meeting**
15:00 - 17:00	**5th Energy Day - Experts advisory**
17:00 - 18:00	**Master Class:** Writing in Scientific Journals **Speaker:** Adonis Yatchew – **University of Toronto**
18:00 - 18:30	Snacks sponsored by **5th Energy Day**

Monday, November 21st

Auditorio Fabio Lozano

7:30 - 8:00 **Registration**

8:00 - 8:30 **Welcome and opening remarks**

José Antonio Vargas Lleras **WEC**
Peter Hartley **IAEE**
Isaac Dyner **UTADEO**

8:30 - 10:00 **Opening plenary lecture**:
Postpandemia, Economic crisis and Latin-American Energy

Moderator: Ricardo Raineri **Exministro de Energía Chile**

Speakers:
Medardo Cadena **OLADE**
Amylkar Acosta **Exministro de Minas y Energía Colombia**
Govinda R. Timilsina **World Bank**
Fernando Navajas **FIEL**

10:00 - 10:30 **Coffee Break**

10:30 - 12:00 **Oil in times of crisis**

Moderator: Gerardo Rabinovich **Instituto Argentino de Energía**

Speakers:
Antoine Halff **Columbia University**
Axel Pierru **KAPSARC**
Jean Eudes Moncomble **Conseil Français de l'Énergie**
Astrid Martínez **Fedesarrollo**

12:00 - 13:00 **Concurrent Sessions**

13:00 - 14:30 **Lunch**

Auditorio Fabio Lozano

13:00 - 14:30 **Poster Session**

14:30 - 16:00 **Round table:**

New regulations for electric transportation, energy storage and distributed generation.

Moderator: Christophe Bonnery

Speakers:
Cesar Ramírez **ISA**
Robert Kleinbaum **Mission Driven Energy**
Camila Ochoa **EIA**
Yannick Perez **IEEE**

16:00 - 16:30 **Coffee Break**

16:30 - 18:00 **Concurrent Sessions**

Tuesday, November 22nd

7:30 - 8:00	**Registration**	
8:00 - 9:15	**Is natural gas still a source of energy transition?**	**Energy – Security Supply**
	Moderator: Pablo Ferragut **Arpel** Speakers: Sylvie D'Apote **IBP** Peter Hartley **IAEE** Luz Stella Murgas **Naturgas** Edmilson Moutinho dos Santos **Universidad de São Paulo**	Speakers: Isaac Dyner **UTadeo** Ricardo Raineri **Exministro de Energía Chile** Michael Pollitt **University of Cambridge**
	Auditorio Fabio Lozano	**Hemiciclo**
9:15 - 10:30	**New Electricity Markets**	**Energy Transition in the world / Policy regulations and experiences - Lessons Learned**
	Moderator: Gerardo Rabinovich Speakers: Roberto Brandao **Universidad Federal de Río de Janeiro** Daniel Perczyk **Fundación Torcuato Di Tella** Ruben Chaer **ADME**	Moderator: Isaac Dyner **UTadeo** Speakers: Edmar de Almeida Institut of Energy - PUC-RIO Jorge Valencia **CREG** Christophe Bonnery **PSE (Paris School of Economics)**
	Hemiciclo	**Auditorio Fabio Lozano**
10:30 - 11:00	**Coffee Break**	
11:00 - 12:30	**Concurrent Sessions**	
12:30 - 14:00	**Lunch**	
12:30 - 14:00	**Poster Session**	

14:00 - 15:30

Auditorio Fabio Lozano

Demand, energy efficiency and climate change in the new environment

Moderator: Luciano Losekann **Universidade Federal Fluminense | UFF**

Speakers:
Cristian Cárdenas **University of Florida**
Daniel Bouille **Bariloche Foundation**
Michelle Hallack **BID**
Hamid Al Sadoon **KAPSARC**

Hemiciclo

Electricity companies of the future: transmission infrastructure and distributed generation in the transition

Moderator: Ángela Montoya **Colombian ambassador**

Speakers:
Joisa Dutra **(FGV CERI)**
Jean Michel Glachant **(FSR)**
Olga Lucía Polania **ASOCODIS**
Luis Guillermo Prada **XM Colombia**
Francesco Bertoli **Enel Grids**

15:30 - 16:00 **Coffee Break**

16:00 - 17:30 **Concurrent Sessions**

17:30 - 19:00 **Final plenary session:** Energy and Climate Change

Speakers:
Gerardo Rabinovich **Instituto Argentino de Energía**
Andrés Guzmán **KAPSARC**
Walter Cont **CAF Banco de Desarrollo de América Latina**
Mauricio Moszkowicz **University of Toronto**
Ana Carolina Chaves **GESEL**

LOCATION

The 8th ELAEE will take place at module 21 of Universidad Jorge Tadeo Lozano
Address: Cra|4 No. 22-61

5TH ENERGY DAY SESSION

El 20 de noviembre se realizó la sesión del **5th Energy Day** el cual fue patrocinado por la *Universidad EIA* y *MinCiencias* en el cual se realizaron seis ponencias y se llevo a cabo la master class: Writing in Scientific Journals.

PONENCIAS 5TH ENERGY DAY

1. Complementarity of energy sources in the Colombian electricity market: a system dynamics approach.
   Autores: Sofía Aristizábal, Camila Ochoa

2. Balances de agua y energía en sistemas agrofotovoltaicos.
   Autores: Arley Zapata, Andrés Ochoa

3. Oportunidades de negocio para las hidroeléctricas en el contexto de alta penetración de energías renovables variables.
   Autores: David Delgado Rendón, Carlos Jaime Franco Cardona

4. A bi-objective optimisation approach for budget allocation within regional off-grid electrification planning.
   Autores: Juan Pablo Viteri y Felipe Henao.

5. Comparative analysis of regulatory reform experiences in Brazil, Chile, Colombia and Mexico.
   Autores: Renata Wandroski Peris, Jose Roberto Ferreira Savoia, Virginia Parente de Barros y Eduardo Augusto Do Rosário Contani.

6. Comparative evolution of net energy metering policy in Brazil and California - challenges, lessons, and prospects.
   Autores: Diogo Lisbona Romeiro, Joisa Dutra

COMPLEMENTARITY OF ENERGY SOURCES IN THE COLOMBIAN ELECTRICITY MARKET: A SYSTEM DYNAMICS APPROACH

[Sofía Aristizábal, Universidad EIA, sofia.aristizabal@eia.edu.co]
[Camila Ochoa, Universidad EIA, camila.ochoa@eia.edu.co]

Overview

A rapid transition of the electricity matrix to one where renewable energy predominates is necessary to mitigate and adapt to climate change. Fortunately, over the last years non-conventional renewable energy sources (NRES) have become a cost-competitive alternative to supply power around the globe (Jurasz et al., 2020). However, a significant technological challenge that persists is how to increase shares of NRES in energy systems while maintaining reliability (Bekirsky et al., 2022). Some characteristics of these sources, such as their intermittency, variability, and non-dispatchability, propose difficulties to their integration into the power systems.

One solution that has become more attractive for researchers over the years is the complementarity nature of NRES to facilitate the integration of a large proportion of them to the electricity matrix (Jurasz et al., 2020). The aggregation of multiple intermittent generators can reduce the variability and the uncertainty of the system, either from statistical smoothing of a single technology employed over multiple geographical areas or from combining technologies that use different energy sources (Hart et al., 2012).

Additional to the mitigation of climate change, Colombia has another motive for their increasing interest on NRES. With approximately 68% of its installed capacity consisting of hydroelectric power plants, the country is highly dependent on its hydrology as a source of energy. This dependency on water resources puts it at risk of shortages and high electricity prices, especially when experiencing periods of long droughts due to the ENSO phenomenon (Parra et al., 2020). Alternative energy sources, like thermal generation plants, serve as a backup to make up for energy shortfalls. The main problem with these energy sources is that they involve high operating costs as well as high CO2 emissions, making them a less desirable option.

Non-conventional renewable energy is an alternative to respond to the risk of energy deficit by hydroelectric plants. Recent studies have demonstrated the existence of seasonal complementarity patterns between NRES and water resources in Colombia (Gonzalez-Salazar & Poganietz, 2021). Taking advantage of this complementarity, Colombia could act strategically to protect itself against risks derived from dependence on hydroelectric resources, without the need to expand its thermal generation capacity.

However, in addition to complementarity between water resources and solar and wind resources, the country needs complementarity between renewable energy projects (even when generating from the same resource). If most of the NRE generation is located in places with the highest availability of solar and wind resources, the energy matrix will be less dependent on hydrology. Nevertheless, it could become dependent on the climate conditions and other factors of that specific area where projects are concentrated.

The energy market is a complex system where a large number of variables interact, creating feedback loops, delays and uncertainty. System Dynamics is an ideal approach to analyze the effects of different policies and incentives to complementarity on reliability and prices in the Colombian electricity market.

Methods

The energy sector in Colombia is a highly complex system where countless variables such as the energy demand, the country's hydrology, the price of fossil fuels, the limitations of the transmission system, among many others, influence its general behavior. These variables are constantly changing, and each one of them involves some degree of uncertainty that makes it impossible to predict its behavior at any given point in time. Moreover, there are feedback loops within the system, as well as information delays, that make the relationships between the different variables non-linear, and therefore more difficult to understand.

As if the energy sector was not complex enough, the undergoing transformation towards a cleaner and more diverse energy matrix means the intermittency of the non-conventional renewable energy sources must also be taken into account to analyze the system's capacity more accurately.

We develop a simulation model to analyze the effects of complementarity between NRE projects in the Colombian electricity market. The model considers the hydroclimatic variability, as well as the hourly variations of the electricity demand and price, to simulate an hourly dispatch. The profitability of new renewable energy projects is estimated under different scenarios regarding remuneration schemes and incentives to complementarity. Based on that profitability, investment decisions in different technologies and locations are made, which will then influence electricity prices, closing a feedback loop that results in counterintuitive results.

Results

By simulating the incorporation of NRE projects under the current Colombian electricity market, it was possible to identify some behaviors in the cumulative electricity generation that could bring disadvantages to the system.

The model showed that, without incentives or other interventions from the government, investment on renewable energy projects is more profitable in specific regions of the country, where solar and wind resources are much more available. This could cause investors to prefer specific regions of the country to locate their projects.

However, if most projects are located in the same regions, their generation profiles will be similar. This will result in a highly intermittent cumulative offer from NRES, which will be challenging to balance the system and will affect security of supply in case any unexpected event occurs in any of these regions (such as sudden changes in climate conditions, damages to the transmission lines, etc.). The model results show that locating most projects in the same region can lead to shortages and extremely high energy prices. To guarantee a reliable and affordable electricity supply, renewable energy projects should be located in different regions of the country, where solar radiation and wind profiles are complementary, even though the total amount of electricity generated by those projects will be lower.

Conclusions

Renewable energy projects shouldn't be concentrated in a specific area of the country. The problem is, not all regions in the country are equally attractive for investors, because they do not have as much solar and wind resources, and therefore, their total generation is lower, affecting the projects' ROI.

Considering that most of the investment on renewable energy will come from private funding, projects' profitability is a key factor when making investment decisions. Based on the simulation results, we recommend the implementation of alternative remuneration schemes, policies and incentives, to help regions of the country with less resources, but more convenient availability profiles, become attractive for investors. This will facilitate and accelerate the construction of new renewable energy projects that are complementary to each other, ensuring a clean, reliable and affordable energy matrix.

Acknowledgements

This work is supported by the program "Valuing Variability in the Colombian Electricity Market", funded by Minciencias Colombia, Project call 852, Contract 80740-540-2020.

References

Gonzalez-Salazar, M., & Poganietz, W. R. (2021). Evaluating the complementarity of solar, wind and hydropower to mitigate the impact of El Niño Southern Oscillation in Latin America. *Renewable Energy*, *174*, 453–467. https://doi.org/10.1016/J.RENENE.2021.04.048

Hart, E. K., Stoutenburg, E. D., & Jacobson, M. Z. (2012). *The Potential of Intermittent Renewables to Meet Electric Power Demand: Current Methods and Emerging Analytical Techniques*. *100*(2). https://doi.org/10.1109/JPROC.2011.2144951

Jurasz, J., Canales, F. A., Kies, A., Guezgouz, M., & Beluco, A. (2020). A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. *Solar Energy*, *195*, 703–724. https://doi.org/10.1016/J.SOLENER.2019.11.087

Parra, L., Gómez, S., Montoya, C., & Henao, F. (2020). Assessing the Complementarities of Colombia's Renewable Power Plants. *Frontiers in Energy Research*, *8*, 280. https://doi.org/10.3389/FENRG.2020.575240/BIBTEX

Balances de agua y energía en sistemas agrofotovoltaicos

Arley Zapata[1] **and Andrés Ochoa**[2]

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1. Introducción

Los sistemas agrofotovoltaicos (AFV) hacen referencia a la producción de electricidad y alimentos de forma simultánea en un mismo territorio. En los proyectos AFV se busca optimizar el uso de recursos en general, del territorio y la radiación solar en particular, reduciendo la competencia e incrementando la producción conjunta (Schindele et al., 2020; Goetzberger y Zastrow, 1982). En el abanico de las energías renovables, la energía solar es la fuente más abundante y disponible (Adeh et al., 2018). Los sistemas AFV ofrecen un gran potencial para el aprovechamiento de la energía solar, su uso se ha incrementado en los últimos años (Schindele et al., 2020; Weselek et al., 2019; Fraunhofer ISE, 2020) y han comenzando a tener un rol importante en la transición energética en varios países como Alemania, Japón, Estados Unidos, Italia, Malasia, Egipto y Chile.

La implementación de sistemas AFV, incluyendo su diseño, construcción y operación, plantea diversos retos técnicos, ambientales, legales, etc. Estos sistemas crean un ambiente artificial que funciona de forma diferente a los controlados por agua y los controlados por energía (Elamri et al., 2018; Dinesh y Pearce, 2016; Perna et al., 2019). Según el diseño y la operación, en los ambientes AFV el agua puede ser un forzador estocástico si la lluvia cae directamente sobre el cultivo o el suelo, o determinístico si esta se recoge y se usa un sistema de riego para el suministro de agua. El régimen de radiación solar sobre el cultivo en sistemas AFV necesariamente es diferente al de cultivos a campo abierto. Parte de la radiación solar no llega al cultivo sino que sale en forma de electricidad generada por el sistema fotovoltaico. El efecto sobre el cultivo depende, entre otras cosas, de las bandas espectrales que requiera la generación de electricidad (que es función de la tecnología que se utilice) y las que requiera el cultivo (que pueden variar según las fases de crecimiento y desarrollo).

En este proyecto de tesis se plantea desarrollar un modelo para estudiar los efectos de la variación estocástica de la radiación y la precipitación en los sistemas AFV, teniendo en cuenta las interacciones en el continuo suelo-planta-atmósfera. Los flujos de agua, energía y carbono en los sistemas AFV estarán acoplados a través de las ecuaciones diferenciales de los balances correspondientes. La modelación de la precipitación y la radiación solar como procesos estocásticos permite plantear ecuaciones diferenciales estocásticas cuya solución provee la función de densidad de probabilidad de los diferentes flujos y almacenamientos. Estas funciones de probabilidad permitirían estimar riesgos de diversa índole, estimar el rendimiento energético y de los cultivos, teniendo en cuenta las condiciones climáticas locales, con el fin de optimizar el diseño y el manejo de los proyectos AFV.

2. Metodología

Para estudiar los efectos del comportamiento estocástico de la radiación y la precipitación en los diferentes flujos en los sistemas agrofotovoltaicos, se tomará como base el esquema planteado en la Figura 1 donde se pueden observar los distintos flujos de energía (flechas de color rojo), agua (flechas de color azul) y carbono (flechas de color verde). Estos flujos están acoplados a través de las ecuaciones diferenciales que representan los balances de energía, agua y carbono. Si la precipitación (P) y la radiación solar (R_{solar}) se modelan como procesos estocásticos, entonces las ecuaciones de balance serán ecuaciones diferenciales estocásticas cuya solución dará la función de probabilidad de los almacenamientos y flujos ilustrados.

La variabilidad de la radiación solar y su comportamiento estocástico debido a los aerosoles , gases y nubes que componen la atmósfera, se plantea estudiarlas mediante índices de claridad de la atmósfera tales como el *clear-sky index* (c), definido como la relación entre la radiación real y la radia-

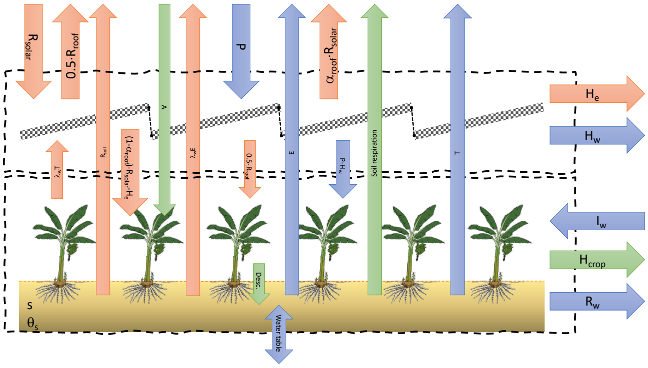

Figura 1. Esquema de flujos y almacenamientos en sistemas agrofotovoltaicos.

ción de la atmósfera limpia y seca, y el *clearness index* (k), que es la relación entre la radiación solar en superficie y radiación solar en la parte superior de la atmósfera (es decir, sin atenuación atmosférica). La radiación disponible para la generación de energía fotovoltaica se estimará a partir de la metodología propuesta por Muñoz (2019) y Broeck (1983) la cual involucra los índices de claridad atmosféricos, y será una función de entrada a al modelo de generación de energía en sistemas AFV que estará basado en las metodologías propuestas por Elamri et al. (2018); Dinesh y Pearce (2016); Perna et al. (2019); Masson et al. (2014) y permitirá estimar la función de densidad de probabilidad de generación de energía fotovoltaica.

El enfoque propuesto por Rodríguez-Iturbe et al. (1999) y Laio et al. (2001) de un modelo estocástico diario para estudiar las dinámicas de la humedad del suelo en un punto, se utilizará para modelar la lluvia, la interceptación por parte de los módulos solares y el cultivo, infiltración, percolación profunda y escorrentía. La evapotranspiración se considerará en función de la humedad del suelo y la energía disponible sobre el cultivo bajo un enfoque también estocástico.

La energía disponible en el cultivo para realizar los procesos fotosintéticos en sistemas AFV se estimará como un proceso estocástico. Se relacionará la transpiración y la energía disponible a través de la conductancia estomática, usando la ecuación de Penman-Monteith (PM) para estimar la transpiración junto con el enfoque de conductancia estomática de Leuning's (Leuning, 1990; Leuning et al., 1995). El carbono neto asimilado A_n se estimará a partir del modelo de Farquhar (Farquhar, 1973; Farquhar et al., 1980) siguiendo la metodología propuesta por Daly et al. (2004); Muñoz (2019) a la cual se le incorporará los efectos de la sombra generada por los módulos solares para la estimación de radiación neta que llega al cultivo. El modelo de Farquhar es el mas ampliamente usado para cuantificar las respuestas de las plantas C_3 a las perturbaciones externas.

3. Resultados esperados

Un modelo matemático que permita acoplar los flujos de energía, agua y carbono en sistemas AFV y que sea de utilidad estudiar el efecto de las diferentes condiciones de clima, suelo y cultivo a la cual están sometidos los sistemas AFV. Al final se espera contar con una herramienta que sirva de apoyo para la planificación agrícola en cuanto a: optimización de los recursos hídricos y energéticos, prácticas de siembra en sistemas AFV, y optimización del uso de la tierra. Adicionalmente se espera determinar la viabilidad teórica de la implementación de sistemas AFV en Colombia.

4. Conclusiones

El trabajo planteado busca generar un aporte científico y una herramienta práctica que permita la integración y optimización de los recursos energéticos, hídricos y alimentarios especialmente en el territorio colombiano. La implementación de este tipo de sistemas generaría un impacto positivo en la economía del sector rural, al mismo tiempo que se contribuiría a la transición a el uso de energías alternativas no convencionales con todos los beneficios e impactos que esto implica.

Referencias

Adeh, E. H., Selker, J. S., y Higgins, C. W.: Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency, PLoS ONE, 13, https://doi.org/10.1371/journal.pone.0203256, 2018.

Broeck, C.: On the relation between white shot noise, Gaussian white noise, and the dichotomic Markov process, Journal of Statistical Physics, 31, 467–483, https://doi.org/10.1007/BF01019494, 1983.

Daly, E., Porporato, A., y Rodríguez-Iturbe, I.: Coupled Dynamics of Photosynthesis, Transpiration, and Soil Water Balance. Part II: Stochastic Analysis and Ecohydrological Significance, Journal of Hydrometeorology, 5, 559–566, https://doi.org/10.1175/1525-7541(2004)005<0559:CDOPTA>2.0.CO;2, 2004.

Dinesh, H. y Pearce, J. M.: The potential of agrivoltaic systems, Renewable and Sustainable Energy Reviews, 54, 299–308, https://doi.org/10.1016/j.rser.2015.10.024, 2016.

Elamri, Y., Cheviron, B., Lopez, J. M., Dejean, C., y Belaud, G.: Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces, Agricultural Water Management, 208, 440–453, https://doi.org/10.1016/j.agwat.2018.07.001, 2018.

Farquhar, G. D.: A study of the responses of stomata to perturbations of environment, Phd thesis, The Australian National University, 1973.

Farquhar, G. D., von Caemmerer, S., y Berry, J. A.: A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species, Planta, 149, 78–90, https://doi.org/10.1007/BF00386231, 1980.

Fraunhofer ISE: Agrivoltaics: Opportunities for agriculture and the energy transition. A Guide for Germany, Fraunhofer

Institute for Solar Energy Systems ISE, Freiburg, Germany, https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/APV-Guideline.pdf, 2020.

Goetzberger, A. y Zastrow, A.: On the Coexistence of Solar-Energy Conversion and Plant Cultivation, International Journal of Solar Energy, 1, 55–69, https://doi.org/10.1080/01425918208909875, 1982.

Laio, F., Porporato, A., Ridolfi, L., y Rodríguez-Iturbe, I.: Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress II. Probabilistic soil moisture dynamics, Advances in Water Resources, 24, 707–723, https://doi.org/10.1016/S0309-1708(01)00005-7, 2001.

Leuning, R.: Modelling Stomatal Behaviour and and Photosynthesis of Eucalyptus grandis, Functional Plant Biology, 17, 159, https://doi.org/10.1071/PP9900159, 1990.

Leuning, R., Kelliher, F. M., Pury, D. G. G., y Schulze, E.-D.: Leaf nitrogen, photosynthesis, conductance and transpiration: scaling from leaves to canopies, Plant, Cell and Environment, 18, 1183–1200, https://doi.org/10.1111/j.1365-3040.1995.tb00628.x, 1995.

Masson, V., Bonhomme, M., Salagnac, J. L., Briottet, X., y Lemonsu, A.: Solar panels reduce both global warming and urban heat island, Frontiers in Environmental Science, 2, 14, https://doi.org/10.3389/fenvs.2014.00014, 2014.

Muñoz, E.: Soil moisture dynamics in water- and energy-limited ecosystems. Application to slope stability, Phd thesis. adviror: A.Ochoa, Universidad Nacional de Colombia, Sede Medellín, https://repositorio.unal.edu.co/handle/unal/76885, 2019.

Perna, A., Grubbs, E. K., Agrawal, R., y Bermel, P.: Design Considerations for Agrophotovoltaic Systems: Maintaining PV Area with Increased Crop Yield, in: 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), pp. 0668–0672, IEEE, Chicago, IL, USA, https://doi.org/10.1109/PVSC40753.2019.8981324, 2019.

Rodríguez-Iturbe, I., Porporato, A., Ridolfi, L., Isham, V., y Cox, D.: Probabilistic modelling of water balance at a point: the role of climate, soil and vegetation, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 455, 3789–3805, https://doi.org/10.1098/rspa.1999.0477, 1999.

Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., Goetzberger, A., y Weber, E.: Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications, Applied Energy, 265, 114 737, https://doi.org/10.1016/j.apenergy.2020.114737, 2020.

Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., y Högy, P.: Agrophotovoltaic systems: applications, challenges, and opportunities. A review, Agronomy for Sustainable Development, 39, https://doi.org/10.1007/s13593-019-0581-3, 2019.

UNIVERSIDAD NACIONAL DE COLOMBIA

Oportunidades de negocio para las hidroeléctricas en el contexto de alta penetración de energías renovables variables

Resumen para 8° ELAEE

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1. Introducción

Las centrales hidroeléctricas han sido una de las principales fuentes de energía eléctrica en muchos países, como Brasil, Canadá, Francia, Turquía (Sokulski et al., 2022) y Colombia (XM, 2021); y probablemente continuará siendo la principal fuente de energía de bajo carbono a nivel mundial en la próxima década (IEA, 2021b). Sin embargo, todo apunta a que la expansión de capacidad de generación en los próximos años será principalmente a través de fuentes de energía renovable variable (ERV), como la solar y eólica (IEA, 2021a). En este nuevo contexto, el negocio de las hidroeléctrica enfrenta varios retos que podrían afectar sus ingresos significativamente: dificultad para crecer el negocio a través de proyectos hidroeléctricos, disminución de los precios debido al "efecto de orden de mérito" (Rubino et al., 2021; Sensfuß et al., 2008) y aumento de la volatilidad del precio de Bolsa (Milstein & Tishler, 2015; Pereira da Silva & Horta, 2019).

A pesar de estas amenazas, el contexto de alta penetración de ERV también ofrece oportunidades para las centrales hidroeléctricas. Éstas podrían aprovechar sus características especiales (e.g. flexibilidad, disponibilidad de terrenos, puntos de conexión y capacidad de almacenamiento) para desarrollar nuevos negocios que permitan compensar las deficiencias de las ERV, aprovechar sus complementariedades y así potenciar sus beneficios.

Varios estudios han analizado aplicaciones de tecnologías particulares combinadas con centrales hidroeléctricas, tales como: solar flotante (Zhou et al., 2020; Rauf et al., 2020; Laoharojanaphand & Ongsakul, 2021; Mehadi et al., 2021); centrales hidroeléctricas reversibles (Su et al., 2019; Karhinen & Huuki, 2019; Serrano-Canalejo et al., 2019; Kiene & Linkevics, 2021); producción de hidrógeno (Mohammadi & Mehrpooya, 2018; Choe et al., 2021; Nadaleti et al., 2021), entre otras, así como la optimización de la operación de hidroeléctricas y ERV (Knežević et al., 2019; Jamii et al., 2019; Riddervold et al., 2021; Jamii et al., 2021). Sin embargo, no se encontró ningún estudio que identifique, de una forma amplia, las opciones de negocio para las hidroeléctricas.

Esta brecha de conocimiento es abordada en el presente trabajo, el cual tiene como objetivo identificar las oportunidades de negocio para centrales hidroeléctricas, en el contexto de alta penetración de ERV. Esta información servirá a las empresas hidroeléctricas para orientar sus planes de investigación e inversión, de manera que obtengan el mayor provecho posible a la infraestructura existente y exploten sus ventajas competitivas.

2. Metodología

A partir de una revisión de literatura amplia, se están identificando las oportunidades de negocio para hidroeléctricas, relacionadas con la incursión masiva de ERV, considerando experiencias locales y de otros países, especialmente aquellos con alta generación hidroeléctrica (e.g. Noruega, Suiza y Brasil). En la revisión de literatura se identificarán también los principales problemas asociados con la alta penetración de ERV, y a partir de éstos se definirán posibles aplicaciones de las hidroeléctricas para solucionar estos problemas, que podrían constituir oportunidades de negocio.

Finalmente, cada alternativa de negocio se caracterizará con sus principales variables, tales como CapEx, OpEx, tiempo de construcción, ingresos, vida útil, riesgos, entre otros.

3. Resultados esperados

Se espera obtener una matriz en la que se caractericen las principales opciones de negocio de las centrales hidroeléctricas, en el contexto de alta penetración de ERV. Esta matriz tendrá un nivel de información general, suficiente para entender la lógica de negocio de cada alternativa.

En la siguiente tabla se presenta un avance de la identificación inicial de opciones de negocio:

Opción de negocio	Aspecto	Referencias
Plantas solares fotovoltaicas flotantes en embalses de hidroeléctricas	Optimización de la operación	(Silvério et al., 2018) (Zhou et al., 2020) (Rauf et al., 2020) (Laoharojanaphand & Ongsakul, 2021) (Mehadi et al., 2021)
	Evaluación de potencial	(Maués, 2019) (da Rocha Santos et al., 2019) (Lee et al., 2020) (Stiubiener et al., 2020) (Gonzalez Sanchez et al., 2021) (Mammadov et al., 2021)
	Comparación entre tecnologías	(Perez et al., 2018)
	Efecto sobre la calidad del agua, y la generación hidroeléctrica	(Haas et al., 2020)
	Evaluación como alternativa de modernización	(Quaranta et al., 2021)
Centrales hidroeléctricas reversibles (o de rebombeo)	Rol de las centrales reversibles en el contexto de alta penetración de energías renovables intermitentes	(Ayza, 2013) (Gurung et al., 2016) (Cheng, 2021)
	Conversión de hidroeléctrica a central reversible	(Kiene & Linkevics, 2021)
	Integración con plantas eólicas	(Su et al., 2019) (Karhinen & Huuki, 2019) (Serrano-Canalejo et al., 2019)
	Integración con plantas solares y eólicas	(Jurasz et al., 2018) (Xu et al., 2020) (Timmons et al., 2020) (Wu et al., 2021)
Operación comercial conjunta de hidroeléctricas y ERV	Integración con eólica	(Liu et al., 2015) (Knežević et al., 2019) (Jamii et al., 2019) (Riddervold et al., 2021) (Jamii et al., 2021)
	Integración con solar fotovoltaica	(Jakub Jurasz et al., 2020)
	Integración con solar	(Igder et al., 2017)
Producción de hidrógeno con la energía de hidroeléctricas	Evaluación de potencial	(Nadaleti et al., 2021) (Nadaleti et al., 2021)
	Comparación de tecnologías	(Mohammadi & Mehrpooya, 2018) (Choe et al., 2021)
	Optimización de la operación	(Huang et al., 2021)
	Viabilidad económica	(Jovan & Dolanc, 2020)
Hidrógeno como forma de almacenamiento de energía para hidroeléctricas		(Lu et al., 2015) (Valente et al., 2015) (Sauhats et al., 2016) (Posso Rivera et al., 2022)

Servicios auxiliares prestados por hidroeléctricas, para compensar los problemas asociados con la incursión de FNCER.	(Ayza, 2013) (Dujardin et al., 2017) (Igder et al., 2017) (Jamii et al., 2019) (Jovan & Dolanc, 2020)

4. Conclusiones

A continuación se describen algunas conclusiones parciales, con base en el trabajo realizado a la fecha:

- Existen por lo menos seis opciones de negocio para las hidroeléctricas, asociadas con el nuevo contexto de alta penetración de ERV, y con el eventual desarrollo de un mercado de hidrógeno verde.
- Algunas opciones de negocio, como las centrales reversibles y la prestación de servicios auxiliares, se derivan principalmente de las características especiales de las hidroeléctricas (capacidad de almacenamiento y flexibilidad, respectivamente). Otras, están relacionadas con sinergias entre las hidroeléctricas y las ERV, como en el caso de las solares flotantes y la operación comercial conjunta (optimización de las ofertas conjuntas en el mercado de corto plazo y en contratos).

Referencias

Ayza, J. R. W. (2013). The role of hydropower in the context of renewable energies in Spain. *Revista de Obras Publicas*, *160*(3548), 35–42. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84890899730&partnerID=40&md5=f6c87640b27812b4a38e742acd3d057b

Cheng, C. (2021). Function Remolding of Hydropower Systems for Carbon Neutral and Its Key Problems. *Dianli Xitong Zidonghua/Automation of Electric Power Systems*, *45*(16), 29–36. https://doi.org/10.7500/AEPS20201220003

Choe, C., Lee, B., Kim, A., Cheon, S., & Lim, H. (2021). Comprehensive assessment of CO2 methanation: Which H2 production pathway is practicable for green methane production in terms of technical, economic, and environmental aspects? *Green Chemistry*, *23*(23), 9502–9514. https://doi.org/10.1039/d1gc02755g

da Rocha Santos, F., D'Angela Mariano, J., Sestrem Junior, J. A., & Junior, J. U. (2019). Analysis of solar photovoltaic energy potential in Brazilian hydroelectric reservoirs through floating panels. *Brazilian Archives of Biology and Technology*, *62*(specialissue). https://doi.org/10.1590/1678-4324-SMART-2019190012

Dujardin, J., Kahl, A., Kruyt, B., Bartlett, S., & Lehning, M. (2017). Interplay between photovoltaic, wind energy and storage hydropower in a fully renewable Switzerland. *Energy*, *135*, 513–525. https://doi.org/10.1016/j.energy.2017.06.092

Gonzalez Sanchez, R., Kougias, I., Moner-Girona, M., Fahl, F., & Jäger-Waldau, A. (2021). Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa. *Renewable Energy*, *169*, 687–699. https://doi.org/10.1016/j.renene.2021.01.041

Gurung, A. B., Borsdorf, A., Füreder, L., Kienast, F., Matt, P., Scheidegger, C., Schmocker, L., Zappa, M., & Volkart, K. (2016). Rethinking Pumped Storage Hydropower in the European Alps. *Mountain Research and Development*, *36*(2), 222–232. https://doi.org/10.1659/MRD-JOURNAL-D-15-00069.1

Haas, J., Khalighi, J., de la Fuente, A., Gerbersdorf, S. U., Nowak, W., & Chen, P.-J. (2020). Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. *Energy Conversion and Management*, *206*. https://doi.org/10.1016/j.enconman.2019.112414

Huang, J., Wu, X., Zheng, Z., Huang, Y., & Li, W. (2021). Multi-Objective Optimal Operation of Combined Cascade Reservoir and Hydrogen System. *IEEE Transactions on Industry Applications*. https://doi.org/10.1109/TIA.2021.3138949

IEA. (2021a). *World Energy Outlook 2021*. https://www.iea.org/reports/world-energy-outlook-2021

IEA. (2021b). Hydropower Special Market Report. In *Hydropower Special Market Report*. OECD. https://doi.org/10.1787/07a7bac8-en

Igder, M. A., Niknam, T., & Khooban, M.-H. (2017). Bidding strategies of the joint wind, hydro, and pumped-storage in generation company using novel improved clonal selection optimisation algorithm. *IET Science, Measurement and Technology*, *11*(8), 991–1001.

https://doi.org/10.1049/iet-smt.2017.0014

Jamii, J., Abbes, D., & Mimouni, M. F. (2019). Energy management of wind power generation with pumped hydro energy storage and participation in frequency control: Study in electricity market. *International Journal of Renewable Energy Research*, *9*(4), 2082–2091. https://doi.org/10.1002/9781118100509.ch@

Jamii, J., Abbes, D., & Mimouni, M. F. (2021). Joint operation between wind power generation and pumped hydro energy storage in the electricity market. *Wind Engineering*, *45*(1), 50–62. https://doi.org/10.1177/0309524X19868473

Jovan, D. J., & Dolanc, G. (2020). Can green hydrogen production be economically viable under current market conditions. *Energies*, *13*(24). https://doi.org/10.3390/en13246599

Jurasz, J, Mikulik, J., Krzywda, M., Ciapała, B., & Janowski, M. (2018). Integrating a wind- and solar-powered hybrid to the power system by coupling it with a hydroelectric power station with pumping installation. *Energy*, *144*, 549–563. https://doi.org/10.1016/j.energy.2017.12.011

Jurasz, Jakub, Kies, A., & Zajac, P. (2020). Synergetic operation of photovoltaic and hydro power stations on a day-ahead energy market. *Energy*, *212*, 118686. https://doi.org/10.1016/J.ENERGY.2020.118686

Karhinen, S., & Huuki, H. (2019). Private and social benefits of a pumped hydro energy storage with increasing amount of wind power. *Energy Economics*, *81*, 942–959. https://doi.org/10.1016/j.eneco.2019.05.024

Kiene, S., & Linkevics, O. (2021). Simplified Model for Evaluation of Hydropower Plant Conversion into Pumped Storage Hydropower Plant. *Latvian Journal of Physics and Technical Sciences*, *58*(3), 108–120. https://doi.org/10.2478/lpts-2021-0020

Knežević, G., Topić, D., Jurić, M., & Nikolovski, S. (2019). Joint market bid of a hydroelectric system and wind parks. *Computers and Electrical Engineering*, *74*, 138–148. https://doi.org/10.1016/j.compeleceng.2019.01.014

Laoharojanaphand, V., & Ongsakul, W. (2021). Virtual battery storage service using hydropower plant with co-located floating solar and wind generation. *Sustainable Energy Technologies and Assessments*, *47*. https://doi.org/10.1016/j.seta.2021.101531

Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., & Cox, S. (2020). Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential. *Renewable Energy*, *162*, 1415–1427. https://doi.org/10.1016/J.RENENE.2020.08.080

Liu, Y., Jiang, C., Shen, J., Hu, J., & Luo, Y. (2015). Coordination of hydro units with wind power generation based on RAROC. *Renewable Energy*, *80*, 783–792. https://doi.org/10.1016/j.renene.2015.02.062

Lu, D., Wang, B., Wang, Y., Zhou, H., Liang, Q., Peng, Y., & Roskilly, T. (2015). Optimal operation of cascade hydropower stations using hydrogen as storage medium. *Applied Energy*, *137*, 56–63. https://doi.org/10.1016/j.apenergy.2014.09.092

Mammadov, Z. A., Kerimov, R. E., Kerimov, O. Z., & Rahmanov, N. R. (2021). Estimation of energy resources potential for solar photovoltaic systems located on the water surface of small lakes and reservoirs. *International Journal on Technical and Physical Problems of Engineering*, *13*(2), 107–111. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85111021533&partnerID=40&md5=29dc909fe4cfd2d315f68c93a61f0b73

Maués, J. A. (2019). Floating solar PV-hydroelectric power plants in Brazil: Energy storage solution with great application potential. *International Journal of Energy Production and Management*, *4*(1), 40–52. https://doi.org/10.2495/EQ-V4-N1-40-52

Mehadi, A. A., Nahin-Al-Khurram, Shagor, M. R. K., & Sarder, M. A. I. (2021). Optimized seasonal performance analysis and integrated operation of 50MW floating solar photovoltaic system with Kaptai hydroelectric power plant: a case study. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. https://doi.org/10.1080/15567036.2021.1962434

Milstein, I., & Tishler, A. (2015). Can price volatility enhance market power? The case of renewable technologies in competitive electricity markets. *Resource and Energy Economics*, *41*, 70–90. https://doi.org/10.1016/J.RESENEECO.2015.04.001

Mohammadi, A., & Mehrpooya, M. (2018). A comprehensive review on coupling different types of electrolyzer to renewable energy sources. *Energy*, *158*, 632–655. https://doi.org/10.1016/j.energy.2018.06.073

Nadaleti, W. C., Lourenço, V. A., & Americo, G. (2021). Green hydrogen-based pathways and alternatives: Towards the renewable energy transition in South America's regions – Part A. *International Journal of Hydrogen Energy*, *46*(43), 22247–22255. https://doi.org/10.1016/j.ijhydene.2021.03.239

Pereira da Silva, P., & Horta, P. (2019). The effect of variable renewable energy sources on electricity price volatility: the case of the Iberian market. *Https://Doi-Org.Ezproxy.Unal.Edu.Co/10.1080/14786451.2019.1602126*, *38*(8), 794–813. https://doi.org/10.1080/14786451.2019.1602126

Perez, M., Perez, R., Ferguson, C. R., & Schlemmer, J. (2018). Deploying effectively dispatchable PV on reservoirs: Comparing floating PV to other renewable technologies. *Solar Energy*, *174*, 837–847. https://doi.org/10.1016/j.solener.2018.08.088

Posso Rivera, F., Zalamea, J., Espinoza, J. L., & Gonzalez, L. G. (2022). Sustainable use of spilled turbinable energy in Ecuador: Three different energy storage systems. *Renewable and Sustainable Energy Reviews*, *156*. https://doi.org/10.1016/j.rser.2021.112005

Quaranta, E., Aggidis, G., Boes, R. M., Comoglio, C., De Michele, C., Ritesh Patro, E., Georgievskaia, E., Harby, A., Kougias, I., Muntean, S., Pérez-Díaz, J., Romero-Gomez, P., Rosa-Clot, M., Schleiss, A. J., Vagnoni, E., Wirth, M., & Pistocchi, A. (2021). Assessing the energy potential of modernizing the European hydropower fleet. *Energy Conversion and Management*, *246*. https://doi.org/10.1016/j.enconman.2021.114655

Rauf, H., Gull, M. S., & Arshad, N. (2020). Complementing hydroelectric power with floating solar PV for daytime peak electricity demand. *Renewable Energy*, *162*, 1227–1242. https://doi.org/10.1016/j.renene.2020.08.017

Riddervold, H. O., Aasgård, E. K., Haukaas, L., & Korpås, M. (2021). Internal hydro- and wind portfolio optimisation in real-time market operations. *Renewable Energy*, *173*, 675–687. https://doi.org/10.1016/j.renene.2021.04.001

Rubino, A., Sapio, A., & Scala, M. La. (2021). *Handbook of Energy Economics and Policy: Fundamentals and Applications for Engineers and Energy Planners*. Elsevier.

Sauhats, A., Coban, H. H., Baltputnis, K., Broka, Z., Petrichenko, R., & Varfolomejeva, R. (2016). Optimal investment and operational planning of a storage power plant. *International Journal of Hydrogen Energy*, *41*(29), 12443–12453. https://doi.org/10.1016/j.ijhydene.2016.03.078

Sensfuß, F., Ragwitz, M., & Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy Policy*, *36*(8), 3086–3094. https://doi.org/10.1016/J.ENPOL.2008.03.035

Serrano-Canalejo, C., Sarrias-Mena, R., Garcia-Trivino, P., & Fernandez-Ramirez, L. M. (2019). Energy management system design and economic feasibility evaluation for a hybrid wind power/pumped hydroelectric power plant. *IEEE Latin America Transactions*, *17*(10), 1686–1693. https://doi.org/10.1109/TLA.2019.8986447

Silvério, N. M., Barros, R. M., Tiago Filho, G. L., Redón-Santafé, M., Santos, I. F. S. D., & Valério, V. E. D. M. (2018). Use of floating PV plants for coordinated operation with hydropower plants: Case study of the hydroelectric plants of the São Francisco River basin. *Energy Conversion and Management*, *171*, 339–349. https://doi.org/10.1016/j.enconman.2018.05.095

Sokulski, C. C., Barros, M. V., Salvador, R., Broday, E. E., & de Francisco, A. C. (2022). Trends in Renewable Electricity Generation in the G20 Countries: An Analysis of the 1990–2020 Period. *Sustainability*, *14*(4), 1–21. https://doi.org/10.3390/su14042084

Stiubiener, U., Carneiro da Silva, T., Trigoso, F. B. M., Benedito, R. D. S., & Teixeira, J. C. (2020). PV power generation on hydro dam's reservoirs in Brazil: A way to improve operational flexibility. *Renewable Energy*, *150*, 765–776. https://doi.org/10.1016/j.renene.2020.01.003

Su, C., Cheng, C., Wang, P., Shen, J., & Wu, X. (2019). Optimization model for long-distance integrated transmission of wind farms and pumped-storage hydropower plants. *Applied Energy*, *242*, 285–293. https://doi.org/10.1016/j.apenergy.2019.03.080

Timmons, D., Elahee, K., & Lin, M. (2020). Microeconomics of electrical energy storage in a fully renewable electricity system. *Solar Energy*, *206*, 171–180. https://doi.org/10.1016/j.solener.2020.05.057

Valente, A., Iribarren, D., Dufour, J., & Spazzafumo, G. (2015). Life-cycle performance of hydrogen as an energy management solution in hydropower plants: A case study in Central Italy. *International Journal of Hydrogen Energy*, *40*(46), 16660–16672. https://doi.org/10.1016/j.ijhydene.2015.09.104

Wu, Y., Zhang, T., Gao, R., & Wu, C. (2021). Portfolio planning of renewable energy with energy storage technologies for different applications from electricity grid. *Applied Energy*, *287*. https://doi.org/10.1016/j.apenergy.2021.116562

XM. (2021). *Reporte integral de sostenibilidad, operación y mercado 2021*. https://informeanual.xm.com.co/informe/pages/home.html

Xu, X., Hu, W., Cao, D., Huang, Q., Chen, C., & Chen, Z. (2020). Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. *Renewable Energy*, *147*, 1418–1431. https://doi.org/10.1016/j.renene.2019.09.099

Zhou, Y., Chang, F.-J., Chang, L.-C., Lee, W.-D., Huang, A., Xu, C.-Y., & Guo, S. (2020). An advanced complementary scheme of floating photovoltaic and hydropower generation flourishing water-food-energy nexus synergies. *Applied Energy*, *275*. https://doi.org/10.1016/j.apenergy.2020.115389

A bi-objective optimisation approach for budget allocation within regional off-grid electrification planning

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Abstract

Regional off-grid electrification planning is about finding ways to improve energy access in groups of communities located in a wide geographic area. It entails managing and allocating limited economic resources to install, renovate and operate power energy solutions to enhance the region's welfare. Approaches involving the economic dimension of planning have dominated the literature, these seek to ensure that energy provision is at the minimum cost. The social dimension of planning has not been widely studied in the literature, this dimension is relevant to address issues such as allocating resources to enhance social impacts on populations living in off-grid regions. This paper attempts to fill a literature gap by proposing a budget allocation approach based on bi-objective optimization that: 1) assesses the overall potential impacts of energy provision on the region's economic and social dimensions; 2) calculates the trade-offs of prioritizing one dimension over the other and; 3) models the social dimension through a welfare measure. The model optimally allocates portions of the budget available for regional electrification and offers different levels of energy access to the group of communities under analysis. It minimises energy costs and maximises the potential impacts on the Human Development Index (HDI). The model is applied to the Colombian Pacific Coast, a region with hundreds of off-grid communities under high poverty levels, violence and political negligence. The results show an unreported trade-off between the HDI and energy costs. When the budget allocation is based on minimum energy cost, the communities with more renewable resources benefit the most, hindering energy access for less endowed communities. However, energy access balances across the entire region when the HDI maximisation is sought. As a result, the model suggests various budget allocation strategies that differ from the traditional ways practised in the region. Nevertheless, regardless of the strategy, the model suggests abandoning the widely employed diesel generation technology for solar photovoltaic (PV), reducing CO2 emissions by 14.870 tons annually.

Keywords: Off-grid electrification planning, Colombia, Solar energy, Budget allocation, Bi-Objective Optimization.

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COMPARATIVE ANALYSIS OF REGULATORY REFORM EXPERIENCES IN BRAZIL, CHILE, COLOMBIA AND MEXICO

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Overview

This article maps the main regulatory marks of the electricity reforms that took place in four countries: Brazil, Chile, Colombia and Mexico. It does so by analyzing differences and similarities in the regulatory framework evolution over three decades: the 1990s, the 2000s and the 2010s. To do so, it is performed a comparative analysis amongst the regulatory reforms in these countries. It is also considered the effects of the new regulatory framework in the expansion of electricity supply throughout this 30-year period. The research is based on documental research, and it is performed the analysis of differences-in-differences. From the compilation and analysis of regulatory marks, three distinct phases are perceived. The first phase is dedicated to provide the bases for electricity sector operation in the studied countries, which includes unbundling activities, working on tariffs scheme, and the overall creation of a new regulatory body to encouraged the entry of new agents For Brazil, Colombia and Mexico this first phase corresponds to the 1090s, while in Chile, it happens much earlier, from 1982 onwards. The second phase, which occurred throughout the 2000s, was directed to compensate for the distortions observed in the first one, as well as it to draw incentives to deploy alternative energy sources. In this period, the countries faced some electricity crisis, pressed by the increased demand for electricity. The third phase was dedicated focus on the modernization of the electricity chain, by improving some previous regulatory marks. During this third phase, Chile, Colombia and Mexico promulgated several important reforms, while Brazil, for it turn, kept the discussion on hold, pending on National Congress approval. In the 2010s, the model captured long-term improvement effects due to reforms, that were not captured in the two previous decades.

Keywords: Regulatory Marks, Latin American Electricity Sector, Differences-in-Differences.

Methods

This article analyses the electricity markets in four Latin American (LATAM) countries: Brazil, Chile, Colombia and Mexico. It considers the period from 1990 until 2019. It uses data that has been collected on websites of regulatory agencies of the above-mentioned countries, as well as from World Bank and the International Energy Agency.

The focus is on the power generation activity. Although the selected countries present distinct levels of electricity access and grid integration, they share aspects related to history, culture and institutional development [1]. The choice regarding these countries is based on the following reasons: (i) they are considered developing economies which have peer energy markets; (ii) together they represent 75% of the GDP of Latin America and the Caribbean; (iii) they are part of the G20, with worldwide representation; (iv) they correspond to the largest electricity producing and consuming markets in the LATAM region, in part due to the concentration of production centers of the main industries that use energy as an input; and (v) they hold part of the largest volumes of private investments in the electricity sector, according to World Bank data [2].

To develop our models, we use four principal variables: per capita installed capacity, per capita generated electricity, per capita electricity consumption, and electricity access. First, we conducted documental research, with statements from primary data sources. The categorization was performed using the inductive method. We use the discursive textual analysis for documental research. Then, we applied the differences-in-differences method, or just *diff-in-diff*, aiming at quasi-experimental causal inference. The method estimates allow testing to be performed by controlling for unobserved characteristics and combining them with observed or complementary information [3].

It can be represented mathematically by equation (1):

$$\mathrm{Y_{it}} = \beta_0 + \beta_1 Treat_i + \beta_2 Period_t + \beta_3\, Treat\ x\ Period_t + u_{it} \qquad (1)$$

where: $Treat_i$ e $Period_t$ are binary variables: $Treat_i$ = 1 indicates if is treated and $Period_t$ = 1 after the treatment. β_0 captures the untreated baseline before treatment; β_1 captures basic, unobserved and fixed differences between groups before treatment (assuming they are the same after treatment); β_2 comprises general controls, common trends that affect outcomes even in the absence of a treatment (assuming the same for both groups); β_3 estimates the treatment effect (when it occurs, in the treated group) [3].

The present study intends to contribute to the international literature realizing an analysis of similarities and differences of the countries in the sample through their main regulatory marks. The analysis is separated by decade: a model for each period corresponding to ten consecutive years, and the control and treatment groups is done by the countries that underwent regulatory reforms in each of the decades.

Our Research Hypothesis H1 is:

H1: The implementation of Regulatory Reforms positively affected the growth of the power generation industry in Latin American countries, through the impact on sectoral indicators.

The test steps consist of: first, performing the separation of the sample observations, for each country individually, in the periods before and after the main regulatory marks of the country.

Next, a dummy time variable is created, called time, which in this case will be for t<year of the regulatory mark referring to the analyzed decade = 0 (control group before the exogenous event) and for t>year of the regulatory mark referring to the analyzed decade = 1 (control group after the exogenous event).

The next step is to generate a treatment dummy, called treatment, which, for this study, will have a value for each country, as well as the time variable. For id<number of observations before the regulatory mark referring to the analyzed decade = 0 (treatment group before the exogenous event) and for id>number of observations before the regulatory mark referring to the analyzed decade = 1 (treatment group after the exogenous event).

The treatment variable reflects the occurrence of each relevant regulatory mark for the countries' electricity sector. After these procedures, the interaction variable between time and treatment is generated. This variable is a dummy and corresponds to the DID estimator, which allows the comparison of periods before and after the main regulatory marks.

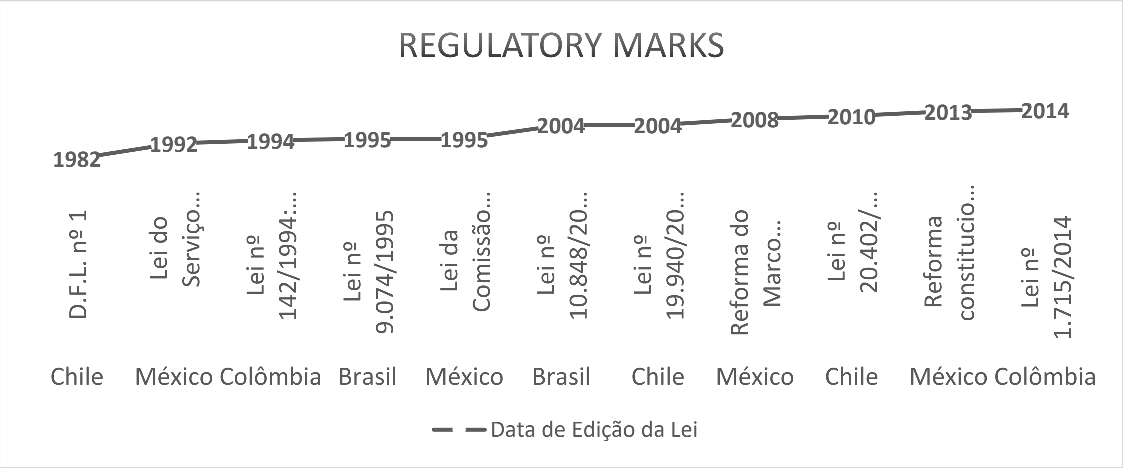
Finally, the Diff-in-Diff Test is applied according to the sequence of commands in the Stata software. The analysis was separated by decade in order to capture the effect of regulatory reforms in countries and establish treatment and control groups. Each decade generated a model with its initial period according to the regulatory marks.

Results

The documental research finded that regulatory evolution, therefore, occurs in phases. In the first phase, in general, countries create the conditions for the electricity sector development, promote the entry of companies, generally with private capital, define prices and stimulate electricity supply. The countries Brazil, Chile and Colombia performed the first phase from this perspective. The second phase aims to correct the effects generated by the first and, consequently, advances with more changes to the arrangement of distortions and improvement of costing methods. In the sampled countries, the second phase took place a decade after the first.

The third phase incorporates consumer protection innovations, expansion of installed capacity and aims at the sustainability of the sector as a whole. The third phase varied between countries. Chile, Colombia and Mexico realized a third reform in the 2010s. Brazil started discussions on a new reform in 2017, in public consultation with sector agents, but it has not formalized the legislation and the reform is in progress. Figure 1 evidences the timeline of regulatory marks in selected countries.

Figure 1 – Timeline of Regulatory Marks



Source: Research Data, 2021.

The pioneering experiences in privatization in Chile initiated discussion of the political and technical aspects for the other economies of the continent, and it can be inferred that they had effects in the other countries, in their initial stage.

Evidently, considering the idiosyncrasies of each country's national systems, the characteristics of this first stage involved: the establishment of regulatory agencies, the legal-institutional apparatus, the conditions of access to market participants, the unbundling of activities, and the rules for setting tariffs, quality of services, among others.

After the initial stage, lasting between ten and fifteen years, there was a later stage of adjustments to competitive conditions, with new parameters for setting tariffs and moving towards tentative forms of a free market.

In general, in the second stage, some previous measures are corrected and an attempt is made to improve the competitive aspect, the independence and quality of regulatory agencies, and numerous attempts to expand the electricity supply in response to climate challenges and insufficient investments. This last problem would become critical in the energy sectors of the countries and led to advances in the private sector in the supply of other forms of energy, namely: wind, solar, biomass and natural gas.

There is still a third stage, which is more dissimilar between the countries. It seeks institutional and regulatory changes, sometimes more aligned with climate change, sometimes with a greater supply of electricity, with a strong influence of economic requirements and investments by private sector and greater participation of international capital.

It is noted, therefore, that the phenomenon of geographic diffusion, conditioned by the dependence of the countries' trajectory, allowed the sequencing of similar reforms, where in certain periods the predominance of regulatory progress can be observed, in others an emphasis on the technical vision, and meeting the wishes of consumers demanding changes in energy supply and tariffs.

We cannot forget the actions of Governments that, due to a structural defect, interfere seriously in the sector's issues, sometimes producing increased risks – of demand, regulatory, financial and contractual, which make the regulatory environment in these countries highly judicialized.

The diff-in-diff analysis, At first, there was no expected response to the variables. Over the decades, the treatment effect became positive, as expected, even if alternations occur.

A possible conclusion in relation to these results would be to consider the existence of problems in the specification of regulatory reforms, inhibiting a positive and significant result of differences in the periods before and after the enactment of the reforms.

No matter how good a reform is, if it does not become a tool to encourage investment, the result could be this negative effect. The findings of this research show how dependent the infrastructure sector is on other areas within the Governments themselves.

The electricity sector or regulatory bodies want to implement a reform, however, the scenario becomes unfavorable, due to the absence of incentives from the Ministry of Economy, for example. It is observed that the infrastructure has particularities.

The decision may be favorable to optimize the generation of revenue, the coverage of the public electricity service, the generation of taxes, the service to the low-income social stratum, and the objective of self-sufficiency in the production of electricity, factors whose choice stems from political and non-technical acts, the process gives rise to a very different result than expected.

Conclusions

This word focused on evaluating the regulatory marks for the electricity sector in selected Latin American countries. The analysis considered the periods in which those reforms took place, classifying them into three phases.

Chile was at the forefront of the process, enacting its first regulatory reform in 1982. The other analyzed countries began their reforms in the 1990s, following the movement towards liberalizing infrastructure markets and proposing an environment conducive private investment take place. From what was observed, only Mexico had kept its key energy companies under state regimes, unlike the other examined countries.

In relation to the aspects sought by the reforms, the countries followed a similar path. By the end of the modernization process, Chile, Colombia and Mexico promoted actual changes to boost their electricity sector, while Brazil kept the changes still in progress.

Regarding the highlights of the different moments of regulatory interference, three decades were analyzed separately, to check for differences and similarities throughout the process of the distinct countries. In the beginning, in the 1990s, the results of the reforms, especially any possible improvement, could not yet be felt by the local markets. In the 2000s, the positive changes could be captured by sectoral indicators. The exception was regarding the access to electricity, which had not shown an important improvement. Nevertheless, in the 2010s that there was a real reversal, and the results of regulatory reforms were positively felt by the countries. In this decade, the expected reforms were finally implemented, and at the same time adjusted. The correction of a sequency of distortions were made, which promoted the actual improvements. One can expect that future public policy proposals can be made for the electricity sector in the analyzed countries. They are even more urgent in those that have not yet completed the third phase of their reform process.

In general, one can say that regulatory reforms have a period of greater effectiveness and periodically need improvement. In this study, it was observed that those changes occurred in cycles of ten to fifteen years, following the dynamics of the evolution of institutions, political changes, and international trends in the electricity sector. In addition, the role of investors was key to direct society's view regarding electricity generation, attributing a greater value to renewable sources, especially at the end of their reform’s cycles.

References

[1] Rivero, A. B, & Colom, J. B. (2010). La integración económica y la competitividad en el sector eléctrico: análisis de casos en América Latina. *Latinoamérica. Revista de Estudios Latinoamericanos*, (51), 37-61.

[2] WORLD BANK DATA, Private Participation in Infrastructure (PPI). Disponível em: https://ppi.worldbank.org.

[3] Villa, J. M. (2016). diff: Simplifying the estimation of difference-in-differences treatment effects. *The Stata Journal*, *16*(1), 52-71.

Comparative Evolution of Net Energy Metering Policy in Brazil and California - Challenges, Lessons, and Prospects

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According to the International Energy Agency, variable renewable energy (VRE) are the leading technologies to advance decarbonization till 2030. In this path, solar PV stands out, often supported by incentive schemes for distributed generation. There is extensive economic literature on the distributive impacts of Net Energy Metering (NEM) in the context of increasing insertion of distributed energy resources (DER) and not-yet-adapted electricity tariffs (Borenstein, 2017; Mallapragada et al., 2022).

NEM was implemented in California in the 1990s and has spread to different geographies around the globe. In California, the program went through a revision of rules and parameters, updating the prosumers' electricity tariff, and since 2020 a new update is under discussion. Plans to revisit it in the quest for fairness follow the guiding principles of the ratemaking (efficiency, cost recovery, equity, and feasibility).

In the first version of the program (NEM 1.0), defined by Senate Bill 656 in 1995, prosumers received a full retail rate bill credit for electricity generated by their onsite systems and injected into the grid, when generation exceeded onsite energy demand. The monetary credits (Net Billing) offset future monthly bills, valid for one year (CPUC, 2021).

In 2013, a new law (Assembly Bill 327) mandated that the California Public Utilities Commission (CPUC) adopt a successor to the existing net energy metering tariff. In NEM 2.0, in effect since 2016, prosumers continue to receive full retail rate credit for excess energy exported to the grid during a 12-month billing cycle, as well as receive net surplus compensation. However, NEM 2.0 prosumers must pay additional charges – one-time interconnection fee and monthly nonbypassable charges – to align their costs more closely with non-NEM customer costs. Further, NEM 2.0 prosumers must be subject to a time-of-use tariff. A review of NEM 2.0 was scheduled to be conducted in 2019 by the CPUC, which was also responsible for monitor the implementation of NEM 2.0 and explore other compensation structures for prosumer-sited generation with a view to considering an export compensation tariff that considers locational and time-differentiated values.

In Latin America, ten countries adopted net metering from 2008 to 2018 (Mejdalani et al., 2018). Of these countries, only in Brazil is the prosumer compensated in full for the electricity injected into the distribution grid. Income distribution is unequal, and deployment of DER without adapting regulation conflicts with the guiding principles.

In Brazil, the Net Metering Program (NM) was initially established by resolution of the Regulatory Agency (ANEEL) in 2012, contemplating a energy credits related to a full retail rate credit for for the balance of electricity generated in excess of the prosumers' monthly consumption, valid for 60 months. In 2015, a new resolution extended the possibility of NM adoption by remote generation units within the distribution's area (virtual-NM), in addition to shared generation and compensation schemes. The resolution also provided for a review of rules and parameters in 2019. The regulatory review process was tumultuous and politicized, taking the discussion to the National Congress. A new law focused on distributed generation was enacted in 2022, establishing a gradual transition

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rule to remove the costs related to the distribution activity from the compensation of net metering, preserving the acquired right to the current rules by units installed and requested until the end of 2022.

As Gruespecht et al. (2022) discuss, efficient electrification and investment in variable and distributed resources require that retail tariffs can vary with wholesale market spot prices, which must include the social cost of emissions. On the other hand, the prevalence of fixed costs from systems dominated by variable sources imposes tariffs with high fixed components. The challenge is to establish schemes that provide efficient signals to retail consumers while, at the same time, a significant fraction of the tariffs covers invariably fixed costs. As Mallapragada et al. (2022) note, "these costs should be covered by customer-specific charges that are fixed in the short run but respond to long-run demand patterns and that vary among customers in a politically acceptable way".

Borenstein et al. (2021) investigate the gap between electricity rates for three utilities in California. Electricity rates are significantly higher than the private marginal costs and even the social marginal costs. Therefore, the adoption of rooftop solar – which has increased considerably and is expected to keep on rising on the road to decarbonization – shifts costs from adopters to non-adopters.

Initiatives to revise the NEM have met with significant opposition in Brazil and California. However, while California already applies a ToU tariff and is still discussing further revision of the program, Brazil has defined a gradual transition to mitigate cross-subsidies and has restricted the scope of action of the regulatory agency.

This paper aims to revisit recent regulatory trends and changes to adapt regulation to a more decentralized environment in Brazil and California. The main objective is to present the recent evolution of Net Energy Metering regulation in Brazil and its effects on the power sector in light of California's experience and its ongoing discussions.

References:

Borenstein, S. (2017). Private Net Benefits of Residential Solar PV: The Role of Electricity Tariffs, Tax Incentives, and Rebates. Journal of the Association of Environmental and Resource Economists, 2017, vol. 4, issue S1, S85 – S122.

Borenstein, S.; Fowlie, M.; Sallee, J. (2021). Designing Electricity Rates for An Equitable Energy Transition. Energy Institute WP 314.

CPUC – California Public Utility Commision (2021). Proposed Decision R.20-08-020 – Decision Revising Net Energy Metering Tariff and Subtariffs. December 13, 2021.

Gruespecht, H.; Pfeifenberger, H.; Joskow, P.; Schmalensee, R. (2022). Electricity Sector Policy Reforms to Support Efficient Decarbonization. MIT CEEPR WP 2022-007, April 2022. Early Release of Chapter 8 of the MIT Future of Storage Study.

Mallapragada, D.; Junge, C.; Wang, C.; Pfeifenberger, H.; Joskow, P.; Schmalensee, R. (2022). Electricity Pricing Problems in Future Renewables-Dominant Power Systems. MIT CEEPR WP-2021-017R.

Mejdalani, A.; Chueca, J. E.; Soto, D.; JI, Y.; Hallack, M. (2018). Implementing net metering policies in Latin America and the Caribbean: Design, incentives, and best practices. Energy Division – Infrastructure and Energy Sector. BID. Technical Note nº IDB-TN-1594.

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56. Potencial de inserción de vehículos de celdas de combustible en el parque automotor colombiano.
Autores: Paula Riveros, Cesar Barraza Botet y John Sanchez Cardozo

DETERMINANTES DEL CONSUMO DE ENERGÍA DEL SECTOR RESIDENCIAL UN ANÁLISIS BIBLIOMÉTRICO

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Abstract

La presente publicación busca entregar distintos tópicos utilizados en diversas investigaciones, realizando un análisis bibliométrico de la situación actual. Se consideran en este estudio, artículos publicados entre los años 2000 y 2020. El documento describe distintos tipos de información que se han incorporado a las bases de datos, tales como cantidad de citaciones, principales autores, países en los cuales se ha avanzado en estas temáticas. Se realiza un análisis teórico de la información, utilizando herramientas como VosViewer. Se realiza una discusión de los principales desarrollos presentados por los investigadores

El sector residencial es responsable del 22 % del consumo total de energía a nivel global. Su relevancia ha motivado una literatura emergente orientada a reducir tanto los requerimientos de consumo como de la reducción de las emisiones de GHG generadas. Esta literatura se ha generado en diferentes campos científicos que abordan cuestiones tal como el propio consumo de energía, las características óptimas de los edificios, las mejoras en su eficiencia energética, el tipo de materiales utilizados en su construcción, los combustibles utilizados con fines de calefacción, entre otros.

Tomando como punto de partida el inicio del siglo XXI y sólo la base de datos electrónica Scopus, es posible identificar 2936 documentos científicos peer review publicados sobre consumo de energía y emisiones de GHG en el sector residencial. La mayor parte de documentos se han publicado a partir de 2014. Más exactamente el promedio de publicaciones anuales a partir de 2014 ha sido de 146.8. No obstante, la publicación más citada corresponde a 2008, contando con 3926 citas en el momento de realizar esta investigación, (aproximadamente más del doble de la que le sigue con 1719, publicada en 2004).

A pesar del emergente número de publicaciones, la falta de conexión entre los diferentes abordajes del tópico entre investigadores de diferentes campos científicos actúa como una barrera para encontrar medidas eficaces orientadas a reducir el consumo energético. Los análisis bibliométricos ayudan a identificar áreas comunes en las que trabajan investigadores desde distintas áreas científicas en torno al mismo tópico.

El objetivo de este artículo es encontrar los principales determinantes del consumo de energía en el sector residencial y de las emisiones de GHG asociadas. Para hacer esto se desarrolla un novedoso análisis bibliométrico de la literatura emergente relacionada con ambos tópicos. El análisis se realiza mediante el uso de software bibliométrico aplicado a una rica base de datos que incluye documentos científicos peer review incluidos en las bases de datos Scopus, Web of Science (WOS) y Scielo.

Especial interés se presta al caso de Chile. La elección está motivada en la diversidad dos aspectos de interés. El primero es el de la climática del país que cuenta con 5 tipos de clima diferentes. El segundo es la reciente entrada de vigor de normas orientadas a la mejora de la eficiencia energética como la ley 21.305 (BCN, 2021). La nueva norma está en línea con el compromiso de Chile de alcanzar la neutralidad en emisiones de carbono en 2050 en el contexto del acuerdo de París (Unfccc, 2015).

La utilización de combustibles fósiles ya está cuestionado desde todas las aristas, dándole énfasis al uso de energías renovables no convencionales. Otro punto importante a considerar, está referido a la actual mirada de incorporar soluciones inteligentes que permitan optimizar los gastos energéticos de las viviendas, más esto lleva a pensar en cómo seguimos alimentando esta demanda a lo largo del tiempo en temas de electricidad.

Países como Estados Unidos, Reino Unido, China, Italia, España, han puesto como tema de investigación las políticas energéticas con las que actualmente se cuenta, generando discusiones que aporten al desarrollo de países más pequeños como Chile. Esto muestra que, si no se cuenta estas políticas públicas, es difícil generar los cambios energéticos que hoy se están buscando.

References

Albatayneh, A., Juaidi, A., Abdallah, R., Peña-Fernández, A. & Manzano-Agugliaro, F. (2022a). Effect of the subsidised electrical energy tariff on the residential energy consumption in Jordan. Energy Reports, 8, 893–903. https://doi.org/10.1016/j.egyr.2021.12.019

Dou, X., Wang, Y., Ciais, P., Chevallier, F., Davis, S. J., Crippa, M., Janssens-Maenhout, G., Guizzardi, D., Solazzo, E., Yan, F., Deng, Z. & Liu, Z. (2022). Near-real-time global gridded daily CO<inf>2</inf> emissions. The Innovation, 3(1). https://doi.org/10.1016/j.xinn.2021.100182

Doytch, N. & Narayan, S. (2021). Does transitioning towards renewable energy accelerate economic growth? An analysis of sectoral growth for a dynamic panel of countries. Energy, 235. https://doi.org/10.1016/j.energy.2021.121290

Ibañez Iralde, N. S., Pascual, J. & Salom, J. (2021a). Energy retrofit of residential building clusters. A literature review of crossover recommended measures, policies instruments and allocated funds in Spain. Energy and Buildings, 252. https://doi.org/10.1016/j.enbuild.2021.111409

Magerl, A., Matej, S., Kaufmann, L., Noë, J. L., Erb, K. & Gingrich, S. (2022). Forest carbon sink in the U.S. (1870–2012) driven by substitution of forest ecosystem service flows. Resources, Conservation and Recycling, 176. https://doi.org/10.1016/j.resconrec.2021.105927

Mercader-Moyano, P., Anaya-Durán, P. & Romero-Cortés, A. (2021). Eco-efficient ventilated facades based on circular economy for residential buildings as an improvement of energy conditions. Energies, 14(21). https://doi.org/10.3390/en14217266

Ministerio de Energía. (2021). Ley 21305 SOBRE EFICIENCIA ENERGÉTICA MINISTERIO DE ENERGÍA SOBRE EFICIENCIA ENERGÉTICA. https://www.bcn.cl/leychile/navegar?idNorma=1155887

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M. & Abd. Majid, M. Z. (2015). A global review of energy consumption, CO<inf>2</inf> emissions and policy in the residential sector (with an overview of the top ten CO<inf>2</inf> emitting countries). Renewable and Sustainable Energy Reviews, 43, 843–862. https://doi.org/10.1016/j.rser.2014.11.066

Safarzadeh, S., Rasti-Barzoki, M. & Hejazi, S. R. (2020). A review of optimal energy policy instruments on industrial energy efficiency programs, rebound effects, and government policies. Energy Policy, 139. https://doi.org/10.1016/j.enpol.2020.111342

Unfccc. (2015). Paris Agreement Spanish. https://unfccc.int/sites/default/files/spanish_paris_agreement.pdf

U.S. Energy Information Administration. (2016). International Energy Outlook 2016. www.eia.gov

RETOS DE LA RESPUESTA DE LA DEMANDA EN ZNI Y SU IMPACTO EN LA EFICIENCIA ENERGÉTICA

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INTRODUCCIÓN:

A través de la literatura se ha identificado que la Respuesta de la Demanda (RD) consiste en modificaciones del consumo de energía eléctrica de un consumidor con respecto a un patrón usual en respuesta a señales de precios o incentivos económicos trazados para gestionar óptimamente los consumos energéticos, así mismo, los mecanismos RD permiten a los consumidores desempeñar un rol protagónico en la cadena de suministro, interactuando ellos con la reducción y la modificación del uso de energía principalmente [1].Un reto interesante es modelar su desarrollo en las Zonas No Interconectadas de Colombia-ZNI [2]. La importancia de impulsar mecanismos RD radica en que través de ellos, es posible alcanzar mayores eficiencias para abastecer la demanda de energía y brindar confiabilidad al sistema con aprovechamiento de la oferta renovable local, la cual es ampliamente aprovechable en las ZNI

METODOLOGIA:

Se analizó primero el impacto positivo de la RD en la Eficiencia Energética (EE). En este primer escenario, encontramos que las interacciones de la EE y la RD probablemente son impulsadas por cambios en la carga discrecional, la adición de controles técnicos u otras capacidades para controlar las cargas y la coincidencia de los ahorros con los períodos pico de un sistema [3-7], estos escenarios pueden ser modelados secuencialmente por bloques, tal como se indica en la figura 1 y sus resultados ser aplicados en una población objetivo de las ZNI

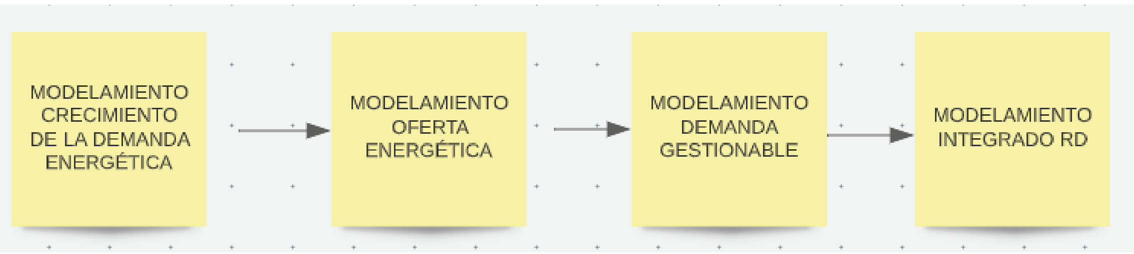

Figura 1. Diagrama de bloques modelamiento RD

El segundo análisis fue referido al escenario del impacto de las nuevas tecnologías en el consumo energético y su relación con la respuesta de la demanda. Al respecto (En-Ze Wang a, Chien-Chiang Lee) considera un modelo de demanda de energía extendida con un modelo de mezcla finita que es incorporado para dar cuenta del nexo heterogéneo entre la comunicación de la información tecnología (TIC) y la demanda de energía [8]. En ese sentido el primer bloque de modelamiento con la incorporación de la variable nuevas tecnologías y fuentes de energía renovables permitiría proyectar un crecimiento de la demanda energética bajo este escenario.

RESULTADOS ESPERADOS

Propuesta de modelamiento de la demanda energética en localidad ZNI que incorpore aspectos de nuevas tecnologías, Respuests de la Demanda y Fuentes renovables de energía. Se muestran resultados preliminares de la investigación. En estos se pueden apreciar como con respuesta de la demanda se podrán lograr mayores avances que sin este mecanismo, además se logrará hacerlo de manera sostenible en términos sociales, económicos y ambientales, también analizando costos y beneficios

CONCLUSIONES:

Las nuevas tecnologías ejercen un efecto positivo en la demanda de energía, no obstante, a través del modelamiento también se puede identificar el impacto de la RD en la eficiencia energética

Los perfiles de consumo de los usuarios tienden a la disminución bajo escenarios de eficiencia energética.

Finalmente, en comparación con un modelo de crecimiento de demanda de energía innovador, un modelo de demanda de energía tradicional no podría estimar con mayor precisión tendencias de consumo alineados con nuevas tecnologías. Los análisis comparativos de Modelo con y sin RD contribuyen a una mejor toma de decisión.

Las Zonas No Interconectadas por su disponibilidad de potenciales energéticos renovables se constituye en escenarios ideales de aplicación de mecanismos RD

REFERENCIAS

[1] Cappers, P., Goldman, C., & Kath, D. Demand response in U.S. electricity markets: Empirical Evidence. Berkeley: Berkeley Lab. (2009).

[2] http://www.secretariasenado.gov.co/senado/basedoc/ley_0855_2003.html

[3]. Satchwell, A.J.; Cappers, P.A.; Deason, J.; Forrester, S.P.; Mims Frick, N.; Gerke, B.F.; Piette, M.A. A Conceptual Framework to Describe Energy Efficiency and Demand Response Interactions. Energies 2020, 13, 4336.

[4].. Mier, M.; Weissbart, C. Power Markets in Transition: Decarbonization, Energy Efficiency, and Short-Term Demand Response. Energy Econ. 2020, 86, 104644.

[5] Goldman, C. Coordination of Energy Efficiency; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2010.

[6] Webb, E.; Wu, O.Q.; Cattani, K. Coordinating Energy Efficiency and Incentive-Based Demand Response; Elsevier: Amsterdam, The Netherlands, 2019.

[7] Farzaneh, H.; Malehmirchegini, L.; Bejan, A.; Afolabi, T.; Mulumba, A.; Daka, P.P. Artificial Intelligence Evolution in Smart Buildings for Energy Efficiency. Appl. Sci. 2021, 11, 763.

[8] En-Ze Wang a, Chien-Chiang Lee. The impact of information communication technology on energy demand: Some international evidence; Elsevier: International Review of Economics and Finance 81 (2022), 128-146

The energy potential of residual biomass for gasification in Colombia for energizing off-grid zones (ZNI). Assessment of its pertinence through data analysis and composite indicator.

Background and potential impacts

The proportion of the population without access to electricity worldwide has been decreasing over the last decades, reaching about 9% of the total world population, but maintaining 17% for the rural population in 2021, especially in Sub-Saharan Africa, Southeast Asia, and Latin America [1], [2]. It represents progress towards meeting SDG-7 [3], [4]; however, as progress is made towards this target, difficulties increase because much of this population is located in remote and off-grid localities, where plants with small capacities and operating at low load factors are required, which increases energy costs [5]. In addition, it is a challenge for governments in different countries, such as Colombia, where, by the year 2020, 6% of the population, most of them in the NIZ, will not have access to electricity (14% of this population), a value similar to the average of other developing countries [6].

Identifying the energy potentials of renewable energy sources such as residual biomass represents an opportunity to project sustainable energy solutions for electrification in these localities in Colombia. Potentially, this energy resource can represent between 14% and 29% of the country’s electricity demand, according to the 2019 national demand of 259 PJ [7]–[9]. Therefore, it could be an environmentally viable solution for reducing greenhouse gas (GHG) emissions in the country, contributing to the fulfillment of the country’s international commitments in the fight against climate change to reduce these emissions by 51% by 2030[10].

Methodology

Energy service data analysis

Initially, nine technical and commercial variables on electricity service in the ZNI localities were obtained from the Unique Information System (SUI) of the Superintendence of household public services (SSPD) [11], reported by the service operators. Data were cleaned, leaving only stratum one residential users (about 99% of users) and only localities with less than 500 kW of installed capacity. Localities with implemented or planned photovoltaic solutions were also discarded. It results in 1553, 1618, 1608, and 1589 localities, respectively, for four moments: Mar-2019, Sep-2019, Mar-2020, and Sep-2020. Missing data was filled in different forms, as recommended in [12]. COE missing data were filled according to values in localities with the same service operator, and billing was filled using energy data and COE. For diesel unit and transport costs, missing data were filled according to localities with the same fuel collection site and municipality. For some localities with more than one Genset, only one was taken according to with maximum power reported for these localities in CNM telemetry reports [13]. The analysis of the four moments results in 1489 localities with data at each moment, showing an invariable behavior of the data according to the P-value test, which allows selecting only one data set, being the selected one the one corresponding to Sep-2020.

The nine variables were normalized by the Z-score method to avoid the dominance of those with higher ranges or scales. Subsequently, they have been dimensionally reduced by Principal Component Analysis (PCA), and some outliers have been removed by the percentile method. The first three principal components add up to a variance higher than 90% and are the ones selected to analyze the data. Finally, using the k-medoids method and the Partitional Around Medoids (PAM) algorithm, using a Square Euclidean distance, clustering the data has been made according to the values obtained for the 3 PCs representing the highest variance.

Analysis of waste biomass data and its energy potential

The residual biomass data were obtained from the municipal agricultural assessments (EVA) projected for 2020. [14] for all the municipalities that contain the localities of the sep-2020 dataset, for a total of 1522 localities with energy service data and residual biomass data considered for energy use [7]. The EVAs' relevant data for estimating residual biomass's energy potential are the cultivated area, the yield per hectare, and the annual tons of production. These data, together with the product/residue ratio taken from [7] and a residual biomass harvesting factor of 0.8 [15], [16], allow estimating the theoretical energy potential of these residual biomasses, similar to other published works. [17], [18]. The lower calorific value of each waste is established according to different references and estimates [7], [19]–[24]. Finally, the technical energy potential for biomass gasification is estimated using a conversion efficiency of 13%, the minimum value referenced for downdraft biomass gasifier systems coupled to internal combustion engines [25], [26], the most suitable for small-scale power generation from biomass [27]–[29].

The residual biomass energy potential data are then obtained for each municipality with localities in ZNI and normalized similarly to the energy service data. Allocation of energy potential for each locality is made by weighting the number of stratum one users of the service in each locality of each municipality, assuming that the area of their agricultural activities is proportional to the number of users and people in each one.

Results and conclusions

The analysis of energy service data in the localities of the ZNI has made it possible to determine clusters that group these localities into five typologies according to their technical and commercial energy service data. Furthermore, the characteristics of each cluster have made it possible to establish two deficit indicators, one for users served and the other for diesel fuel deficit. Finally, a weighted aggregation was used to generate an energy service deficit indicator for each locality according to its typology or cluster.

The analysis of residual biomass energy potential data has made it possible to establish a possible energy margin indicator between the potential for each location and the theoretical electrical energy to be supplied by the operators in each location.

These two indicators have been weighted-aggregated, and using adjustment factors; it has been possible to establish an indicator of the relevance of energizing localities in ZNI from biomass gasification based on public data and analysis of these data. This indicator allows identifying those localities where this possible energy solution deserves to be analyzed in terms of its feasibility and sustainability, achieving greater precision when considering possible projects in these localities. Likewise, this methodology can be replicated for other renewable energy sources such as photovoltaic or thermal solar energy or livestock waste. Finally, the results show how the data analysis is a helpful tool for studying energy solutions aligned with the fulfillment of national goals in the fight against climate change in isolated localities.

References

[1] International Energy Agency, International Renewable Energy Agency, United Nations Status Division, World Bank, and World Health Organization, “Tracking SDG 72020 - The energy progress report 2020,” Washington DC, 2020. [Online]. Available: www.worldbank.org

[2] DNV GL, “Energy Transition Outlook 2020 - A global and regional forecast to 2050,” *Dnv Gl Energy Transition Outlook*, p. 306, 2021, [Online]. Available: https://eto.dnvgl.com/2020/index.html

[3] International Renewable Energy Agency IRENA, “Off-grid renewable energy solutions to expand electricity access An opportunity not to be missed,” 2019.

[4] UNDP and ETH Zurich, “Derisking Renewable Energy Investment: Off-Grid Electrification,” 2018.

[5] R. V. Siemons, “Identifying a role for biomass gasification in rural electrification in developing countries: The economic perspective,” *Biomass Bioenergy*, vol. 20, no. 4, pp. 271–285, 2001, doi: 10.1016/S0961-9534(00)00085-4.

[6] IEA, “World Energy Outlook 2020,” Paris, 2020.

[7] Unidad de Planeación Minero Energética (UPME), IDEAM, COLCIENCIAS, and UIS, *Atlas del potencial energetico de la biomasa residual en colombia*. Ministerio de minas y Energía, 2011.

[8] L. E. Cáceres-Martínez, D. C. Guío-Pérez, and S. Rincón-Prat, “Potencial energético teórico y técnico de biomasa residual disponible en Colombia para el aprovechamiento en procesos de trasformación termoquímica,” in *3er Congreso de Energía sostenible*, 2016, pp. 106–111. [Online]. Available: https://www.researchgate.net/publication/327232550

[9] XM, “Demanda de energía nacional,” 2020. https://informeanual.xm.com.co/2020/informe/pages/xm/23-demanda-de-energia-nacional.html (accessed Aug. 19, 2022).

[10] Ministerio de Ambiente y Desarrollo Sostenible, “ACTUALIZACIÓN NDC COLOMBIA-2020 Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC),” Bogotá DC, 2020.

[11] Superintendencia de Servicios Públicos Domiciliarios SSPD, “Sistema Único de Información.” http://www.sui.gov.co/web/energia (accessed Oct. 06, 2021).

[12] IAEA, “Selecting and Using Energy Indicators,” in *Energy Indicators for Sustainable Development: Guidelines and Methodologies*, 2008, pp. 25–29.

[13] “Informe Mensuales Telemetría – IPSE-CNM.” https://ipse.gov.co/cnm/informe-mensuales-telemetria/ (accessed Oct. 19, 2021).

[14] Ministerio de Agricultura y Desarrollo Rural, “Evaluaciones Agropecuarias Municipales EVA | Datos Abiertos Colombia,” 2019. https://www.datos.gov.co/Agricultura-y-Desarrollo-Rural/Evaluaciones-Agropecuarias-Municipales-EVA/2pnw-mmge (accessed Aug. 23, 2022).

[15] S. Karaj, T. Rehl, H. Leis, and J. Müller, “Analysis of biomass residues potential for electrical energy generation in Albania,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 493–499, Jan. 2010, doi: 10.1016/j.rser.2009.07.026.

[16] L. Pérez Saldarriaga and S. Salazar Briceño, “Elaboración de una guía ambiental para el manejo limpio en el aprovechamiento energético de la biomasa residual,” Universidad de La Salle, Bogota DC, 2015. [Online]. Available: https://ciencia.lasalle.edu.co/ing_ambiental_sanitaria

[17] G. G. da Costa, I. F. S. dos Santos, R. M. Barros, G. L. Tiago Filho, G. de O. Machado, and M. D. G. Barbedo, “Mapping and energy analysis of Brazilian bioenergy power potential for three agricultural biomass byproducts,” *J Clean Prod*, vol. 349, May 2022, doi: 10.1016/j.jclepro.2022.131466.

[18] L. la Picirelli de Souza *et al.*, “Theoretical and technical assessment of agroforestry residue potential for electricity generation in Brazil towards 2050,” *Energy Reports*, vol. 7, pp. 2574–2587, Nov. 2021, doi: 10.1016/j.egyr.2021.04.026.

[19] R. J. Evans, R. A. Knight, M. Onischak, and S. P. Babu, “Development of biomass gasification to produce substitute fuels,” Richland, WA, Mar. 1988. doi: 10.2172/5206147.

[20] D. Aguilar, “Determinación del potencial energético de la biomasa residual de cultivos de banano en el cantón Machala, El Oro, Ecuador,” Universidad Politecnica Salesiana, Cuenca, 2019.

[21] “Rice straw - IRRI Rice Knowledge Bank.” http://knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products/rice-straw (accessed Aug. 23, 2022).

[22] M. Palacios, “Caracterización química de la biomasa procedente de las hojas, pseudotallo, raquis y pseudopeciolo de la planta de banano y su relación con el poder calorífico,” 2016. Accessed: Aug. 23, 2022. [Online]. Available: http://dspace.ucuenca.edu.ec/handle/123456789/26232

[23] J. A. Ortiz-Ulloa, M. F. Abril-González, M. R. Pelaez-Samaniego, and T. S. Zalamea-Piedra, “Biomass yield and carbon abatement potential of banana crops (Musa spp.) in Ecuador,” *Environmental Science and Pollution Research*, vol. 28, no. 15, pp. 18741–18753, Apr. 2021, doi: 10.1007/s11356-020-09755-4.

[24] I. Kabenge, G. Omulo, N. Banadda, J. Seay, A. Zziwa, and N. Kiggundu, “Characterization of Banana Peels Wastes as Potential Slow Pyrolysis Feedstock,” *J Sustain Dev*, vol. 11, no. 2, p. 14, Mar. 2018, doi: 10.5539/jsd.v11n2p14.

[25] E. Bocci, M. Sisinni, M. Moneti, L. Vecchione, A. di Carlo, and M. Villarini, “State of art of small scale biomass gasification power systems: A review of the different typologies,” *Energy Procedia*, vol. 45, pp. 247–256, 2014, doi: 10.1016/J.EGYPRO.2014.01.027.

[26] A. A. P Susastriawan and Y. Purwanto, “Biomass gasifier-internal combustion engine system: review of literature,” 2020, doi: 10.1080/19397038.2020.1821404.

[27] A. S. Mednikov, “A Review of Technologies for Multistage Wood Biomass Gasification,” *Thermal Engineering* , vol. 65, no. 8, pp. 531–546, 2018, doi: 10.1134/S0040601518080037.

[28] P. Basu, *Biomass Gasification, Pyrolisis and Torrefaction. Practical Design and Theory.* Academic Press, 2013.

[29] J. J. Cheng, *Biomass to renewable energy processes, second edition*. 2017. doi: 10.1201/9781315152868.

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Decarbonization of the power sector with CCS: Case study in two regions in the U.S. and lessons for Latin America

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Keywords: Decarbonization, Power Sector, Electricity, Carbon Capture and Storage

Abstract

This paper estimates potential changes in the total systems cost (TSC) of two regional transmission organizations (RTOs) in the United States (U.S.)—Midcontinent Independent System Operator-North (MISO-N) and Southwest Power Pool (SPP) RTO West—under the traditional decarbonization pathway of replacement of fossil-power plants with variable renewable energy (VRE) and the less traditional pathway of retrofitting fossil fuel units with carbon capture and storage (CCS). Although the power mixes of MISO-N and SPP RTO West are particular to those regions, the results can apply to other regions, including Latin American countries that are planning to decarbonize their power sectors. This case study serves to highlight lessons on the difference in technology costs between these two pathways, as well as the costs associated with decarbonization rates close to 100%.

Introduction

The power sector is undergoing fundamental changes led by policy action, technology innovation, and an increasing urgency to tackle climate change [1]. Electricity systems worldwide are modifying their mix of generation technologies in response to changing economic conditions (e.g., consistently low natural gas prices) and environmental goals focused on curtailing carbon dioxide (CO_2) emissions [2]. Regions are choosing to decarbonize their power systems by adopting variable renewable energy (VRE) and the retirement of fossil-based generators, i.e., “replacing” legacy emissions-intensive power generators with low-carbon generators. These replacements require large overnight capital investments, and they influence the cost of maintaining and operating a reliable grid system [3]. An alternative pathway (and potentially more sustainable in the long-term) is to, in addition to deploying existing VRE technologies, deploy carbon capture and storage (CCS) and diversify the existing decarbonization alternatives. CCS technologies can extend the lifetime of existing fossil-based infrastructure and its supporting supply chain, while reducing at least 90% its carbon emissions footprint.

While the costs of current technologies point to the need to continue adopting VRE as the main resource at hand, it is important to consider other decarbonization strategies that may offer complementarity and long-term gains. It is critical that other decarbonization technologies emerge and to consider how to spur their deployment. Some of the long-term benefits of deploying CCS technologies as an alternative to VRE in the power sector include its environmental spillover effect in the industrial sector and the continuing use of existing combustion turbine engines (e.g., reducing the emissions from burning fossil-fuels in hard-to-electrify industries, supporting blue hydrogen production, and supporting clean synfuels production). In the short term, CCS may appear to be expensive, but its advantages—the ability to use existing infrastructure for a few more

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decades—and its continued use can, in fact, mitigate the costs of the transition. This paper offers this alternative perspective. It compares the costs of decarbonizing the power sector via the traditional VRE pathway versus an alternative pathway in which CCS is also considered (i.e., both CCS and VRE are deployed) for two regional transmission organizations (RTOs) in the United States (U.S.): Midcontinent Independent System Operator-North (MISO-N) and Southwest Power Pool (SPP) RTO West.

Methods

Total system costs (TSCs) are estimated using a capacity expansion tool ("SCoRE tool") developed for each region in which a future hourly load year is matched with a set of power technologies that are operated via a simplified version of a least-cost hourly dispatch.[3] The total installed capacity for that future year results from meeting a future load profile with the technologies considered, using scenarios that are centered on one technology—each scenario prioritizes the expansion using one chosen technology to replace emitting technologies. Thus, the SCoRE tool does not minimize total costs for a future year but instead estimates total costs when one technology is chosen as the main capacity expansion driver. This approach allows for testing differences at the extremes (i.e., when a large amount of VRE is deployed versus a large amount of CCS), which is useful for drawing comparisons.

The SCoRE tool provides estimates of changes to the TSC from technology retrofits or replacements to mitigate a set amount of CO_2 emissions in the region. The two cases, plus a business-as-usual case, considered for each region to achieve a 98.8% decarbonization level compared to the 2019 system are described as follows:

1. Case A "VRE Centered": 2035 load[4] is met via the minimum fossil fuel capacity possible (all coal retires, all natural gas combined cycle [NGCC] retires, and all combustion turbine [CT] and internal combustion [IC] units retire) and the addition of new VRE capacity.
2. Case B "CCS Centered": 2035 load[5] is met via the retrofit of existing natural gas capacity with CCS, the addition of new NGCC units with CCS technologies (99% capture), and the addition of new VRE capacity. Coal-fueled and CT/IC units retire.

Data

The analysis was conducted using day-ahead hourly generation by fuel and technology type and hourly load in 2019, in MWh, in MISO-N and SPP RTO West (reference); total overnight costs (TOC), in $/MW, of greenfield VRE technologies (wind, solar photovoltaics); various energy storage technologies and natural gas with post-combustion CCS technologies; and TOC of decommissioning and dismantling fossil-based power plants (natural gas, coal, and oil-fueled power plants).

Preliminary Results

Table 1 summarizes the FE retirements under Case A "VRE Centered" and Case B "CCS Centered." Both cases achieve a 98.8% decarbonization level compared to 2019. For both cases, and for both regions, all coal power capacity retires, and nuclear, hydro, biofuel-fired,

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[3] The SCoRE tool matches the hourly load with the available technologies, constrained by technology ramping rates, minimum operating levels, and other technical characteristics of the available electricity mix.

[4] 2035 load is assumed to be equal to 2019 load for simplicity.

[5] 2035 load is assumed to be equal to 2019 load for simplicity.

geothermal and "other" power generation technologies remain unchanged and equal to 2019 capacity levels. The only capacity changes occur in the regions' fossil energy power technologies (Coal ST, NGCC, NG ST and FE-CT/IC) and their VRE technologies (utility-scale PV and wind). In both scenarios, a significant share of FE-fired power plants is retired. In MISO-N, 79% of FE-fired power plants retire in Case A, and 68% of FE-fired power plants retire in Case B. In SPP RTO West the percentages are 95% and 67%, for Case A and Case B, respectively. NGCC and ST-NG power plants are the technologies that continue to operate in Case B compared to Case A.

Table 1 FE retirements under Case A and Case B for both regions

	Retirements in MISO-N	**Retirements in SPP RTO West**
Case A: FE-coal, FE-NGCC* and FE-CT/IC* retires and VRE replaces it (98.8% decarbonization)	46 GW of coal (100%), 10 GW of NGCC+ST gas (55%), 14 GW of CT/IC gas/oil (60%), for a total of 70 GW (79% of all FE-fueled power plants)	6.1 GW of coal (100%), 3.9 GW of NGCC+ST gas (100%), 3.1 GW of CT/IC gas/oil (83%), for a total of 13.1 GW (95% of all FE-fueled power plants)
Case B: FE-coal and FE-CT/IC retires, FE-NGCC is retrofitted with CCUS (98.8% decarbonization)	46 GW of coal (100%), 14 GW of CT/IC gas/oil (60%), for a total of 60 GW (68% of all FE-fueled power plants)	6.1 GW of coal (100%), 3.1 GW of CT/IC gas/oil (83%), for a total of 9.2 GW (67% of all FE-fueled power plants)

*Some fossil energy (FE) power plants do not retire. In Case A, the unretired FE power plants balance the high VRE penetration. In Case B, all existing NGCC does not retire and is retrofitted with CCUS. ST = steam turbine

Table 2 and Table 3 list the technologies that account for the remaining carbon emissions for MISO-N and SPP RTO West, respectively. The remaining 1.2% of emissions in both cases come either from fossil fuel power plants that balance the high VRE output (for Case A) or the non-capture emissions of the CCS systems (Case B). Also, total system costs of Cases A and B are presented for MISO-N and SPP RTO West in Table 2 and Table 3, respectively. Keeping the systems as they exist today requires operating and maintaining existing infrastructure. Today's operation and maintenance (O&M) costs—which include fixed operation and maintenance (FOM), variable operation and maintenance (VOM), and fuel purchases—of MISO-N and SPP RTO West are approximately $15 B and $2 B, respectively. Fully decarbonizing the electricity systems (reducing carbon emissions by 98.8%, compared to 2019 emissions) can be achieved at significant additional costs. In the case of retiring most of the existing fossil fuel power plants and replacing them with VRE (Case A), the costs are $1,190 B (MISO-N) and $248 B (SPP RTO West). In the case of maintaining existing natural gas fired plants and retrofitting them with carbon capture, utilization, and storage (CCUS) while adding new VRE (Case B), the costs are $312 B (MISO-N) and $42 B (SPP RTO West).

In terms of the equivalent cost of avoided carbon emissions for SPP RTO West, Case B yields a cost of avoided ton equal or less than $60/ton avoided over the period 2035–2075, while Case A yields a cost of avoided ton five times higher at $300/ton avoided. For MISO-N, Case A yields a cost of avoided ton six times higher compared to Case B.

Table 2 Comparison of cases in MISO-N

	Case A "VRE Centered"	**Case B "CCS Centered"**
TSC	$1,190 B	$312 B
Coal power capacity	0 MW	0 MW

Source of 1.2% emissions	10 GW of NGCC/ST gas 10 GW of CT/IC gas/oil	Non-captured emissions of the CCS system
Retrofitting existing power plants	No	Yes, 100% of NGCC and ST gas (20 GW)
Cost of ton avoided over 40-yr lifetime of system (2035–2075)	More than \$300/ton avoided (over 12 billion tons of CO_2 avoided)	Less than \$50/ton avoided (over 12 billion tons of CO_2 avoided)

*Today's (2019) MISO-N O&M annual costs (FOM, VOM, and fuel costs) are \$15 B.

Table 3 Comparison of cases in SPP RTO West

	Case A "VRE Centered"	**Case B "CCS Centered"**
TSC	\$248 B	\$42 B
Coal power capacity	0 MW	0 MW
Source of 1.2% emissions	2.7 GW of NGCC/ST gas 0.7 GW of CT/IC gas/oil	Non-captured emissions of the CCS system and 0.7 GW of CT/IC gas/oil and other fossil fuels
Retrofitting existing power plants	No	Yes, 100% of NGCC and ST gas (3.9 GW)
Cost of ton avoided over 40-yr lifetime of system (2035–2075)	More than \$300/ton avoided (over 1.5 billion tons of CO_2 avoided)	Less than \$60/ton avoided (over 1.5 billion tons of CO_2 avoided)

*Today's (2019) SPP RTO West O&M annual costs (FOM, VOM, and fuel costs) are \$2 B.

References

[1] IEA, "Power Systems in Transition – Analysis," *IEA*, Oct. 2020. https://www.iea.org/reports/power-systems-in-transition (accessed Jul. 28, 2022).

[2] A. Iyengar, A. H. Steele, S. Sharma, I. Pena Cabra, and L. Clahane, "A Tool for Measuring the System Cost of Replacement Energy," Rochester, NY, May 14, 2022. doi: 10.2139/ssrn.4109808.

[3] S. Byrom, A. Boston, G. Bongers, P. Dargusch, A. Garnett, and N. Bongers, "Total Systems Cost: A Better Metric for Valuing Electricity in Supply Network Planning and Decision-Making," *J. Environ. Inform. Lett.*, vol. 6, no. 2, Art. no. 2, Apr. 2021.

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8º ELAEE - Encuentro Latinoamericano de Economía de la Energía, 2022

IMPACTOS DE LA VALORACIÓN DE CRITERIOS AMBIENTALES EN LA EXPANSIÓN DEL SISTEMA ELÉCTRICO BRASILEÑO: COMPARACIÓN ENTRE CERTIFICADOS DE ENERGÍA RENOVABLE Y EL MERCADO DE CARBONO

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RESUMEN

En el contexto de la transición energética sostenible, varios países han estado fijando metas para reducir sus emisiones de gases de efecto invernadero (GEI). Teniendo en cuenta este objetivo, instrumentos de mercado como los sistemas *Cap-and-Trade* y los Certificados de Energías Renovables son presentados por la experiencia internacional como mecanismos que incentivan la reducción de emisiones del sector eléctrico, ya que permiten la valoración explícita de las emisiones y de los beneficios de las energías renovables. Este trabajo investiga los impactos de la adopción de tales instrumentos en la Expansión y Operación del Sistema Eléctrico Brasileño. Se modela un mecanismo de penalización explícita de las emisiones en el valor de BRL 100 y BRL 500 por tonelada de CO_2e, así como un mecanismo de certificados de energía renovable. Como criterio adicional de confiabilidad sistémica se utiliza un criterio de Reserva Probabilística Dinámica, con el objetivo de sustentar la mayor penetración de fuentes renovables intermitentes. El caso de estudio se lleva a cabo mediante el uso de un modelo de optimización bajo incertidumbres derivadas de la generación renovable y de los caudales afluentes, utilizando granularidad temporal horaria y representación individualizada de plantas para el horizonte de 2050.

PALAVRAS-CLAVE

Planificación de la expansión de la generación; Mercados de Carbono; Certificados de energía renovable; Reserva Probabilística Dinámica; Integración de fuentes renovables.

1.0 – INTRODUCCIÓN

Desde la entrada en vigor del Acuerdo de París en 2016, 55 países (que representan el 55% de las emisiones mundiales de gases de efecto invernadero) se han comprometido a limitar las emisiones de estos gases con el objetivo de frenar el cambio climático [1]. Desde entonces, 194 países (más la Unión Europea) se han convertido en signatarios del Acuerdo de París [2]. En cuanto a Brasil, enfoque de este trabajo, el país actualizó sus compromisos durante la Convención Marco de las Naciones Unidas sobre el Cambio Climático de 2020, estipulando objetivos de reducción de las emisiones de gases de efecto invernadero en un 37% para 2025 y en un 43% para 2030, ambos con referencia a las emisiones de 2005. Además, se añadió el objetivo de que Brasil se convierta en un país neutro en emisiones de carbono hasta 2060.

Ante la necesidad de cumplir con los compromisos adquiridos y promover una matriz eléctrica sostenible, es imprescindible estimular la sustitución de las fuentes basadas en combustibles fósiles por fuentes renovables. Para ello, es importante adoptar un mecanismo de mercado transparente y explícito como forma de considerar los aspectos ambientales en la expansión y operación del sistema eléctrico brasileño.

El objetivo principal de este trabajo es investigar los posibles impactos en la Expansión y Operación del Sistema Eléctrico Brasileño con la adopción de dos mecanismos utilizados internacionalmente para la valoración explícita de los beneficios ambientales, conocidos como (i) Certificados de Energía Renovable y (ii) Mercado de Carbono. Los principales impactos analizados se refieren a las fuentes presentes en la expansión, los costes asociados a la expansión y operación del sistema y las emisiones totales, así como en los costes de proporcionar confiabilidad al sistema (ilustrados por un análisis de la precificación de la disponibilidad de la reserva operativa).

2.0 – METODOLOGÍA

2.1 Modelo de optimización de la expansión

Para resolver el problema de expansión, en este trabajo se utiliza una herramienta computacional de optimización estocástica que utiliza la programación lineal entera mixta con el objetivo de determinar el programa de inversión de menor coste para la construcción de nuevas plantas de generación y nuevos circuitos para la red de transporte, calculando el *tradeoff* entre los costes de inversión para la construcción de nuevos emprendimientos y el valor esperado de los costes de operación del sistema [3]–[7].

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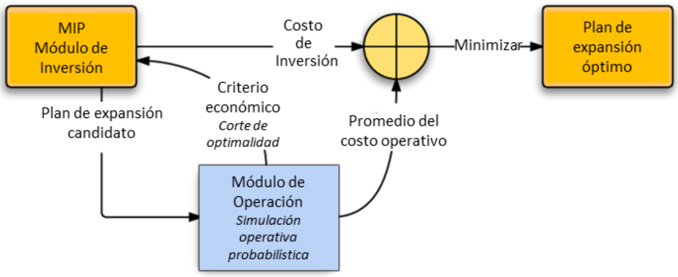

Figura 1 – Metodología de la expansión de la generación

La simulación de la operación se realiza considerando representaciones detalladas del parque de generación, como las restricciones de *commitment* térmico y los detalles de la operación de las centrales hidroeléctricas, representadas individualmente. Ambas las etapas, operación y simulación, se realizan con discretización horaria de la demanda y de la generación renovable, para permitir la correcta representación de la intermitencia de las fuentes renovables y sus impactos en la cuantificación de la reserva necesaria para asegurar la confiabilidad del sistema.

2.2 Cuantificación de la reserva

Como metodología para cuantificar la reserva, este trabajo utilizará como criterio la Reserva Probabilística Dinámica (RPD). Esta metodología tiene como principio fundamental la estimación de la reserva basada en la intermitencia de la generación renovable, utilizando como dato de entrada múltiples escenarios de generación en discretización horaria [7]. El criterio de RPD comprende cinco pasos:

(i) Determinación de un escenario medio para cada hora, determinado a partir de la media de los escenarios de generación renovable considerados;
(ii) Cálculo del error de previsión de la generación renovable, determinado como la diferencia entre la generación de cada escenario y la generación media;
(iii) Cálculo de la variación del error de previsión entre horas consecutivas del mismo escenario;
(iv) Determinación de la distribución de probabilidad del error de previsión para cada hora del día de cada día típico, a partir de los *n* escenarios considerados en la optimización estocástica de la planificación de la expansión;
(v) Determinación de la cantidad de reserva necesaria, tomada como un percentil de la distribución de probabilidad determinado a partir de los criterios de planificación del Operador considerando su aversión al riesgo.

La consideración del criterio de Reserva Probabilística Dinámica permite que la planificación de la expansión incorpore los efectos de una mayor penetración de renovables intermitentes en el sistema. De este modo, una mayor inserción de fuentes renovables no convencionales provocará una mayor necesidad de reserva, que deberá ser satisfecha por las centrales existentes o por nuevas centrales candidatas.

2.3 Metas de generación renovable

Con respecto al certificado de energía renovable, se utiliza una modelización de la demanda de energía firme del sistema, donde cada generador renovable tendrá un valor de energía firme individualizado, y la suma de los generadores del sistema debe tener un valor mayor o igual al valor requerido. Este abordaje es análogo a la definición de una restricción de penetración mínima de renovables. La contribución de cada planta en el sistema se define como la capacidad total de generación que tiene, considerando su factor de capacidad promedio. De este modo, tras definir un requisito de certificados de energía limpia, en MW promedios, la herramienta de optimización definirá qué plantas deben entrar en el sistema teniendo en cuenta esta nueva restricción.

2.4 Precificación del carbono

El uso de un mecanismo que penalice las emisiones de CO_2 (o, de manera más general, las emisiones de GEI) busca desincentivar la generación de centrales eléctricas más contaminantes, fomentando que los generadores más eficientes en el ámbito de las emisiones sean premiados. La fijación del precio del carbono ya sea a través de un mecanismo de mercado como un sistema de "*cap-and-trade*" o mediante la imposición directa por parte de entidades gubernamentales, puede representarse de forma simplificada mediante un valor de penalidad medio anual que se aplicará a todas las centrales eléctricas que emitan GEI, abordaje que será utilizada en este trabajo.

La penalidad por las emisiones se añade a la función objetivo del problema de optimización, aumentando el coste variable de las plantas más contaminantes. De este modo, en el modelo de optimización se tendrá en cuenta el equilibrio entre costes y emisiones, es decir, utilizar plantas con menor costo variable y/o coste de instalación, pero más contaminantes, o utilizar plantas más caras pero más eficientes en cuanto a sus emisiones.

3.0 – SISTEMA ELÉCTRICO BRASILEÑO

3.1 Características actuales

Históricamente, el sistema eléctrico brasileño tiene como tecnología principal las centrales hidroeléctricas. En términos de capacidad instalada, las centrales hidroeléctricas fueron responsables de aproximadamente el 60% de la matriz en 2021 [8], como puede verse en la Figura 2. Sin embargo, la participación de dichas centrales se ha reducido en las últimas décadas, especialmente debido a la entrada de otras tecnologías en la matriz, como las centrales eólicas y solares, así como a la existencia de barreras socioambientales en los últimos años que han impedido la construcción de nuevas centrales hidroeléctricas a gran escala.

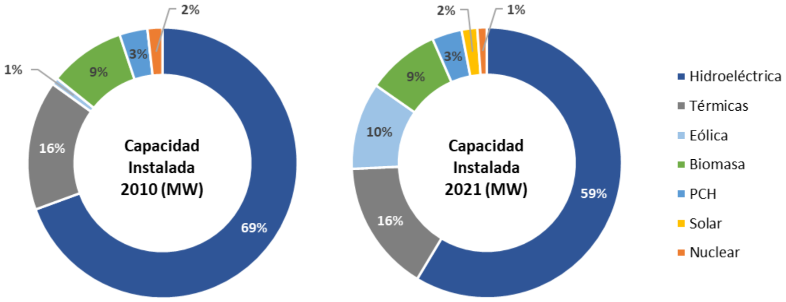

Figura 2 – Comparativo de capacidad instalada del Sistema Interconectado Nacional Brasileño en 2010 y 2021

En cuanto a la red de transmisión, el país cuenta actualmente con 145.600 km de líneas, concentradas en las redes de 500 kV y 230 kV. Para 2025, se espera que la extensión de la red crezca hasta los 184.000 km, aumentando la solidez del sistema [9].

3.2 Candidatos a la expansión

El presente trabajo considerará como candidatas centrales termoeléctricas y baterías, así como diferentes tecnologías renovables, a saber, la fotovoltaica, la eólica terrestre, la eólica marina, las pequeñas centrales hidroeléctricas y la biomasa.

En relación con los candidatos renovables, un aspecto importante a considerar es la disponibilidad del recurso para su instalación. Como base principal, se utilizaron las fuentes de [10] e [11], además de los datos históricos disponibles en [12]. Por último, dadas las incertidumbres políticas sobre la construcción de grandes centrales hidroeléctricas con embalses, principal factor para la instalación de esta tecnología, éstas no se consideran en este estudio.

En cuanto a los candidatos térmicos, se considerarán las fuentes nucleares y de gas natural. Con respecto a las centrales térmicas de gas natural, este trabajo tratará de emular la respuesta de los agentes a las señales de precios en un mercado que considera explícitamente las restricciones medioambientales. De este modo, se modelan cinco proyectos diferentes de centrales térmicas a gas natural, que tienen diferentes supuestos en cuanto a la inflexibilidad operativa (es decir, si el despacho de la planta es obligatorio), el coste variable de operación, el coeficiente de emisión de GEI y los costes de inversión y mantenimiento. Este enfoque permitirá analizar si, a partir de las políticas ambientales aplicadas al sector eléctrico, cuál es la tecnología óptima que debe instalarse, es decir, si el sistema preferirá invertir en centrales térmicas con mayor coste de inversión y/o mantenimiento pero que contaminen menos.

Tabla 1 – Supuestos operativos para candidatos a gas natural

Tecnología	Precio del Gas ($/MMBTU)	Inflexibilidad operativa	Eficiencia (MMBTU/MWh)	Costo Operativo (R$/MWh)	Coeficiente Emisión (tCO_2e / MWh)
Gas Flexible 1	8.5	Totalmente flexible	8.5	453.9	0.451
Gas Flexible 2	7.48	Totalmente flexible	7.2	348.1	0.382
Gas Flexible 3	7.48	Totalmente flexible	6.6	322.3	0.350
Gas Inflexible 1	6.63	Inflexibilidad de 50% durante el periodo seco	6.6	290.1	0.350
Gas Inflexible 2	4	Inflexibilidad de 50% para todos los meses	6.9	197.2	0.366

Por último, en cuanto a la representación de la transmisión, la metodología utilizada en este trabajo para la planificación de la expansión de la generación considera una red de transmisión simplificada, utilizando una representación de 10 nodos. La red de transmisión se representará de forma simplificada sin tener en cuenta las restricciones de la red, lo que se conoce como "modelo de tubo" o "modelo de enlace de CC". Esta representación nos permite evaluar la competitividad de las fuentes en diferentes regiones considerando el factor de localización, es decir, si el menor coste total de expansión pasa por ampliar una planta de mayor capacidad más cercana al centro de demanda o si la mejor decisión pasa por construir una planta más lejana con refuerzos en la capacidad de transmisión.

Además de los candidatos, si hacen necesarios también escenarios de proyección de (i) demanda e y (ii) de precios de combustibles. Para la definición de los supuestos a considerar en el caso de estudio propuesto, se decidió utilizar como fuentes primarias los trabajos recientemente desarrollados por la EPE y el Ministerio de Minas Energía para los estudios del Plan Energético Decenal 2030 [13] y el Plan Nacional de Energía 2050 [14].

4.0 – RESULTADOS

Como forma de evaluar el impacto de las políticas ambientales explícitas en la expansión y operación del sector eléctrico, se presentan seis diferentes casos, todos con un horizonte para 2050 y aplicando la Reserva Probabilística Dinámica como criterio de cuantificación de la reserva operativa. Una descripción de los casos se presenta en Tabla 2.

Tabla 2 – Descripción de los casos de estudio realizados

Caso	Descripción
Caso 1	Caso Base
Caso 2	Precio del carbono de R$ 100/tCO_2e
Caso 3	Precio del carbono de R$ 500/tCO_2e
Caso 4	Precio del carbono de R$ 100/tCO_2e sin carbón inflexible
Caso 5	Precio del carbono de R$ 500/tCO_2e sin carbón inflexible
Caso 6	Certificado de Energía para una generación renovable meta de 97,2%.

4.1 Impacto del incremento del precio de carbono – Casos 1, 2 y 3

Se puede señalar que el aumento del precio del carbono tiene un incentivo directo a la expansión de la fuente fotovoltaica, además de la reducción de la inflexibilidad operativa en las centrales térmicas. Además, las tecnologías consideradas más caras, como la eólica marina y las baterías, son viables en un escenario con una penalidad más significativa para las emisiones. En cuanto a la viabilidad de la energía eólica marina, cabe destacar la señal locacional percibida por el modelo: aunque las plantas ubicadas en otros subsistemas, como el del Noreste, son financieramente más atractivas dados los mayores factores de capacidad, es preferible instalarlas en el subsistema del Sur para evitar una mayor necesidad de expansión de la transmisión.

Con respecto a la expansión de las centrales térmicas, también se pueden hacer observaciones importantes. En primer lugar, se observa en el caso con mayor penalidad la viabilidad de la central térmica de Gas Flexible 3, la cual tiene un menor factor de emisión frente a un mayor coste de instalación. Además, se observa la reducción casi total de la expansión inflexible a fin de evitar emisiones innecesarias.

Paralelamente, dado el aumento de la expansión renovable y la disminución de la expansión de la central térmica Gas Inflexible 2, las baterías aportan al sistema a fin de satisfacer el requerimiento por reserva y reducir la variabilidad de precios, con una aportación de 4,7 GW en el Caso 3, la mayor parte de ellos instalados en la región noreste. La mayor expansión de la transmisión (7 GW más en el caso 3 en relación con el caso 1) permite que las regiones del noreste, sur y sureste estén más acopladas en cuanto a los precios de la energía. Por otro lado, la ausencia de expansión de la transmisión en la región Norte, junto con una expansión anclada en las centrales térmicas de esta región, provoca un aumento de los precios de este subsistema. La Figura 3 presenta los importes agregados al sistema en cada caso, detallados por tecnología.

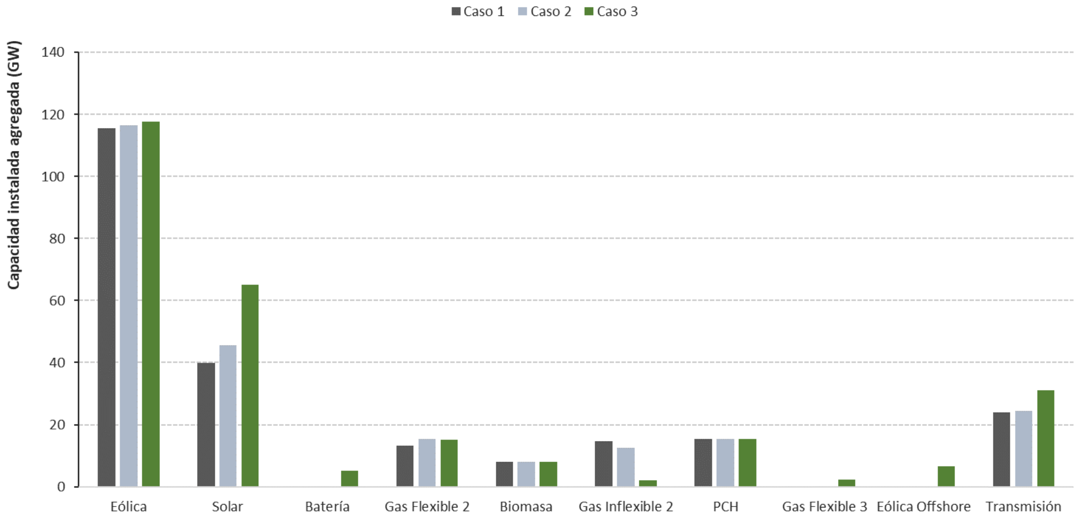

Figura 3 – Comparación de Capacidad de Generación Agregada al sistema para los Casos 1, 2 y 3

La Tabla 3 presenta los costes totales (expansión + operación) de cada caso. Como esperado, se puede observar que el uso de precios más altos para penalizar las emisiones conduce a un coste total más elevado, especialmente debido al mayor coste de expansión.

Centrándose en los costes de expansión, es posible compararlos a la luz de los resultados del mix óptimo de expansión y los resultados de operación. A medida que aumenta el precio de la penalidad por las emisiones, es posible observar una mayor proporción relativa del coste del carbono en cada caso. Otro punto que vale la pena mencionar es que, como era de esperar, el consiguiente aumento de los costes de expansión proviene de una mayor expansión renovable, aunque también resulta en una reducción de los costes de operación dado sus costes operativos nulos.

Por último, puede observarse que los aumentos de costes del 3% y el 13% en los costes totales de los casos 2 y 3 en relación con el caso 1 inducen significativas reducciones de las emisiones de 9% y el 61%, respectivamente. La Tabla 4 presenta los valores de emisión totales para cada caso, así como el factor de emisión promedio.

Tabla 3 – Resultados de costos para los casos 1 a 3 (en miles de millones de reales)

	Caso 1	Caso 2	Caso 3
Costo Expansión	142,714	145,209	165,411
Costo Operación	26,565	24,223	12,286
Costo Emisiones	-	5,624	14,731
Otros Costos	7,004	7,104	7,035
Costo Total	176,283	182,160	199,463
Costo Total (sin costo emisiones)	176,283	176,536	184,732

Tabla 4 – Resultados de emisiones para los casos 1 a 3

	Caso 1	Caso 2	Caso 3
Emisiones totales - MMtCO_2e	53	48	20
Factor de Emisión Promedio - tCO_2e/MWh	0.037	0.034	0.015
Reducción relativa (%)	---	9%	61%

4.2 Impacto del desmantelamiento de centrales a carbón y gasóleo – Casos 4 y 5

Tomando como ejemplo el caso 3 (escenario de carbono R$ 500), se puede observar que el 32% de las emisiones totales provienen de las centrales eléctricas de carbón. Sin embargo, estas plantas son responsables de sólo el 1% de la generación total. Este hecho se produce debido a la inflexibilidad de dichas plantas, haciendo obligatoria su generación aunque no sea la opción más adecuada económicamente (y mucho menos medioambientalmente) para el sistema.

Como forma de emular el impacto de la continuidad en operación de dichas centrales, las cuales poseen restricciones de generación inflexible, los casos 4 y 5 siguientes consideran un sistema en el que estas centrales son desmanteladas.

En un primer momento, al comparar los casos 2 (coste de las emisiones de R$ 100 / tCO_2e) y el caso 4 (coste de las emisiones de R$ 100 / tCO_2e sin centrales a carbón), el desmantelamiento forzoso de estas centrales provoca un aumento de los costes totales a pesar de la reducción del coste total de las emisiones.

Por otro lado, al considerar los casos 3 (coste de emisión de R$ 500 / tCO_2e) y 5 (coste de emisión de R$ 500 / tCO_2e sin centrales a carbón) se observa que el desmantelamiento de las centrales listadas induce una reducción de los costes totales de expansión. Este factor se debe especialmente a los menores costes de las emisiones de carbono, además del menor coste de explotación debido a la mayor penetración de las renovables. Los costes totales de cada caso se presentan en Tabla 5.

Tabla 5 – Resultados de costos para los casos 1 a 5 (en miles de millones de reales)

	Caso 1	Caso 2	Caso 3	Caso 4	Caso 5
Costo Expansión	142,714	145,209	165,411	146,719	169,292
Costo Operación	26,565	24,223	12,286	24,774	11,187
Costo Emisiones	-	5,624	14,731	4,903	10,459
Otros Costos	7,004	7,104	7,035	7,106	7,040
Costo Total	176,283	182,160	199,463	183,502	197,978
Costo Total (sin costo emisiones)	176,283	176,536	184,732	178,599	187,519

El punto más relevante de la retirada de las centrales es el impacto significativo en el perfil de generación y en las emisiones, como se puede ver en la Tabla 6. Comparando los casos 4 y 6, se observa una reducción del 45% en las emisiones totales, teniendo por otro lado un aumento de sólo el 1,5% en el coste total (expansión más operación, este último sin tener en cuenta el coste del carbono).

Tabla 6 – Resultados de emisiones para los casos 1 a 5

	Caso 1	Caso 2	Caso 3	Caso 4	Caso 5
Emisiones totales - $MMtCO_2e$	53	48	20	42	11
Factor de Emisión Promedio - tCO_2e/MWh	0.037	0.034	0.015	0.030	0.009
Reducción relativa (%)	---	9%	61%	21%	79%

4.3 Implementación de certificados de energía renovable – Caso 6

Para el caso 6, la meta establecida fue de 97,2% para la generación renovable (considerando la generación por las centrales hidroeléctricas), un porcentaje idéntico al alcanzado por el caso 5. De este modo, es posible hacer una comparación entre los dos mecanismos estudiados aquí (penalidad por las emisiones frente a certificado de energía renovable) en términos de costes y emisiones totales.

Dado el incentivo puramente para las plantas renovables, la nueva restricción fomenta especialmente la fuente solar. Esta tecnología presenta una expansión mucho más expresiva que la obtenida anteriormente en el caso 5, con un aumento de casi 20 GW, como puede verse en la Figura 4. Por otro lado, la inexistencia de una penalización directa por las emisiones no proporciona tantos incentivos para una instalación más eficiente para el suministro de la demanda de punta y el servicio de reserva, como visto en los casos anteriores. Esto conduce a un aumento significativo de la expansión de la central térmica de Gas Flexible 2, sustituyendo la expansión de las baterías y de la central térmica de Gas Flexible 3 observada en el caso 5.

Estos cambios suponen importantes modificaciones en la operación del sistema. Con la mayor participación de las renovables, combinada con la inexistencia de una penalización por las emisiones, los precios spot se reducen considerablemente en comparación con los casos anteriores. Por otro lado, hay una mayor volatilidad de los precios, especialmente en el subsistema del Nordeste, variando entre R$ 16 / MWh en los meses con mayor generación eólica y R$ 150 / MWh en los momentos con mayor demanda neta.

Por otro lado, hay que recordar el "coste oculto" relativo a la entrada forzada de nuevas centrales eléctricas, que representa el coste del certificado de energía renovable. En este caso, el costo del certificado, obtenido por medio del valor dual de la restricción de energía firme, ascendió a R$ 99 / kWpromedio / mes a pagar para cada planta renovable de acuerdo con su asignación de energía firme, equivalente a R$ 135/MWh. En la práctica, el generador de energías renovables vendería energía y certificados como productos separados, y su remuneración total es dada por la suma de estos dos flujos de ingresos.

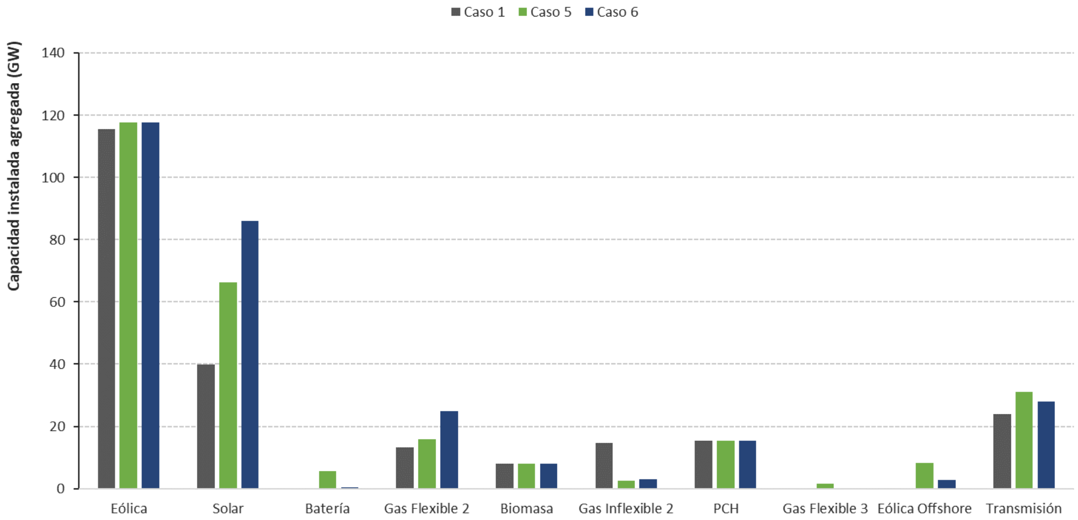

Figura 4 – Comparación de Capacidad de Generación Agregada al sistema para los Casos 1, 2, 3 y 4

Con el incentivo a la generación renovable mediante certificados, las plantas fotovoltaicas se ven intensamente favorecidas por este beneficio. A partir de la implementación de dicho mecanismo, donde existe una remuneración por el simple hecho de instalarse en el sistema, la fuente solar disminuye su dependencia de los ingresos por la venta de energía, siendo remunerada por entregar o no energía al sistema. Aunque desde el punto de vista del inversor se trata de un mecanismo que proporciona más previsibilidad, dado el conocimiento *ex-ante* de cuánto recibirá la planta, esta característica también puede constituir un riesgo desde el punto de vista del consumidor, ya que estaría pagando por un servicio que puede no estar siendo utilizado en caso de vertimiento.

La expansión guiada puramente por los objetivos de inserción de fuentes renovables también va acompañada de un coste total más elevado, dados los puntos abordados anteriormente, como se señala en la Tabla 7. Excluyendo el coste debido a las emisiones y considerando, por tanto, sólo los costes de expansión y operación, se produce un aumento del 0,8% en los costes totales.

Tabla 7 – Resultados de costos para los casos 1, 5 y 6 (en miles de millones de reales)

	Caso 1	Caso 5	Caso 6
Costo Expansión	142,714	169,292	168,602
Costo Operación	26,565	11,187	13,229
Costo Emisiones	-	10,459	-
Otros Costos	7,004	7,040	7,127
Costo Total	176,283	197,978	188,958
Costo Total (sin costo emisiones)	176,283	187,519	188,958

Por último, una expansión guiada por los objetivos de generación renovable permite una importante reducción de las emisiones. Sin embargo, comparando los casos 5 y 6 (Carbono R$ 500 / tCO$_2$e sin carbón y Certificado de Energía Renovable, respectivamente), se observa que el primero induce una reducción más significativa de las emisiones., Esto se explica por el hecho de que el caso 6 tiene más generación de gas natural y la expansión del mix de generación se compone de centrales térmicas menos eficientes en términos de emisiones. Esta combinación de factores produce un aumento de 1,5 $MMtCO_2e$ en las emisiones totales del caso 6 en comparación con el caso 5, como se ve en la Tabla 8.

Tabla 8 – Resultados de emisiones para los casos 1 a 6

	Caso 1	Caso 2	Caso 3	Caso 4	Caso 5	Caso 6
Emisiones totales - $MMtCO_2e$	53	48	20	42	11	13
Factor de Emisión Promedio - tCO_2e/MWh	0.037	0.034	0.015	0.030	0.009	0.009
Reducción relativa (%)	---	9%	61%	20%	79%	76%

4.0 – CONCLUSIONES

Con base en la metodología presentada, fue posible verificar que para el caso brasileño el aumento del precio del carbono incentiva un cambio significativo en la expansión de la generación del sector eléctrico brasileño, con especial énfasis en el incremento de participación de la fuente solar al considerar precios de penalización más altos, frente a la reducción del parque de generación térmico. Además, a medida que aumenta la penalización a las emisiones, es posible notar cómo nuevas tecnologías se vuelven viables, como las baterías, la energía eólica marina o incluso centrales térmicas de gas más eficientes que tienen un mayor coste de inversión. En términos cuantitativos, siempre tomando como referencia el caso base, la adopción de un escenario más conservador a partir de una penalización de carbono de $BRL100/tCO_2e$ induce una reducción de las emisiones del 9%, mientras una reducción más significativa del 62% de las emisiones considerando una penalización de BRL $500/tCO_2e$. En cuanto a los costes totales (expansión más costes reales de operación, sin considerar los costos de emisión), se produce un aumento del 0,1% y del 4,8%, respectivamente.

Un factor que merece ser destacado es la permanencia forzada de plantas consideradas obsoletas y/o contaminantes, causando fuertes externalidades negativas al sistema. Estas plantas, que en general utilizan carbón o gasóleo como combustible, aunque son poco representativas en la generación del sistema, generan una importante cantidad de emisiones. Si se considera un caso hipotético en el que se desmantelaran dichas centrales, se aprecia una reducción más significativa de las emisiones (-79%), acompañada de una generación renovable del 97,2% del total, con un incremento de los costes totales del 6,4%. Por último, en cuanto al uso de certificados de energía renovable, se observa que este mecanismo proporcionó una reducción menos eficiente de las emisiones (-75%) para alcanzar el porcentaje de energía renovable del 97,2%, acompañado del mayor coste total de los casos estudiados (+7,2%).

En resumen, a partir de los casos estudiados, es posible concluir que una penalización explícita de las emisiones induce una reducción más eficiente de las mismas, en comparación con su reducción indirecta mediante incentivos a los generadores renovables. Por otro lado, su implementación implica en elevados costos marginales de energía, lo que puede generar cierta resistencia para su puesta en práctica. En cuanto a los certificados de energía limpia, aunque dan lugar a una política más costosa y menos eficiente en cuanto a las emisiones, inducen costos marginales significativamente más bajos, aunque están asociados a los costes de los certificados de energías renovables que también deberían pagar los consumidores por medio de las tarifas de energía. Además, se observa que el mantenimiento forzoso de las centrales de carbón impacta significativamente en el sector, impidiendo la reducción de emisiones de forma efectiva y provocando un aumento forzoso de los costes de operación, ya que operan de manera forzada y no por criterios económicos.

5.0 – REFERENCIAS

[1] United Nations Framework Convention on Climate Change, “¿Qué es el Acuerdo de París?,” Dec. 13, 2021. https://unfccc.int/es/process-and-meetings/the-paris-agreement/que-es-el-acuerdo-de-paris (accessed Dec. 12, 2021).

[2] United Nations Treaty Collection, “Status of Treaties,” Dec. 13, 2021. https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en#4 (accessed Dec. 12, 2021).

[3] M. Pinanez and M. Jose, “Multicriteria generation and transmission expansion planning in Paraguay,” 2017.

[4] M. Resende, A. S. v D Aranha, R. Kelman, M. Pereira, and R. Garaffa, “An Integrated Planning Framework for the Peruvian Energy Sector,” hal-03172708, Mar. 2021. Accessed: Jan. 02, 2022. [Online]. Available: https://hal.archives-ouvertes.fr/hal-03172708/document

[5] F. Thome, R. C. Perez, L. Okamura, A. Soares, and S. Binato, “Stochastic Multistage Co-optimization of Generation and Transmission Expansion Planning,” Oct. 2019.

[6] R. C. Perez, S. Binato, L. Okamura, D. Bayma, I. Carvalho, and W. Morais, “DETERMINACIÓN DEL PLAN ÓPTIMO DE EXPANSIÓN DE CADA PAÍS Y EVALUACIÓN DE INTERCONEXIÓN ENERGÉTICA REGIONAL CONTEMPLANDO ALTA PENETRACIÓN DE FUENTES RENOVABLES,” 2019.

[7] W. S. Morais, R. C. Perez, and A. Soares, “APLICACIÓN DE UN MODELO DE EXPANSIÓN DE LA GENERACIÓN CONSIDERANDO EL REQUERIMIENTO DE RESERVA PROBABILÍSTICA DINÁMICA EN EL SISTEMA ELÉCTRICO MEXICANO,” 2019.

[8] ANEEL, “Sistema de Informações de Geração da ANEEL,” *ANEEL*, 2021. https://app.powerbi.com/view?r=eyJrIjoiNjc4OGYyYjQtYWM2ZC00YjllLWJlYmEtYzdkNTQ1MTc1NjM2IiwidCI6IjQwZDZmOWI4LWVjYTctNDZhMi05MmQ0LWVhNGU5YzAxNzBlMSIsImMiOjR9 (accessed Jun. 02, 2021).

[9] Operador Nacional do Sistema Elétrico - ONS, “O sistema em números,” Dec. 14, 2021. http://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros (accessed Dec. 13, 2021).

[10] EPE, “Potencial dos Recursos Energéticos no Horizonte 2050,” 2018. [Online]. Available: www.mme.gov.br

[11] Ministério de Minas e Energia, “Plano Nacional de Energia 2050 - Anexo,” 2020.

[12] ANEEL, “Resultados dos Leilões de Geração no Ambiente Regulado,” Oct. 12, 2021. https://app.powerbi.com/view?r=eyJrIjoiYmMzN2Y0NGMtYjEyNy00OTNlLWI1YzctZjI0ZTUwMDg5ODE3IiwidCI6IjQwZDZmOWI4LWVjYTctNDZhMi05MmQ0LWVhNGU5YzAxNzBlMSIsImMiOjR9 (accessed Dec. 14, 2021).

[13] EPE, “Estudos do Plano Decenal de Expansão de Energia 2030: Parâmetros de Custos – Geração e Transmissão,” 2021.

[14] Ministério de Minas e Energia and Empresa de Pesquisa Energética, “Plano Nacional de Energia 2050,” 2020.

Determinants of sectoral effective carbon rates on energy use *

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Abstract

We extend the measurement of effective carbon rates, adapting the OECD methodology (OECD-ECR, 2019, 2021), to 18 countries in Latin America and the Caribbean (LAC) for 2018, starting from energy balances and revising comprehensively the level and structure of excises and carbon taxes across countries and accounting for specificities in the emission structure (eg biofuels) and the existence of energy subsidies, all that quite differ from OECD patterns. This allows us to build up a sample of 66 countries (which includes some Asian and African countries also captured by OECD estimates) across 6 sectors and document stylized facts about the sectoral and aggregate level and structure of carbon pricing. Such facts show a biased structure of taxation towards road transport (which has a genesis, decades ago, different from the sole objectives of carbon taxation). This motivates an econometric modelling strategy where we first account for the determinants of economy-wide effective carbon rates (ECR) and then explain differences in road transport and the rest of sectors across countries with an automatic, machine learning model selection and using large set of potential explanatory variables that cover different structural, economic and institutional dimensions. Fiscal variables such as proxies for the marginal cost of public funds are important determinants of ECR in the road transport sector, as expected from the genesis of fuel excises. Emission trading systems tend to increase the value of ECR, while the same does not happen for carbon taxes suggesting that the later are introduced in a reform that substitute for excises. We document that LAC has a lower ECR and that energy subsidies are relevant in changing results only for some countries. However, we find that LAC does not depart from the model estimated for the whole sample insofar the main determinants of ECR. The exception are ETS since these are not observed in LAC, suggesting there might be an avenue for improving ECR by the introduction of ETS in some LAC countries.

Keywords: Carbon pricing, effective carbon rates, energy taxation

JEL class. numbers H23, Q54

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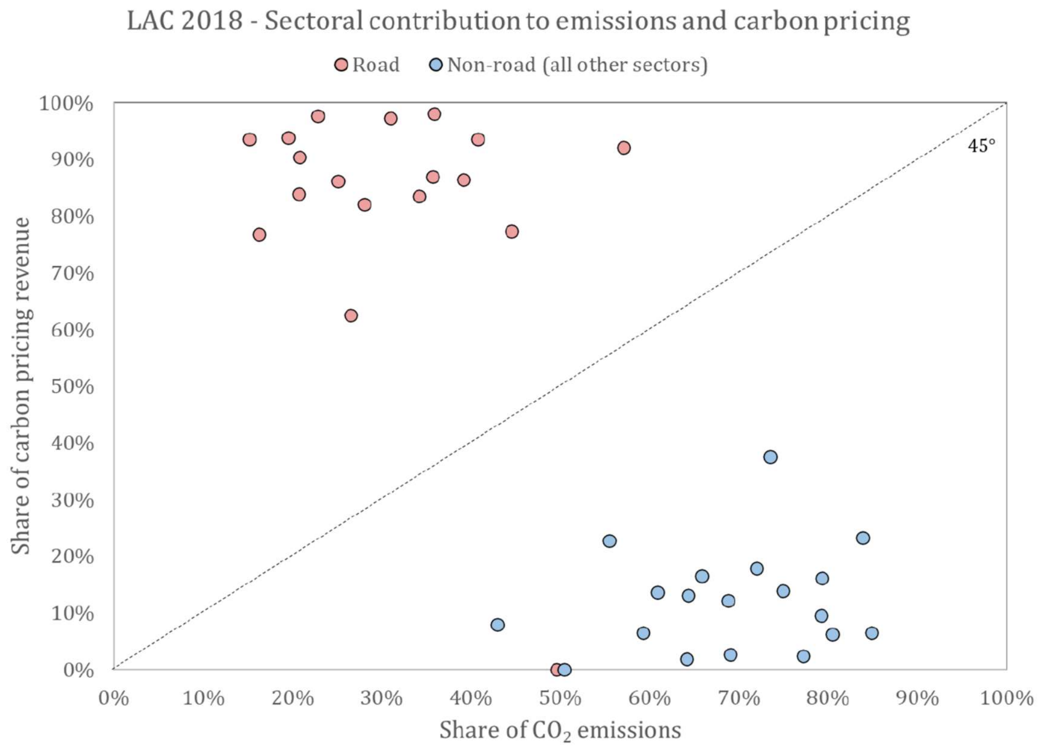
Determinants of sectoral effective carbon rates on energy use

1. Introduction

This paper starts with an effort to extend the measurement of carbon pricing in Latin America and the Caribbean (LAC), supported by an already standardized methodology applied to a group of countries monitored by the OECD (see OECD, 2019, 2021). The methodology is based on detailed studies of a broad and at the same time sectoral measurement of taxation on energy use (OECD, 2019a) where the bulk of carbon emissions come from, understanding taxation in a broad sense as the sum of three mechanisms or instruments. In the first place, due to their relative importance, we have indirect taxes (excises or so-called specific taxes) which already have a long history and recognition as elements that act "as if" they were "environmentally related" taxes, despite the fact that their initial or later objectives may have been different (see Barde and Bratheen, 2005 for the OECD and Navajas *et al* 2011, 2012; and Conte Grand, Rasteletti and Muñoz, 2022 for LAC). Excises on fuels for road transport have historically been, and still are, the main driver of these environmentally related taxes. Secondly, there are explicit carbon taxes that the countries have decided to incorporate particularly on energy use and that have a differential impact on the sectors, either through differential rates or exemptions. Thirdly, the OECD methodology incorporates into the definition of "effective carbon taxes" the prices resulting from market mechanisms such as emission trading systems (ETS), thus completing the "tripod" on which the estimation methodology is based. These three mechanisms that add up to define effective rates to carbon are applied according to this methodology to a sectorial classification (road transport, other transport, industry, agriculture and fishing, residential and commercial energy use, and the electricity sector). This allows weighting (based on the use of energy from the energy balance data that the IEA of the OECD has managed to standardize for these sectors, see IEA, 2021) the different effective carbon rates of the sectors to measure differences among sectors and instruments and arrive at an aggregate measure of the effective rate on carbon in a given country. This measure, in turn, allows computing the existing gap between the countries' effective carbon rates and a reference benchmark, which results in how far countries are from that benchmark and which sectors explain these differences.

The extension of this methodology to the case of LAC seems important for several reasons, ranging from the level and structure of energy use and emissions to different taxation structures and more pervasive use of energy subsidies in many countries. There is a group of the largest countries in the region (LAC 5 or Argentina, Brazil, Chile, Colombia and Mexico) that are already surveyed by the OECD and among them there are 4 countries of this LAC5 mentioned above (Argentina, Chile, Colombia and Mexico) that have carbon tax mechanisms. None of them have adopted general or sectoral emissions trading mechanisms, although Chile and Colombia are studying this mechanism for the future electricity sector and Mexico has a pilot experience for other sectors. In short, LAC is biased in terms of carbon prices and specific taxes on energy towards fuels in the transport sector, something that also occurs globally, but to a lesser extent. Figure 1, based on our estimates, shows how biased is the sectoral structure of carbon pricing in LAC, a fact that is common to OECD economies and also motivates the econometric modelling and reform direction debate insights obtained in this paper. Road transport faces the brunt of current carbon pricing while having a smaller part of the share in emissions compared to the aggregate of other sectors with very low effective rates on carbon emissions.

Figure 1



Much of the pattern shown in Figure 1 is explained by the fact that most of what we term effective carbon rates are excises that had a genesis quite different from environmental (not to mention climate change) objectives, where taxation of fuels used in transport played a major role in providing fiscal revenues and financing sources of transport infrastructure. Models that explain observed tax structures in more positive than normative terms provide a rationale for these observations (see for example, in general terms, Becker, 1983 and Kanbur and Myles, 1992; applied to environmentally related taxes, Navajas *et al*, 2012; applied to fossil fuels taxes and subsides, Mahdavi *et al*, 2022). Looking at observed sectoral effective carbon rates as coming from a previous status quo has a great advantage in terms of both explaining their current determinants and understanding the direction of reforms, being extending a carbon tax to all sectors or using emission trading systems in certain critical sectors. This paper is related to this literature as it estimates and recognizes a status quo of effective carbon rates that respond to a previous interest group equilibrium and needs to progress towards a new rationale based on cost effective climate policy.

The structure of this paper follows from our work to extend ECR measurement to LAC, to explaining the determinants of observed sectoral ECR, and to discuss desired or reasonable direction of reforms. In Section 2 we briefly describe the methodology we use to extend the OECD framework to LAC data. , with Appendix A providing some details and references to our database, which is available upon request along with a large annex, including country specific notes. All our estimates will refer to 2018 as this is a year where a whole OECD dataset was available at the time of writing this paper and best correspond to our own estimates of energy subsidies in LAC. Section 3 deals with observed differences among LAC countries and in relation to OECD countries both in terms of levels and the sectoral structure of ECRs. In Section 4 we report our estimates that depart from the more general OECD methodology and incorporate energy subsidies, observing the effects they have on the economy-wide level of effective carbon pricing in LAC. Section 5 presents our econometric approach to modelling the determinants of observed sectoral ECR in our sample of 66 countries which include OECD, LAC and Asia countries. We separate our econometric analysis in three models. The first is a study of determinants of economy-wide ECR. The second looks at the determinants of ECR in road transport. The third studies a panel of 5 sectors for the 66 countries estimating the determinants of ERC in sectors other than road transport. In all cases we search for differences in LAC vs OECD both in levels and in the interaction with determinants. We also study the effects of energy subsidies in an economy-wide cross section of ECR looking for their relevance both in redefining the dependent variable (ECR adjusted for subsidies) and in their likely effect on non-adjusted ECR. Section 6 briefly reports the variable definitions used in our regressions while Section 7 reports all results. Section 8 explore the relationship between emissions and ECR in our data. Section 9 concludes and suggests further research avenues.

2. Extending sectoral ECR to LAC: Methodology and Measurement

Pricing greenhouse gas emissions is part of a broader climate change mitigation policy. Emissions prices, through taxes or tradable emission permits, encourage emitters to look for profitable reduction options. Prices also signal strong political commitment, creating certainty for investors that carbon-neutral technologies are worth investing in. Carbon prices are effective in reducing emissions because they increase the price of carbon-based energy, thereby lowering demand (Arlinghaus 2015; Martin et al. 2016). Carbon pricing encourages substitution to less carbon-intensive forms of energy and reduces overall energy demand. Taking electricity generation as an example, producers can switch from coal or natural gas to non-carbon energy sources such as solar and wind power. In addition, where the market structure and regulation allow, electricity producers pass on the increased production costs resulting from electricity carbon prices to consumers, in the form of higher electricity prices, and this encourages consumers to reduce consumption. For example, businesses and households may be more vigilant in turning off appliances when they are not in use or may use them less, and may choose more efficient appliances at the time of replacement. Carbon prices are a profitable policy tool and this makes them attractive compared to other policy options (Metcalf, 2019, 2020). The appeal is due to three reasons. First, emitters have an incentive to reduce emissions as long as it is cheaper than paying the price, and this equalizes the marginal abatement costs on emitters, ensuring profitability across the economy. Second, carbon prices decentralize abatement decisions, thereby overcoming the information asymmetry between government and polluters: regulators do not need to stipulate which emissions must be reduced using which technologies. Third, they provide a continuing incentive to reduce emissions, thus stimulating innovation.

ECR/OECD Methodology

The OECD methodology is based on a tripod of three elements that define what constitutes the effective tax on carbon emissions. Effective carbon charges are the full price that is applied to CO_2 emissions from energy use as a result of market-based policy instruments. They are the sum of taxes and tradable emission permit prices, and have three components: first, specific taxes on energy use (mainly consumption taxes), which are normally set per physical unit or unit of energy, but which can be translated into effective tax rates based on the carbon content of each form of energy; second, carbon taxes, which typically establish a tax rate on energy based on its content, and third, the price of tradable emission permits, regardless of the permit allocation method, which represents the opportunity cost of issuing an extra unit of CO_2. The effective carbon rate measures how policies change the relative price of CO_2. As we will see later, the evidence of the application of this methodology (OECD, 2021) shows that for the whole of the sample of 44 OECD countries (where 5 countries of the region are located), the "excises" or taxes specifically explain 89% of the carbon price structure while carbon taxes and ETS explain 4% and 7% respectively. In the case of the LAC5 sample contained in this sample, the role of energy taxes is even greater, due to the lower incidence of carbon taxes (in force in 4 of the 5 countries, excluding Brazil) and due to the non-existence of emissions market prices at the time (beyond the fact that there are initiatives to study and explore ETS in at least 4 countries). The importance of ETS in the participation of carbon prices has increased in recent years due to the operational reforms of the main ETS market, which is the EU ETS and of which a significant group of the sample of countries of the EU is part. The significant rise in the market prices of the EU ETS after the 2018/19 reform and the introduction of ETS mechanisms in China explain why the ETS have increased their participation, especially if we look at their contribution to the increase in effective rates to carbon in recent years.

The three pillars or components of the effective carbon rates are translated into monetary units (Euros) that are applied on a homogenized tax base of energy uses at the level of sectors defined in advance for the purposes of international comparison and that are 1) road transport, 2) other forms of transport (off road transport), 3) industry, 4) agriculture and fishing, 5) residential and commercial sector, 6) electrical sector. This base comes from the extensive compilation of energy balances carried out by the IEA (2021) and known as Extended World Energy Balances (EWEB) that homogenizes the use of energy in common units (TJ, Tera Joules) and is accompanied by conversion matrices of units for each country, which relate commercial units on which taxes are defined with those common units. Conversion factors are then applied to link these homogeneous units with the corresponding carbon emissions associated with energy use and establish the effective carbon rate based on the three components mentioned. There is then a well-established link between the report on effective carbon taxes (OECD-ECR 2019, 2021) and the report on taxes on energy use (Taxing Energy Use (TEU), OECD-TEU, 2019). In turn, the TEU report provides files by country that explain the basis on which taxes on energy use are measured. This combines the information from the EWEBs and their conversion matrices with the taxes that are legally charged on the use of energy in the countries.

As we can see, the OECD methodology has two salient features. The first is that it focuses on emissions from energy use due to the most rigorous possible homogenization between countries provided by the EWEB base. This is what is called a combustion approach to energy. This leaves out emissions associated with activities other than energy use that we know are important in various sectors, such as agriculture and industry. Nor does the OECD methodology follow a life cycle approach or "footprints" of emissions, which in the case of biomass (or rather the production of biomass for the production of fuels or biofuels) is relevant. These differences (whether it is about emissions associated with the use or combustion of energy or that the impact of that combustion is looked at and not the previous life cycle) means that the data from the methodology of emissions of effective rates to carbon of the OECD is not comparable with UNFCCC accounting (which also includes greenhouse gases other than carbon). This is particularly so in the case of biomass, which is why the OECD also reports data excluding biomass to maintain a more homogeneous comparability between countries.

The second salient feature of the OECD methodology is that it has an explicit link with the current legal structure of energy taxes in each country. This implies a careful analysis of the tax code in practice, given the exemptions or special treatments that can change the results, and also including adjustments for differences that occur when different levels of government intervene. As the specific taxes on the use of energy are the object of analysis, other indirect taxes such as VAT are obviously excluded, which, although they fall on energy, are of a general nature for all goods. It is different if the VAT has a differentiated structure that gives rise to lower rates (which is the most common case) or higher rates for the use of energy. Value-added taxes affect end-user prices of energy products in many jurisdictions, in addition to the three components of effective carbon taxes. VAT is not usually specific to energy products: as long as the same rate is applied, the relative prices of energy products remain unchanged. In this case, VAT should not be taken into account, since the effective carbon rates measure the policies that modify the relative prices. However, differential VAT rates change the relative prices of energy products and VAT becomes a de facto specific tax measure. The OECD-TEU (2015) provides a general description of the differential VAT rates applied in the countries analyzed. Seventeen countries apply reduced or zero VAT rates to certain energy products. This counteracts the intention to increase the relative prices of energy products to the final consumer and can mitigate or even offset the effective carbon tax, depending on the relative magnitude of the price differentiation introduced by the differential VAT rate and the effective carbon tax. This effect of the differentiated VAT, which acts as a de facto specific tax, is not captured by the calculation methodology of the OECD.

Data and estimates for LAC

To complete our sample, we extended ECR/OECD methodology to 18 countries in LAC. The overlap with the LAC countries where OECD reports ECR (mainly LAC 5 as Argentina, Brazil, Chile, Colombia and Mexico) is useful to evaluate differences with our estimates. For our purposes we started with energy balances. Data from IEA's World Energy Balances[1] was used to assemble country-level detailed energy balances for 2018.[2] Following OECD-TEU (2019) methodology,[3] the Electricity sector was defined as that where primary energy use for electricity generation occurs (including transformation and distribution losses). Non-energy use of fuels was not taken into account in this document. Energy use not assigned to a particular sector (*Non-specified use*) was not included, with the exception of the Electricity sector, where energy is assigned on a primary-use criteria. Industry sector includes electricity generated in autoproducer plants.

Emission factors by fuel type were taken from EPA's 2018 update,[4] where missing data was completed based on EIA[5] and IPCC Emission Factor Database.[6] These were used to convert energy use from country balances (expressed in TJ) into CO_2 emissions. Regarding taxation, the main direct information sources were country-specific tax codes and national legislation (see Country Notes for details and sources). To convert taxed amounts into a common currency (euros), 2018 exchange rates from OECD[7] and World Bank[8] were used.

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[1] https://www.iea.org/data-and-statistics/data-product/world-energy-balances

[2] OECD TEU 2019 uses energy balances corresponding to 2016. Despite changes in energy balances being gradual across time, some differences regarding results may be explained by this, as well as on data updates (see, for example, Colombia's country notes).

[3] https://www.oecd.org/tax/taxing-energy-use-efde7a25-en.htm

[4] https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf

[5] https://www.eia.gov/environment/emissions/co2_vol_mass.php

[6] https://www.ipcc.ch/data/

[7] https://data.oecd.org/conversion/exchange-rates.htm

[8] https://data.worldbank.org/

In 2018 Latin America and the Caribbean, only Argentina, Chile, Colombia and Mexico had an operative carbon tax; Mexico included an additional subnational instrument in Zacatecas State.[9] In 2020, Chile and Colombia were studying ETS implementations, initiative also considered in Brazil from 2021 (see World Bank, 2021; ICAP, 2021; Amigo *et al* , 2020). Mexico developed a pilot version of this system since 2020, and also included since 2021 subnational carbon taxes in different States (Baja California, Zacatecas and Tamaulipas, with Jalisco under development). None of these regional inceptive ETS count with reference prices which can be included in the computing of Effective Carbon Rates (ECR).

3. ECR in LAC vs. OECD: levels, structures, stylized facts

Our measurement of 2018 Effective Carbon Rates in LAC countries is broadly consistent with existing OECD estimates, and it places most of LAC members below the OECD regional average, as illustrated in Figure 2. Noteworthy exceptions are Costa Rica, that prices CO_2 emissions above the EUR 60 benchmark (OECD, 2021) and ranks above the average OECD member, and Jamaica plus Uruguay, both performing above the EUR 30 benchmark, near the OECD reference mark. Aside from these particular cases, the fifteen remaining countries included in our sample have operative ECRs below the EUR 30 benchmark, where Guatemala and Ecuador stand out pricing carbon below the Asia & Africa regional average at about 10 EUR/tCO_2 (Ecuador in fact lacks a pricing carbon estimate because it places no excises nor carbon taxes on fossil fuels). Thus, the average LAC member would need to approximately double its carbon pricing efforts to catch-up with OECD standards, and apart from counted exceptions most countries fall far behind the low-end benchmark, EUR 30 per ton of CO_2.

On inspection, carbon taxes in LAC countries explain a minimal proportion of ECRs. Operative uniquely in Argentina, Chile, Colombia and Mexico, in none of these countries do carbon taxes contribute more than 2 EUR/tCO_2 to total carbon pricing. For the whole of LAC countries considered, only 1% of carbon prices are explained by carbon taxes, whereas 4% was estimated for the worldwide sample considered in OECD-ECR (2021). Fuel excise taxes thus remain the primary instrument constituting ECRs in LAC, keeping in mind no country had an operative ETS in 2018. This latter observation does indeed distinguish the region from OECD countries, where ETS mechanisms are widespread as a feature of carbon pricing. According to OECD-ECR (2021), permit prices in 2018 accounted for 7% of carbon prices considering the worldwide sample of countries, including those with no ETS on place.

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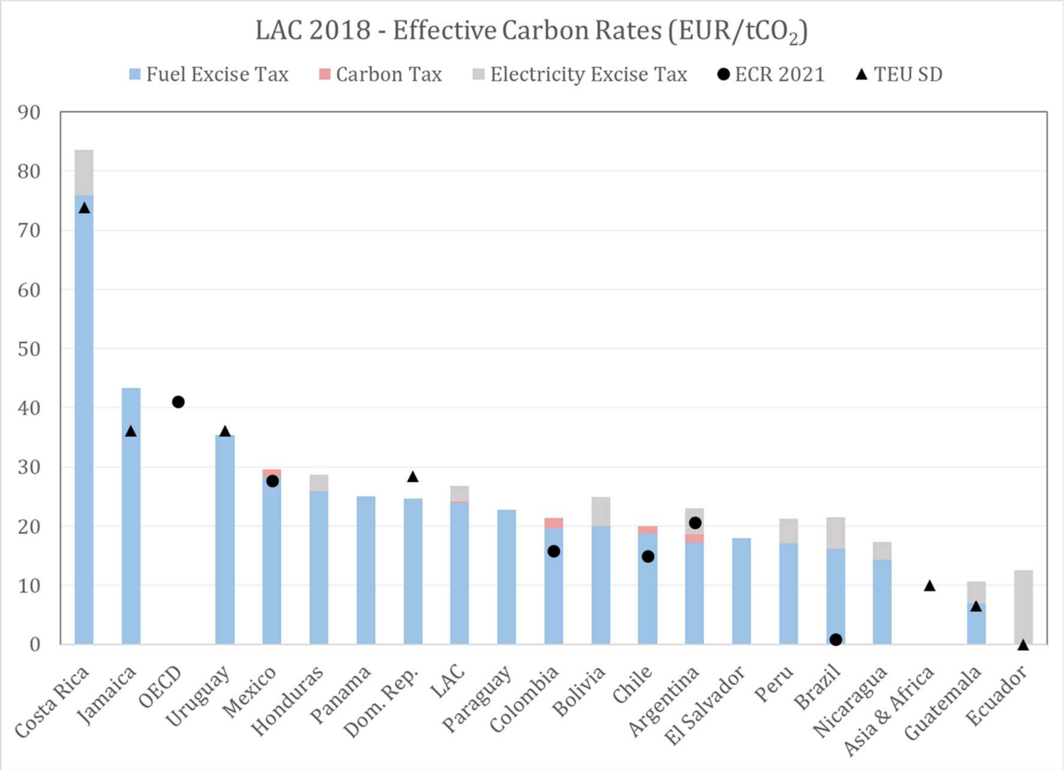
[9] https://carbonpricingdashboard.worldbank.org/map_data

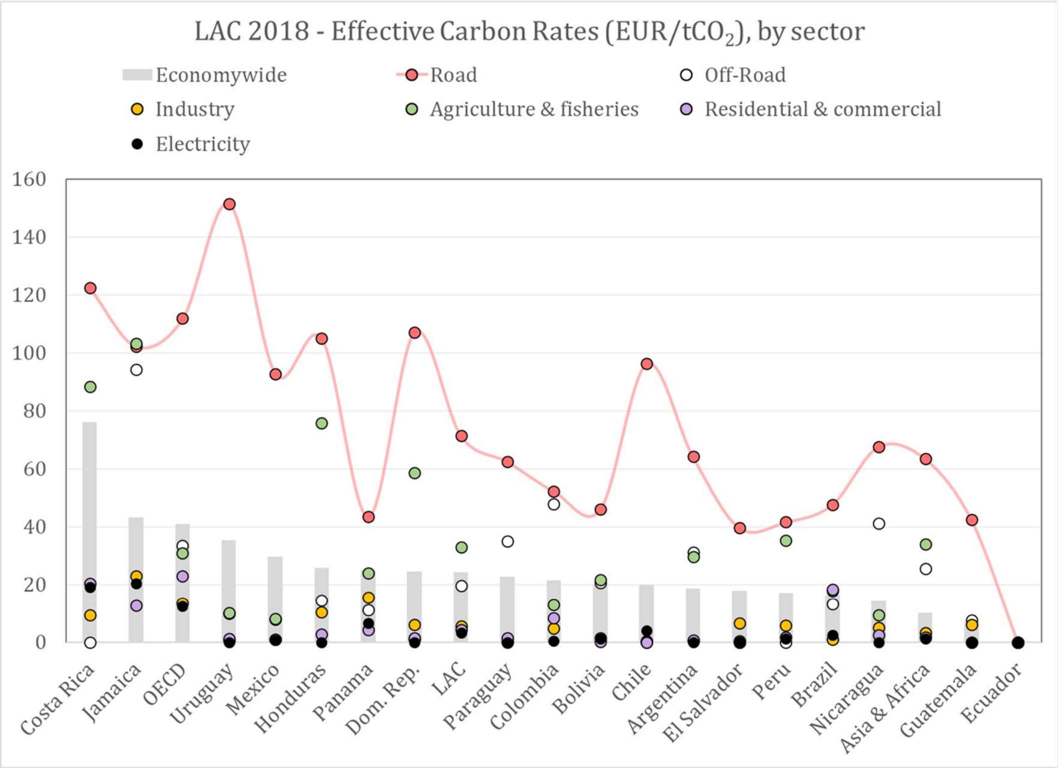
Figure 2



Note: regional averages are unweighted. Asia & Africa includes countries from both OECD (2021) and OECD TEU-SD (2021). Electricity Excise Taxes are shown for reference purposes but are not included in the Effective Carbon Rate definition.

This analysis can be extended from an Economywide, aggregate level to a sectoral representation, acknowledging CO_2 emission contributions from each sector may be priced in a heterogeneous way. Table A1 in Appendix A lists our measurement of ECRs for LAC countries in our sample with sectorial detail. Figure 3 depicts the intersectoral structure of ECRs, where asymmetry is apparent. Emissions stemming from Road transport tend to be priced much higher than those originated in the other sectors, with a sectoral ECR usually above the EUR 60 benchmark or at least well above the EUR 30 benchmark in virtually all LAC countries (apart from Ecuador). On average, the Agriculture & fisheries and the Off-road transport sectors are next in line, although this differs substantially across countries. Lastly, with counted exceptions, Industry, Residential & commercial, and Electricity sectors tend to have the lowest burden in terms of carbon pricing. The average OECD member, in comparison, tends to have a lower carbon pricing intersectoral dispersion than the average LAC member, considering sectors other than road transport.

Figure 3

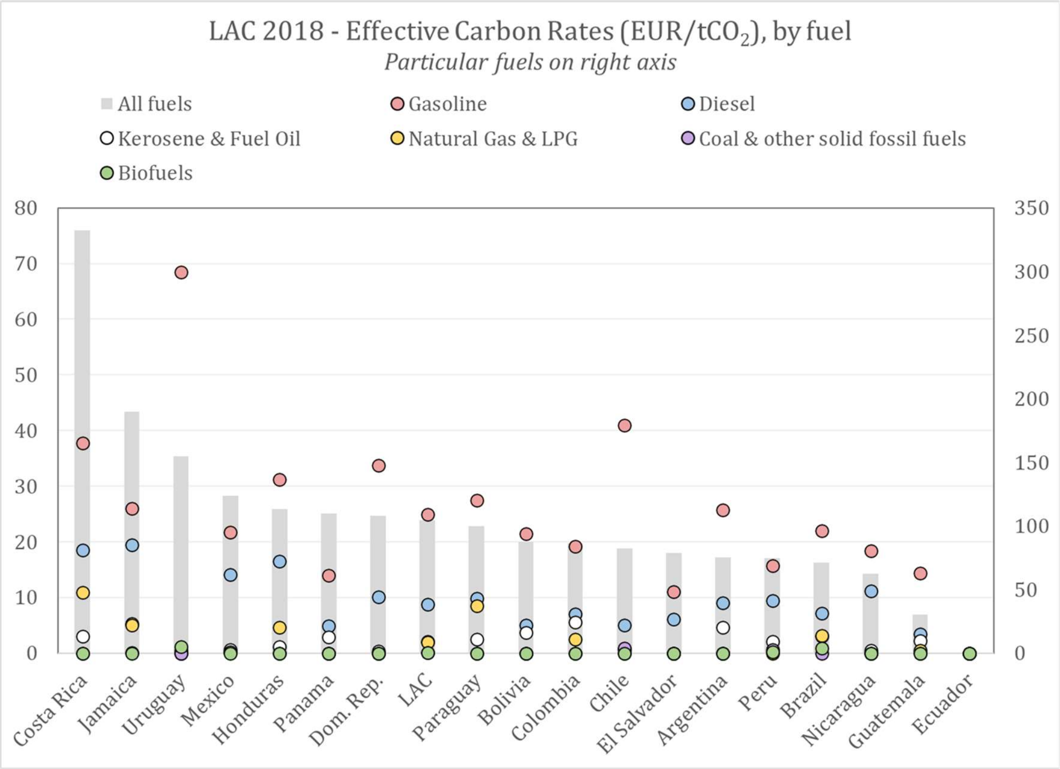


Note: regional averages are unweighted. Asia & Africa includes countries from both OECD ECR (2021) and OECD TEU-SD (2021). Missing sectors correspond to incomplete energy balances.

Altogether, this is consistent with the observation that the road transport sector drives overall ECRs, representing a disproportionate share of related revenues in terms of its contribution to economy-wide emissions. This pattern is consistent across countries and does not appear to be a regional feature of LAC members.

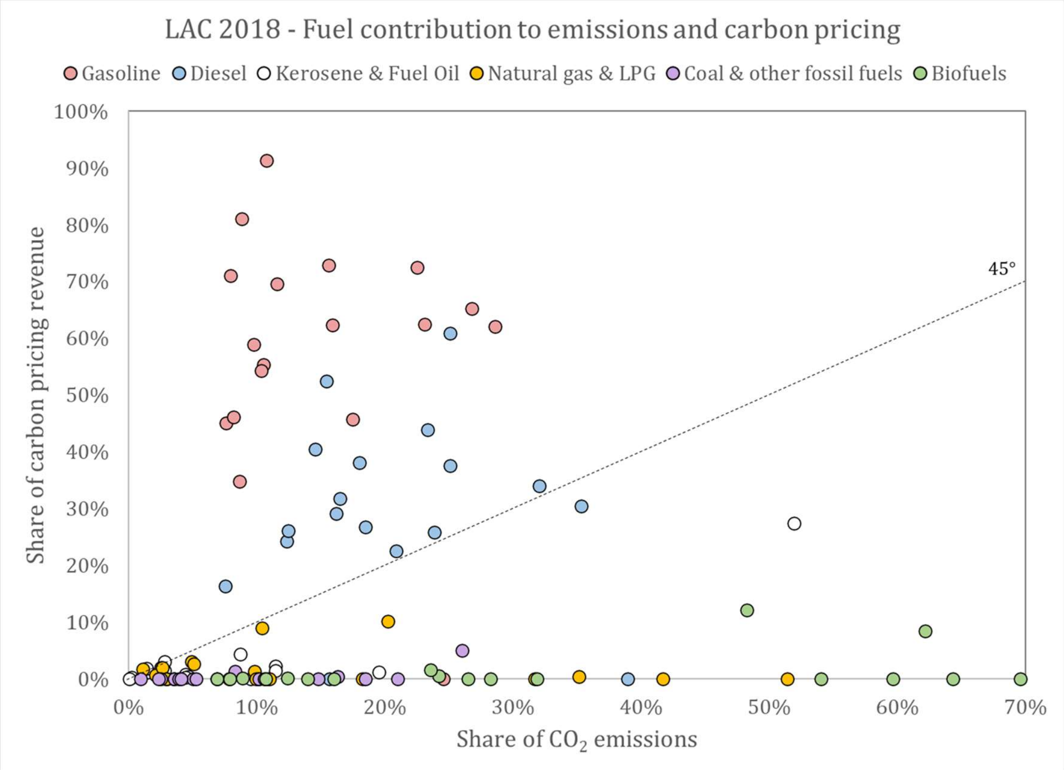
Interestingly, most of intersectoral heterogeneity regarding carbon pricing does not seem to be a consequence of sector-specific special tax treatment (exemptions, rebates, refunds and similar mechanisms). Figure A1 in Appendix A shows that if sector-level tax exonerations are not considered when computing ECRs, the resulting hypothetical increase is far behind from what a catch-up to road transport level would yield. Instead, ECR dispersion across sectors is best explained by examining ECR dispersion across fuels. Carbon pricing heterogeneously distributed across fuels translates into intersectoral dispersion because these enter differentially as inputs in each sector's energy use. Thus, as illustrated in Figure 4, the correlate of Road transport carrying most of the carbon pricing burden is the observation that gasoline and diesel have comparatively high ECRs with respect to other fossil fuels.

Figure 4



ECRs on kerosene, fuel oil, natural gas and LPG vary substantially by country but tend to follow gasoline and diesel in rank, although with no comparable levels. On the other hand, coal and solid fossil fuels in general, as well as biofuels, tend to be almost untaxed. Like in the case of sectors, this arrangement does not follow an ordering derived from fuel contributions to emissions, as depicted in Figure 5. Instead, fossil fuels other than gasoline and diesel can explain significant shares of carbon emissions remaining virtually untaxed. This posits the need for reform regarding carbon pricing across fuels (and thus, across sectors as well). ECRs should converge to homogeneous rates per emission unit or per energy content unit across fuels to align costs of CO_2 emissions and avoid placing incentives on distinct fossil fuels via relative price distortions. Regarding this goal, a critical obstacle for regions like LAC is the structural bias towards untaxed biofuels.

Figure 5



4. Energy subsidies and adjusted ECR

Energy subsidies directed to fossil fuels have remained significant at a global scale and have been pointed out in recent years as a problem for decarbonization (Coady *et al*, 2019; Parry *et al*, 2021). The structure of energy subsidies across regions such as EU and LAC have shown significant differences in both levels and structure with LAC more biased towards subsidies to households and to electricity.[10] Energy subsidies to fossil fuel use operate, in principle and as they alter effective prices, in opposition to ECRs and work as negative taxes on carbon emissions. Carbon pricing may be overestimated if one does not consider the effect of subsidies on energy use, as these can offset the incentives instrumented by excises, carbon taxes and ETS. Adjustment to ECR should ideally proceed in the same bottom-up way as tax rates are measured, i.e. at the sector level of energy used and therefore incorporated in the same way as excises, carbon taxes or ETS prices. This task is rather burdensome and it explains why OECD-ECR (2019, 2021) do not account for subsidies, despite

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[10] European Commission (2021) accounts for the level and structure of fiscal energy subsidies (i.e. those registered in budgetary operations and including tax expenditures, that are captured by the ECR methodology) in the EU-27 showing an average of about 1.2% of GDP with large cross-country differences, mostly directed to renewable energy schemes and with fossil fuels accounting on average for about 0.3% of GDP and located in transport, manufacturing and agriculture. Electricity subsidies are a minor part of energy subsidies and subsidies to households explain less than 10% of aggregate subsidies, with this figure changing dramatically in 2022. On the contrary, electricity explains about two thirds of energy subsidies in LAC (on average 0.6% of GDP in a similar budgetary definition), according to FIEL (2020) and households have also a share of 66%.

that some recent effort in OECD TEU-SD (2021) have moved to account for subsidies in a few emerging countries where energy subsidies are important. Another delicate issue is the treatment of electricity subsidies, because electricity consumption does not directly imply emissions. Effects of electricity subsidies on emissions depend on the structure of electricity generation, as they may give rise to an increase in factor demand for fossil fuels that competes with other substitution effects in energy consumption that work in opposite direction by reducing emissions. These difficulties have probably led OECD TEU-SD (2021) assessment to be cautious on adjusting for electricity subsidies.

As we could not work bottom up from subsidy wedges contained in the pricing of sectoral energy use[11], we instead tried to make an approximation at an economy-wide level to the likely effect of energy subsidies on the picture that emerged from our estimation of ECR. We collected data on energy subsidies for countries in our sample and expressed them in comparable units to ECRs (EUR/tCO_2)[12], considering budgetary data for LAC countries from FIEL (2020), and using OECD-TEU SD (2021) and the OECD Inventory of Support Measures for Fossil Fuels as sources for the rest. Regarding OECD Inventory data, which reports budgetary transfers as well as tax expenditures as subsidy mechanisms, we excluded the latter from our analysis because these are already accounted for under the taxing energy use OECD methodology.

In Appendix B we explain in detail our estimation for an adjustment of ECR after fuel and electricity subsidies, that we take separately because of their differences. In the case of fossil fuels use (excluding use for electricity generation) we use estimates from FIEL (2020) for 2018 that are expressed as a percentage of GDP, use nominal GDP values to express them in US dollars, then in Euros and finally expressed then as a ratio of aggregate CO_2 emissions to obtain a proxy subsidy rate for the whole economy. For electricity we took energy subsidies and adjusted by a percentage factor expressing the share of thermal fossil fuel electricity generation (thus for economies with large renewable sectors electricity subsidies do not affect ECR as in those based on thermal generation) and assumed that variable costs of electricity generation associated with fossil fuels were 50%.

Figure 6 shows the regional averages for ECRs and their adjustments net of fossil fuel subsidies and net of both fossil fuel and electricity subsidies after following our estimation procedure. Because LAC countries place substantial energy subsidies, once their effect is subtracted from ECRs the gap relative to OECD is considerably higher. On average, LAC is the region with the highest subsidies on energy use.

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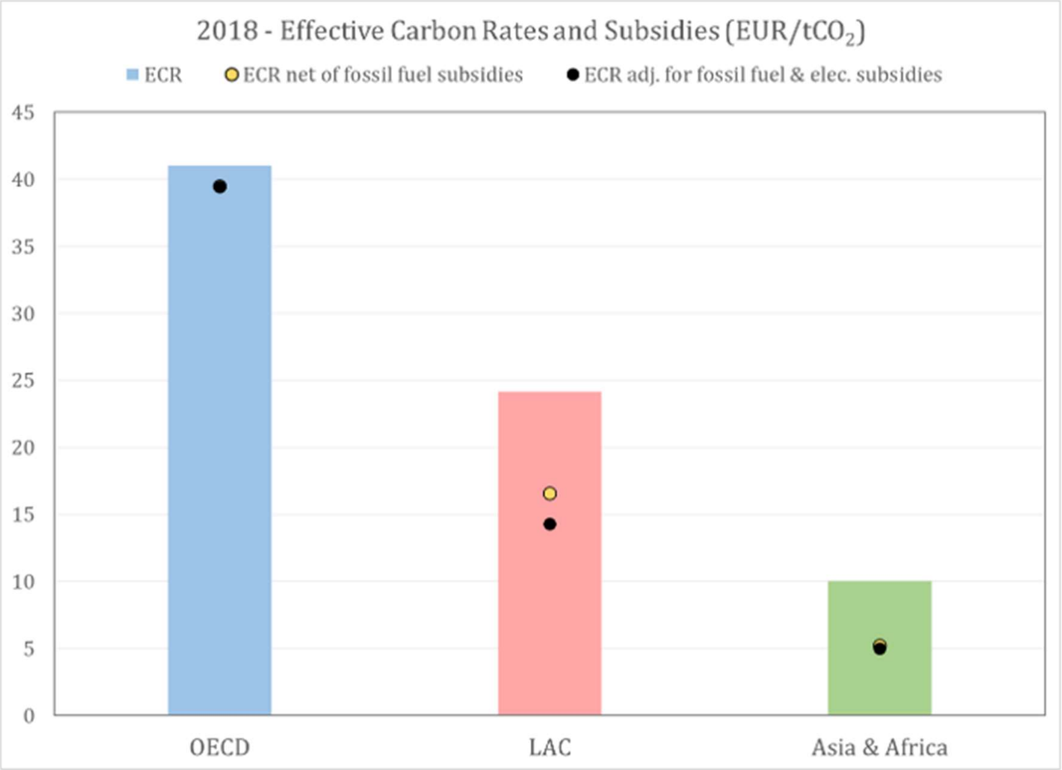
[11] We considered using the data template built up by the IMF to assess global energy subsidies, see Parry, Black and Vernon (2021) and links to www.imf.org/en/Topics/climate-change/energy-subsidies. We had however problems with data compatibility with our OECD/ECR methodology. Also, we found some data errors in prices and subsidies reported in IMF data in some cases where we have first source information and experience, such as the case of Argentina, that made us reluctant. Nevertheless, we believe more effort to make these data sets compatible is well deserved.

[12] Emission data and currency conversion factors were taken from the World Bank, except for LAC countries where emissions were computed from IEA World Energy Balances.

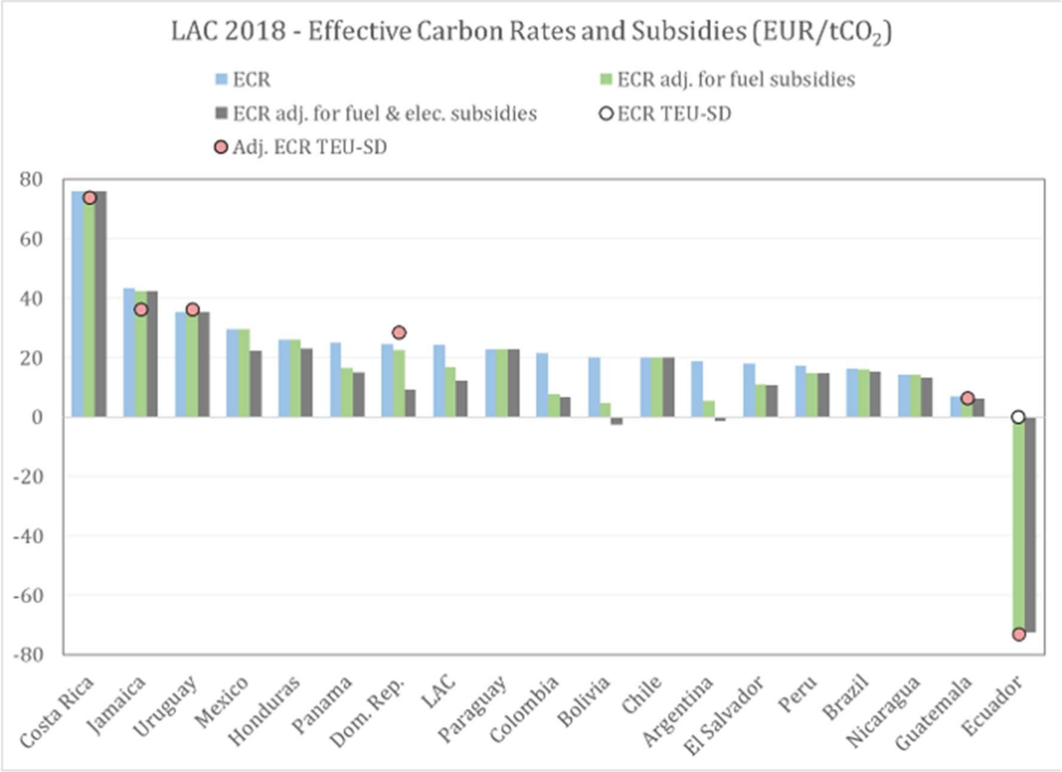
Figure 6



We can take a closer look at country-level subsidies for LAC, as depicted in Figure 7 (Figure A2 in Appendix A shows this detail including OECD and Asia & Africa countries). Costa Rica, Jamaica and Uruguay, ranked with the highest ECRs, do not place significant subsidies on energy use. Paraguay and Chile, with average ECRs compared to the region, do not have significant subsidies.

Dominican Republic, Colombia, Bolivia, and Argentina are noteworthy cases where an average-level ECR is substantially reduced once adjusted for energy subsidies. In Bolivia and Argentina and Dominican Republic, adjusted ECRs turn negative accounting for electricity subsidies, meaning energy use has an overall negative carbon pricing (a net subsidy). Ecuador is an extreme example in this case: not only does it have a null ECR, but it effectively and heavily subsidizes carbon emissions from energy use.

Figure 7



Note: group averages are unweighted. Bolivia provides negative excise (subsidy) rates on imported diesel. These account for transfers of about 1.2% of GDP, consistent with the 1.1% budgetary estimates from FIEL (2020).

Although adjusting ECRs for energy subsidies reveals some countries are further off from the relevant benchmarks, and that emissions may be actually subsidized rather than taxed in particular cases, this opens a direct avenue for reform. Reducing energy subsidies would not only increase effective carbon pricing but would also imply considerable fiscal savings.

5. Econometric modelling approach to ECR determinants

In this section we focus on the determinants of observed ECR, both sectoral and economy-wide in our sample of 66 countries which include OECD, LAC and Asia and Africa countries. In order to find the main determinants, we started by considering as potential explanatory variables a wide set of variables as detailed in the next section.

We separate our econometric analysis in three models. The first is a study of determinants of economy-wide ECR. Then, based on the different nature of taxation at disaggregated sectoral level we studied the determinants of road transport on the one hand and the rest of sectors on the other. With this aim, our second model looks at the determinants of ECR in road transport. The third model moves to the estimation of a panel of 5 sectors, other than road transport, for the 66 countries. In all cases we search for differences in LAC vs OECD both in levels and in the interaction with determinants. We also study the effects of energy subsidies in an economy-wide cross section of ECR looking for their relevance both in redefining the dependent variable (ECR adjusted for subsidies) and in their likely effect on non-adjusted ECR.

To handle many potential variables, an automatic algorithm (Autometrics, see Doornik, 2009 and Hendry and Doornik, 2014) helped us select the relevant determinants. This algorithm uses a tree search to discard paths rejected as reductions of the initial unrestricted model based on ordered squared t-statistics, given a p-value provided by the researcher and providing misspecifications tests. One advantage of using this algorithm is that it allows to obtain more robust estimations by selecting the observations that are outliers among all the observations in the sample (given a p-value). That is, by using impulse dummy saturation we can find countries that can be treated as outliers in the cross-country regressions, apart from testing the regional (OECD and LAC) effects.[13]

In the case of the panel we have the explained (ECR) and the (k.1) vector of explanatory variables $y_{s,i}$, $x_{s,i}$, respectively, where "s" indicates one of the 5 sectors (off-road, industry, agricultural and fisheries, residential and commercial, and electricity) and "i", each of the 66 countries. For this model we can test for the effects of sectoral (α_s) and country (α_i) dummy variables (as fixed effects) but also for "s, i" outliers by using the algorithm. That is, the unrestricted model may have the following form,

$$y_{s,i} = \alpha_s + \alpha_i + \alpha_{si} + x_{si}{}' \beta + x_{si}^{*}{}' \beta_s + \varepsilon_{s,i} \qquad (1)$$

Since several variables are available only at aggregated (economy wide) level we also allow for heterogeneity by sectors using multiplicative dummies (x_{si}^{*})[14] for main variables being their marginal effect β_s .

6. Data and variables definition

Effective Carbon Rates for LAC countries were computed as described in section 2. Regarding OECD members and countries from Asia and Africa, ECR data was taken from OECD-ECR (2021), OECD-TEU (2019) and OECD-TEU SD (2021). All ECR data is expressed in 2018 Euros per ton of CO_2 emissions from energy use (EUR/tCO_2), and open in 6 sectors following OECD Taxing Energy Use methodology: Road transport, Off-Road Transport, Industry, Agriculture & fisheries, Residential & commercial, and Electricity.

Fossil fuel and electricity subsidies were calculated as described in Section 4 and Appendix B. Both expressed in EUR/tCO_2, this allowed us to generate subsidy-adjusted Effective Carbon Rates subtracting fossil fuel subsidies from ECR as explained in detail in Appendix B. To further adjust for electricity subsidies (also explained in Appendix B) we considered the fact that they increase the demand for

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[13] We used 5% target (probability) values for variables and 1% for impulse dummy selection. *Autometrics* evaluates diagnostic tests for heteroscedasticity and normality in the data studied. In some cases, consistent standard errors are reported.

[14] The original variables are multiplied by indicators functions equal to 1 for each sector "s".

fossil fuels to the extent that electricity generation is fossil fuel based. Thus, we corrected the magnitude of electricity subsidies with the share of electricity generated from fossil fuels and assumed an *ad hoc* variable cost structure explaining 50% of total electricity costs for such generation. Dummies coding for the operative presence of nationwide Emission Trading Systems (*ets*) and Carbon Taxes (*carbon*) in 2018.

A broad assortment of candidate explanatory variables was compiled from various sources. These include standard income-level measures as GDP per capita (*gdp*), and indicators that intend to proxy fiscal revenue needs, like gross government debt (*debt*) or the average primary fiscal deficit incurred in the five years prior to 2018 (*deficit_prim_5*). This last set of variables includes a proxy of the marginal cost of public funds (*mcf*) defined in a simple way from optimal indirect taxation formulae (Navajas et al, 2012) and based on the economy wide value added tax (VAT)[15]:

$$mcf = \frac{1 + VAT}{1 + 0.1\,VAT} \qquad (2)$$

It should be noted that ECR estimates in the present document exclude VAT by definition, and thus this measure is included not to control for varying VAT rates across countries, but rather to identify possible revenue-related factors underlying ECRs.[16]

A block of explanatory variables related to governance and institutions includes measures of regulatory quality (*regqual*) and perceived law enforcement (*rulelaw*), as well as the Polity Index that classifies political systems in a spectrum ranging from full autocracy to full democracy (*polity*). Some of these variables, became non significant when GDP was automatically selected. We also included infrastructure quality indicators regarding roads (*road_quality*) and logistic transport in general (*transport_infr*), with alternative objective measures of road quality based of the fraction of roads that are paved (*road_paved*) or the density of road networks

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[15] The optimal uniform percentual tax wedge or margin between consumer (q) and producer (p) prices is defined as m=(q-p)/q=(λ/1)/λη where η is the aggregate good or consumption price elasticity of demand, assumed at 0.9 and λ is the marginal cost of public funds (or revenue constrain multiplier). As by definition q=p(1+t) where t is the uniform tax rate (assumed as the VAT rate) we have m=t/(1+t) and obtain λ=(1+t)/(1+(1-η)t).

[16] We also compiled several indicators related to energy use, as well as related CO_2 emissions. These include the fraction of energy consumption and electricity output derived from renewable sources (*renew_energy* and *renew_elec*, respectively), electric power transmission and distribution losses (*dist_loss*), the intensity of energy use per unit of GDP (*energy_use*), the intensity of derived CO_2 emissions per unit of GDP (*emission*) and the share of these stemming from the Transport sector (*emission_transport*). It should be noted that the included CO_2 emission variables, taken from the World Bank, are based on standard UNFCCC inventories and thus consider biofuels to have a carbon-neutral cycle, unlike the approach taken in ECR methodology where emissions are computed following a combustion approach. This means CO_2 emissions in these explanatory variables are not directly comparable to those implicit in the endogenous variable (ECR), and thus their inclusion in the model is based on control purposes. This set of variables is completed with indicators related to the "energetic trade balance": a dummy captures if the country is a net energy exporter (*net_exporter*), and oil rents are included as a possible measure of fiscal dependence (*oil*).

(*road_density*). These variables are broadly intended to capture services derived from transport infrastructure.

Finally, geographical indicators as latitude (*latitude*) were taken into account, as well as proxies for topographical irregularity like the elevation span, measuring the distance between the highest and lowest points in each country (*elevation_span*).

Table 1 lists a subsample of variables included in our analysis. For full set of variables and their corresponding sources, refer to Table A2 in Appendix A. These include, amongst others, a block of control variables related to public ownership of oil and gas resources, and another one corresponding to specific VAT exemptions on gasoline and diesel as well as their pricing across countries.

Table 1

Variable group	Variable name	Description
Country & group variables	**country**	Country name.
	oecd	Dummy coded =1 if country is OECD member. This definition excludes LAC member countries.
	lac	Dummy coded =1 if country is from LAC
	asia_africa	Dummy coded =1 if country is from Asia or Africa
Sector variables	**economywide**	Dummy coded =1 if sector=Economyide
	road	Dummy coded =1 if sector=Road
	off_road	Dummy coded =1 if sector=Off-road
	industry	Dummy coded =1 if sector=Industry
	agr_fish	Dummy coded =1 if sector=Agriculture & fisheries
	res_com	Dummy coded =1 if sector=Residential & commercial
	electricity	Dummy coded =1 if sector=Electricity
Carbon pricing variables	**ecr**	Effective Carbon Rate (EUR/tCO2) in 2018. ECR includes fuel excises, carbon tax, and marginal permit price for ETS systems, in case these instruments are operative. Data drawn from ECR 2021 was replaced from TEU 2019 uniquely for the Road sector in the particular cases where the sectoral ECR saturated the 120 benchmark.
	ets	Dummy variable coded =1 if Emission Trading System was operative in 2018, excluding subnational systems (as for the case of USA, Canada, Japan, China).
	carbon	Dummy variable coded =1 if Carbon Tax was operative in 2018, excluding subnational systems (USA).
	subsidy_fuel	Fossil fuel subsidies (EUR/tCO2) in 2018. LAC country data is from FIEL (2020). TEU SD countries have fuel subsidy data from OECD TEU SD, but do not have electricity subsidy data, so the latter are filled with zero-values. The remainder of the countries in the document have fuel subsidy data from OECD Inventory of Support Measures for Fossil Fuels, taking into acount uniquely Budgetary Transfers, because Tax Expenditures should already be accounted for under TEU methodology. Electricity-based support measures are taken as Electricity subsidies (see below).
	subsidy_elec	Electricity subsidies (EUR/tCO2) in 2018. Same sources as above.
	adj_ecr	Effective Carbon Rate net of Fuel Subsidies (EUR/tCO2)
	adj_ecr_elec	Effective Carbon Rate net of Fuel Subsidies and adjusted for Electricity subsidies (EUR/tCO2). This estimate is done assuming a cost structure where 90% are explained by variable costs, and considering that subsidies on electricity increase the demand for fossil fuels to the extent that electricity generation is fossil-fuel based. Thus, ECR net of fossil fuel subsidies is hereby adjusted by substracting **subsidy_elec** multiplied by 0.9 and by the share of electricity generated using fossil fuels (**1-renew_elec**).
Control variables	**gdp**	GDP per capita, 2018, PPP (constant 2017 international $)
	emission	CO2 emissions, 2018 (kg per PPP $ of GDP)
	emission_transport	Transport sector share in CO2 emissions from enery use. Keep in mind this sectoral definition encompasses Road and Off-Road transport, and takes into account emissions excluding biofuel combustion, and thus is not directly comparable with our approach.
	oil	Oil rents, 2018 (% of GDP)
	net_exporter	Dummy coded =1 if country is a net energy exporter
	renew_energy	Renewable energy consumption, 2018 (% of total final energy consumption)
	renew_elec	Renewable electricity output, 2015 (% of total electricity output)
	energy_use	Energy use (kg of oil equivalent) per $1000 GDP, 2014 (constant 2017 PPP).
	dist_loss	Electric power transmission and distribution losses (% of output), 2014
	polity	Polity Index, 2018 (10 is full democracy, -10 full autocracy)
	regqual	Normalized estimate based on a standard distribution (ranges from aprox -2.5 to 2.5). Reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development. 2018.
	mcf	Marginal Cost of public Funds, proxied as (1+VAT)/(1+0.1*VAT). VAT data was sourced from PWC. For USA, State-level Sales & Use tax rates were weighted by total energy consumption shares for 2018 from EIA.
	debt	Gross Government Debt (% of GDP), 2018
	deficit_prim_5	General government primary net lending/borrowing (% of GDP), 2014-2018 avg
	pop_density	Population density, 2018 (people per sq. km of land area)
	latitude	Latitude value of capital city
	elevation_span	Elevation span (distance in m from lowest to highest point)
	road_quality	Road quality index, 2017-2018 edition (1 = extremely underdeveloped—among the worst in the world; 7 = extensive and efficient—among the best in the world])
	road_density	km of road per sq. km
	road_paved	Percentage of roads paved (%)
	transport_infr	Logistics performance index: Quality of trade and transport-related infrastructure (1=low to 5=high). Nicaragua was completed due to missing data using the OLS best fit prediction based on its road_quality value, given that the correlation coefficient between both variables is 0.77.
	vehicles	Motor vehicles per 1000 people (2014)

7. Results

Tables 2, 3 and 4 report the results of our econometric estimation of ECR determinants for economy-wide, road transport and rest of sectors respectively. Table 2 shows the selected equations obtained from our automatic selection procedure. Column 1 shows our selected equation for economy-wide ECR while columns 2 and 3 show sensitivity results using estimates of ECR adjusted for fossil fuels and fossil fuels cum electricity subsidies.

Economy-wide ECR rates can be modeled with GDP (in logs), a dummy representing if the country has an ETS mechanism (ets) and our proxy for the marginal cost of public funds (mcf) all with expected signs. Richer countries in our sample tend to have higher ECRs. Marginal cost of funds captures a fiscal, revenue raising motive for ECR, which is consistent with tax theory and with positive economics or politics explanations of energy taxes (Mahdavi et al, 2022). Finally, countries with ETS add up (see in column 1) an effect of about 7%, calibrated against the constant. Other automatically selected dummies stand for specific countries, where ECR is higher, such as Costa Rica (CR) and Switzerland and Luxembourg (SWT+LUX) which are added because both countries enter with similar coefficients. All other variables of our large, extensive dataset are not selected as significant. For instance, dummies related to the adding effect of carbon taxes on ECR are not significant. Our estimated effect of ETS is similar to the 7% share of ETS in ECR mentioned in section 3 and reported in OECD/ECR (2021). Our estimate tells that controlling for other factors (GDP, mcf) countries with ETS end up having a higher ECR in relation to the average of the sample. The same does not happen with carbon taxes. This suggests that ETS introduction is not compensated by a corresponding reduction in other ECR components, particularly excises. Since excises are mainly directed to road transport while ETS cover other sectors and have not yet been extended to transport in spite of current proposals (see Pollitt and Dolphin, 2022) there is no evidence of compensatory adjustment. The same does not happen with carbon taxes, as they are more akin to excises and in fact can be naturally be thought in terms of tax reform that replaces excises with carbon taxes (Navajas et al, 2012). Our evidence is compatible with some compensatory effects that make the introduction of carbon taxes more neutral (than ETS) for the effective level of carbon rates.

Sensitivity analysis to account for ECR definitions that adjust for subsidies show similar results, with same central variables being selected, some minor changes in coefficients and selecting new dummies for some countries with large energy subsidies (Egypt, Ecuador) or relatively large ECR (Jamaica).

Table 2. Economywide

OLS modeling of Effective Carbon Rates (ecr) and their adjustments net of fossil fuel subsidies (ecr_adj) and fossil fuel and electricity subsidies (ecr_adj_elec)

Model	**1**	**2**	**3**
Endogenous variable	**ecr**	**ecr_adj**	**ecr_adj_elec**
Lgdp	6.08**	6.80**	6.28**
	2.08	*2.01*	*2.14*
ets	11.0**	12.5**	16.1***
	4.09	*3.94*	*4.21*
mcf	104**	87.3*	73.8*
	35.08	*33.81*	*36.14*
CR	57.2***	59.9***	62.4***
	10.04	*9.65*	*10.31*
SWT + LUX	37.8***	37.7***	37.2***
	7.81	*7.50*	*8.02*
JAM		29.8**	32.1**
		9.61	*10.27*
EGYP		-35.9***	-33.7**
		9.60	*10.26*
ECU		-84.0***	-82.0***
		9.63	*10.29*
Constant	-157***	-149**	-131**
	45.02	*43.46*	*46.45*
Adjusted R^2	0.726	0.839	0.827
Observations	66	66	66

Standard errors shown in italics below coefficients. *p<0.05; **p<0.01; ***p<0.001

The fact that ETS are a determinant for economy-wide ECR but have not been directed towards the road transport sector, should imply its absence in the estimated equation of ECR for road transport. This is what is reported in Table 3, along with other determinants of ECR. It shows that both GDP and marginal costs of funds enter as controls. In the road sector, the public finance motive captured by our proxy for marginal cost of funds is an important determinant. Other three structural variables are selected by the model. Population density and the elevation span of the country have a positive impact on road transport ECR. On the other hand, being an oil producer has a negative effect. Our model reported in Table 2 does not select any other additional variables.

Table 3. Road Transport
OLS modeling of Effective Carbon Rates (ecr)

Endogenous variable	**ecr**
Lgdp	19.0**
	6.33
oil	-6.24*
	2.51
elevation_span	-0.005*
	0.003
mcf	559***
	125.90
pop_density	0.147***
	0.04
Constant	-725***
	147.40
Adjusted R^2	0.571
Observations	66

*p<0.05; **p<0.01; ***p<0.001

Standard errors shown in italics below coefficients.

With a very different pattern of ECR, captured in Figure 1 in the introduction, the rest of the sectors covered in OECD/ECR methodology (off-road transport, agriculture and fishery, manufacturing, residential/commercial and the electricity sector) must have a different structure of determinants, i.e. the modelling procedure should select another set of variables. These are reported in Table 4 were we estimate a panel regression for 5 sectors across the 66 countries of the sample. Variables such as GDP and the marginal cost of funds are not selected in this model, but ETS is selected with a greater quantitative effect with respect to the constant. Fixed effects are captured through many selected variables. Agriculture is a sector were ECR are substantially lower, an effect that is diminished where the country has an ETS, which increases the (rather low) ECR in the Agriculture and sector by 6.8% (-23.7/-346). Marginal cost of funds only shows up interacting with sectoral dummies, with positive effects in agriculture and off-road transport. Other effects are related to sectoral country dummies. Higher ECR are detected in Baltic countries and Switzerland off-road sectors, Netherlands residential/commercial and Costa Rica agriculture.

To sum up, ECR determinants selected at the economy-wide level are basically three, two of which (GDP and marginal cost of funds) come from ECR determinants in the road transport sector while the third (ETS) come from effects in the rest of sectors. Other structural and institutional elements play an auxiliary or secondary role, while most variables in our large dataset are not selected. The effect of ETS is significant and suggests an avenue for improving ECR. Carbon taxes are probably associated with compensatory effects in road transport excises, given their relatively minor role in other sectors. LAC as a region is not captured as having a different model nor does it interact with individual variable effects. The only test for differences in LAC versus OECD is shown in the role of ETS, since these are not operative in LAC.

Table 4. Sectoral panel, excluding Road
OLS modeling of Effective Carbon Rates (ecr)

Model	**1**
Endogenous variable	**ecr**
agr_fish	-346*** *66.78*
ets	7.27** *2.83*
ets*agr_fish	-23.7** *5.72*
mcf*agr_fish	327*** *59.00*
mcf*off_road	11.5*** *2.23*
Baltic_offroad	80.1*** *10.53*
latitude	0.101** *0.045*
NDL_res_comm	88.3*** *17.72*
SWIT_off_road	81.9*** *17.80*
CR_agr_fish	64.9*** *17.90*
Constant	3.81*** *1.62*
Adjusted R^2	0.462
Observations	330

Robust standard errors shown in italics below coefficients.

*p<0.05; **p<0.01; ***p<0.001

8. ECR and emissions

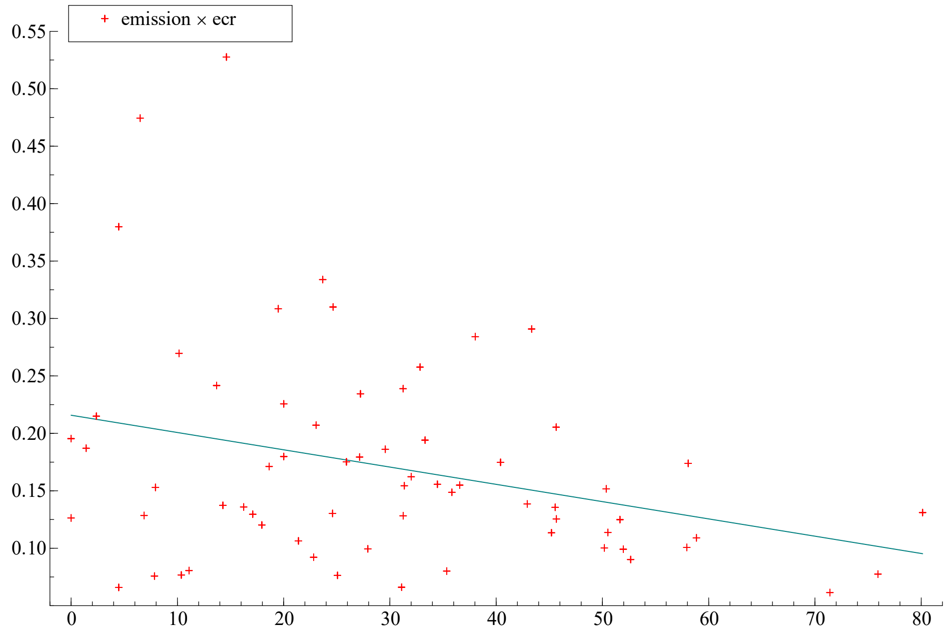
Some reports by OECD (OECD-ECR, 2021, chapter 2) and background papers (e.g. Sen and Vollebergh, 2018; Martin, Muûls and Wagner, 2016) have reported evidence that ECRs reduce energy consumption and emissions. More recently there has been some discussion on the effect of carbon pricing on aggregate emissions. Evidence referred to in Metcalf (2019), an excellent and useful review of carbon pricing in the US, has been challenged by Pretis (2022) on a thorough policy evaluation assessment of the carbon tax reform in British Columbia, where he claims that carbon taxes do show an effect on transport sector emissions, but evidence does not show an effect on aggregate emissions. While our paper is focused on other objectives and cannot contribute to such a discussion due to data limitations, in this section we refer our data on the relationship between ECR and available estimates on aggregate emissions. One must notice that ECR are a combination of three different instruments (excises, carbon taxes and ETS) that works through prices to signal the cost of carbon emissions. In this paper we have found that ECR in road transport (which are mainly formed from excises and, to a lesser extent, carbon taxes) is much more important than ECR in other sectors, where taxation is rather low (beyond exemptions, we found) and ETS mechanisms are incipient and operating in some advanced economies. It is not strange from the perspective of our results that impacts through transport tax signals (including carbon taxes) should emerge as more significant than effects in other sectors were taxation is rather low (See Figure 1 in the introduction).

In this section we use our data base to analyze the cross-country relationship between aggregate emissions (kg of tCO_2 per PPP$ of GDP; see Table 1) and ECR (EUR/tCO_2). Figure 8 shows the cross plot between total emissions and ECR using our data base of 66 countries for 2018.

Figure 8

ECR and aggregate emissions

units: ECR (EUR/tCO2); emissions (kg/PPP$ GDP)



We can observe the negative relationship and from this descriptive picture we can move to estimate a relationship using the log of GDP and population as controls for emissions. Results of the OLS estimation from a conditional model of the log of emissions on ECR are reported in Column 1 and 3 in Table 5.

Table 5. Emissions and ECR

OLS (columns 1 and 3) and IVE (columns 2 and 4) modeling of aggregate Emissions (in Logs) on Effective Carbon Rates (ecr) and their adjustments net of fossil fuel subsidies (ecr_adj)

Model	**OLS**	**IVE**	**OLS**	**IVE**
Endogenous variable	**Lemission**	**Lemission**	**Lemission**	**Lemission**
Lgdp	0.228**	0.302**	0.200*	0.311**
	0.081	*0.11*	*0.08*	*0.11*
ecr	-0.012**	-0.018**		
	0.004	*0.01*		
adj_ecr			-0.0086**	-0.016**
			0.003	*0.006*
pop	0.0006*	0.0005*	0.0007**	0.0006*
	0.0002	*0.0002*	*0.0002*	*0.0002*
Constant	-3.86***	-4.43***	-3.72***	-4.65***
	0.74	*0.92*	*0.73*	*1.02*
Adjusted R^2	0.230		0.220	
SER	0.422	0.429	0.425	0.444
Observations	66	66	66	66

Standard errors shown in italics below coefficients. *p<0.05; **p<0.01; ***p<0.001

Population in millions of habitants.

In columns 2 and 4 additional instruments are **mcf** and dummies for CR and SWIT .

We note that this analysis is different from the policy evaluation approach for a given country of tax impacts on carbon tax over emissions as recently discussed in Pretis (2022) and Metcalf (2019), which find mixed evidence. In our case we report the effect of ECR on emissions from the comparisons of 66 worldwide countries at a point in time. The results from OLS estimates indicate a significant negative effect of ECR on the log of emissions. Given the log linear functional form, the elasticity of emission with respect to ECR is evaluated at mean and maximum values of ECR. In the case of column 1, the elasticity values are 0.36 and 0.96, respectively. These values are consistent with estimates reported in OECD-ECR (2021, chapter 2) based on Sen and Vollebergh (2018). At mean values, a country which has ECR 10% higher than other has 3.6% less of emissions. The model using ECR adjusted for subsidies show lower elasticity values, of 0.22 and 0.69, respectively. To take into account the possibility of biases in the estimates due to the effect of emissions on ECR we re-estimated the models by using IV and making ECR endogenous. We used the marginal cost of public funds (mcf) and two country dummies as instruments. According to the results in section 7, mcf is a determinant of ECR and is not related to the level of country emissions. As shown in Column 2 and 4, the negative effect of ECR on emissions is higher using IV; e.g. the elasticity value is 0.53 in the case of mean values of unadjusted ECR.

9. Conclusions and further research

Effective carbon rate methodology is a useful way to normalize cross country measures of carbon pricing on energy use that encompasses different forms of price signals with the main ones being excises, carbon taxes and ETS prices. The methodology is a bottom-up sectoral measurement in 6 sectors, using IEA energy balances in a format that allows comparison. We have extended this methodology to 18 Latin American and Caribbean countries in 2018, which is a reasonable pre pandemic year where data is available. Our measurement allowed to differentiate the level and structure of ECR in LAC and the OECD and enabled us to construct a sample of 66 countries, to our knowledge the largest assembled data across countries. We included a simple adjustment to account for energy subsidies, which are particularly relevant in LAC and elsewhere. We found a ranking of ECR across counties in 2018, with 40 EUR/tCO$_2$ on average for OECD, 25 for LAC and 10 for the Asian and African countries of our sample. These values are slightly reduced for OECD when energy subsidies are considered, but the adjustment is much more significant for LAC and Asian/African countries. At the sectoral level we found a stylized fact where ECR are biased towards road transport, while the rest of the sectors have much lower tax pressure and face lower carbon price signals. Beyond the fact that this provides an argument for a direction of reform, we acknowledge that this motivates a search of the determinants of ECR across countries and sectors that calls for a separate search in road transport and the rest of sectors, as road transport excises (a main determinant of ECR both in the sector and in aggregate terms) have a genesis related to fiscal revenue collection for different purposes, notably road infrastructure finance, that quite differs from both local and global environmental control.

We complement our data set with a large number variables potentially useful for the study of ECR determinants, which we made available for research and analysis. From this we implement an econometric approach to select determinants of ECR across countries and sectors based on an automatic, machine-learning methodology. We are able to select three regression equations, one for the economy-wide ECR across our sample, another for the road transport sector and another panel regression for the remaining 5 sectors of OECD/ECR methodology. Explanatory variables are selected from a large sample, but the three models end up selecting a few variables that allow us to elaborate a representation of ECR determinants. Economy-wide ECR across countries are explained by GDP, the marginal cost of public funds and the existence or not of an ETS mechanism. The first two variables drive the equation for road transport ECR while ETS significance comes from the panel estimate for the (poorly taxed) rest of sectors. The quantitative contribution of ETS to economy-wide ECR (but not to transport ECR as it relies on excises and carbon taxes) is significant in magnitude (countries with ETS have on average 7% higher ECR) and shows that the introduction of ETS does not carry a compensatory adjustment of other components of ECR, mainly excises. This is reasonable as excises operate on road transport ECR. But the fact that there is no “carbon pricing crowding out” (if we are allowed to use the term) after the introduction of ETS is we believe a significant feature in practice. The same cannot be said in the case of carbon taxes, according to our results, probably do to the fact that carbon pricing results may come with compensatory adjustments in excises in road transport fuels.

Finally, our data, being basically a cross section of ECR across sectors for 2018, is not fit for an evaluation of the effects of ECR or its components on the aggregate or sectoral level of emissions. Our cross-correlation analysis of ECR and emissions show a negative relationship, controlling for factors such as GDP and population. We do not take side on the recent discussion on the sectoral (transport) versus aggregate impact of carbon taxes and are open to coming evidence, subjected to due scrutiny. However, we think price signals in the energy sector are a central ingredient of carbon policy. This applies, symmetrically, to carbon taxes and to the reform of fossil fuel subsidies: in both cases efficiency, cost effectiveness (including fiscal outcomes) and equity considerations must intervene in the analysis. This view underlies our motivation and effort to collect data, extend estimates of ECR to LAC and perform an analysis of its determinants. Further work, we believe, along the line of this work has several avenues. One is to move to a panel ECR across countries and sectors by adding post pandemic 2021. A second is to move towards a more detailed bottom-up, observed price related, estimate of sectoral energy subsidies that can be integrated to ECR methodology. Third, a bottom-up sectoral measurement of emissions from energy sources across time can also be essential to obtain precise estimates of the effects of the different components of ECR on sectoral and aggregate emissions. Fourth, and from a policy reform perspective, the extent of carbon pricing crowding out (i.e. the introduction of an instrument that reduces the use of another) deserves attention. Finally, the introduction of ETS in regions such as LAC, its sectoral orientation or specialization and the extent of its contribution to make progress in ECR on energy use at sectorial level needs to be assessed against the institutional limits to introducing market-based mechanisms in countries where such mechanisms are absent in central energy price formation, and which are the countries were such a reform may look more promising.

References

Amigo P., S. Cea-Echenique y F. Feijoo et al (2020), “An Emissions Trading System to reach NDC targets in the Chilean electric sector”, *arXiv*:2005.03843v1 [econ.GN], May 8.

Arlinghaus, J. (2015), “Impacts of Carbon Prices on Indicators of Competitiveness: A Review of Empirical Findings”*, OECD Environment Working Papers*, No. 87, Paris: OECD

Arlinghaus, J. and K. Van Dender (2017), “The environmental tax and subsidy reform in Mexico, OECD Taxation Working Papers, No.31 Paris: OECD.

Barde J.P. and N. Braathen (2005), “Environmentally Related Levies”, Chapter 5 in Cnossen S. (ed), *Theory and Practice of Excise Taxation: Smoking, Drinking, Gambling, Polluting and Driving*. Oxford: Oxford University Press.

Becker, G. 1983. “A Theory of Competition among Pressure Groups for Political Influence.” *Quarterly Journal of Economics* 96: 371-400.

Coady D., I. Parry, N.P. Le, and B. Shang (2019) “Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates” IMF Working Paper No. 19/89, International Monetary Fund.

Conte Grand M., A. Rasteletti and J. Muñoz (2022), "Impuestos a los combustibles en la teoría y en la práctica", Nota Técnica #2323, Inter-American Development Bank.

Doornik, J.A. 2009. "Autometrics." In: J. L. Castle and N. Shephard, editors. *The Methodology and Practice of Econometrics: A Festschrift in Honour of David F. Hendry*. Oxford, United Kingdom: Oxford University Press.

European Commission (2021), *Study on energy subsidies and other government interventions in the European Union*, Final Report, https://op.europa.eu/en/publication-detail/-/publication/be5268ba-3609-11ec-bd8e-01aa75ed71a1/language-en

FIEL (2017), "Calidad y eficiencia del gasto público en América Latina y el Caribe: actualización de estimaciones de niveles de gasto y filtraciones en asistencia social, energía y gasto tributario." Background paper for Izquierdo *et al* (2018) op.cit.

FIEL (2020), "Análisis de la eficiencia e incidencia del gasto público en países seleccionados de la región", Report paper to the IADB.

Hendry, D., and J. Doornik. 2014. *Empirical Model Discovery and Theory Evaluation: Automatic Selection Methods in Econometrics*. Cambridge, United States: MIT Press.

ICAP (2021), *Emissions Trading Worldwide: Status Report 2021*. Berlin: International Carbon Action Partnership

IEA (2021), *World Energy Balances: Energy balances for 190 countries and regional aggregates.* Paris: International Energy Agency, https://www.iea.org/data-and-statistics/data-product/world-energy-balances

Izquierdo A., C. Pessino y G. Vuletin (2018), *Better spending for better lives*, Washington: Inter-American Development Bank.

Kanbur, S., and G. Myles. 1992. "Policy Choice and Political Constraints." *European Journal of Political Economy* 8: 1-29

Marten, M. and K. van Dender (2019), "The use of revenues from carbon pricing", *OECD Taxation Working Papers*, No. 43, OECD Publishing, Paris.

Mahdavi P., C. Martinez-Alvarez and M. Ross (2022), "Why do governments tax or subsidize fossil fuels", *The Journal of Politics*, https://www.journals.uchicago.edu/doi/suppl/10.1086/719272

Martin, R., M. Muûls and U. Wagner (2016), "The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years?", *Review of Environmental Economics and Policy*, Vol. 10/1, pp. 129-148.

Metcalf, Gilbert E. (2019), "On the Economics of a Carbon Tax for the United States." *Brookings Papers on Economic Activity*, (Spring), 405-458

Navajas, F., M. Panadeiros and O. Natale (2011), "Environmentally Related Energy Taxes in Argentina, Bolivia and Uruguay", *MPRA working paper 37829,* https://mpra.ub.uni-muenchen.de/37829/

Navajas F., M. Panadeiros y O. Natale (2012), "Workable Environmentally Related Energy Taxes.", IDB Research Department Working Paper, IDB-WP-3 51, November.

OECD-TEU (2015), *Taxing Energy Use 2015: OECD and Selected Partner Economies*, , Paris: OECD.

OECD-ECR (2019), *Effective Carbon Rates 2018: Pricing carbon emissions through taxes and emission trading,* Paris: OECD

OECD TEU (2019), *Taxing Energy Use 2019: Using taxes for climate action*, Paris: OECD

OECD ECR (2021), *Effective Carbon Rates 2021: Pricing carbon emissions through taxes and emission trading,* Paris: OECD

OECD TEU-SD (2021), *Taxing Energy Use for Sustainable Development: Opportunities for energy tax and subsidy reform in selected developing and emerging economies*, Paris: OECD

OLADE (2021), *Estadística energética e información legal*, https://sier.olade.og Quito: Organización Latinoamericana de Energía.

Parry I., S. Black and N. Vernon (2021), "Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies", IMF Working Paper No, 2021/236.

Pollitt M. and G. Dolphin (2022), "Should the EU ETS be Extended to Road Transport and Heating Fuels?", *Economics of Energy and Environmental Policy*, 11, 2, pp.125-44

Pretis F. (2022), "Does a Carbon Tax Reduce CO2 Emissions? Evidence from British Columbia", *Environmental and Resource Economics*, published online https://doi.org/10.1007/s10640-022-00679-w

Sen, S. and H. Vollebergh (2018), "The effectiveness of taxing the carbon content of energy consumption", *Journal of Environmental Economics and Management*, Vol. 92, pp. 74-99.

World Bank (2021), *Emission trading in practice: A handbook on design and implementation*, 2nd edition. Washington DC: World Bank

Appendix A

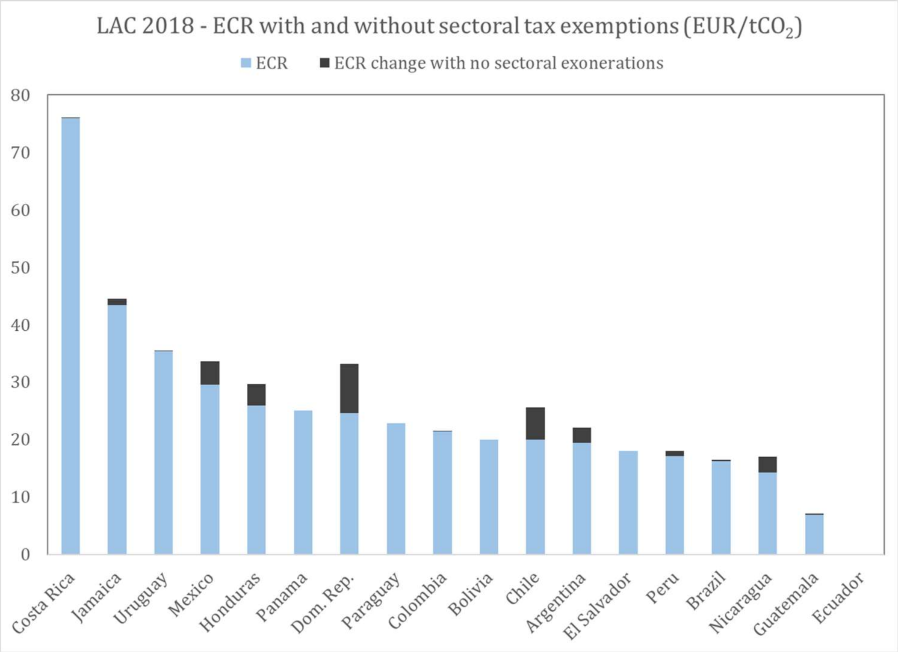
ECR-LAC, exemptions, subsidies and variables database

Table A1

country	Fuel Excise Tax	Carbon Tax	**Effective Carbon Rate**	*Electricity Excise Tax*
	2018, in EUR/tCO $_2$			
Argentina	17.18	1.46	**18.64**	*4.39*
Bolivia	20.02	0.00	**20.02**	*4.95*
Brazil	16.24	0.00	**16.24**	*5.26*
Chile	18.77	1.24	**20.01**	*0.00*
Colombia	19.68	1.72	**21.39**	*0.00*
Costa Rica	75.93	0.00	**75.93**	*7.66*
Dom. Rep.	24.61	0.00	**24.61**	*0.00*
Ecuador	0.00	0.00	**0.00**	*12.59*
El Salvador	17.95	0.00	**17.95**	*0.00*
Guatemala	6.86	0.00	**6.86**	*3.75*
Honduras	25.91	0.00	**25.91**	*2.83*
Jamaica	43.34	0.00	**43.34**	*0.00*
Mexico	28.28	1.28	**29.57**	*0.00*
Nicaragua	14.28	0.00	**14.28**	*3.06*
Panama	25.07	0.00	**25.07**	*0.00*
Paraguay	22.83	0.00	**22.83**	*0.00*
Peru	17.09	0.00	**17.09**	*4.14*
Uruguay	35.35	0.00	**35.35**	*0.00*
LAC simple average	*23.85*	*0.32*	***24.17***	*2.70*

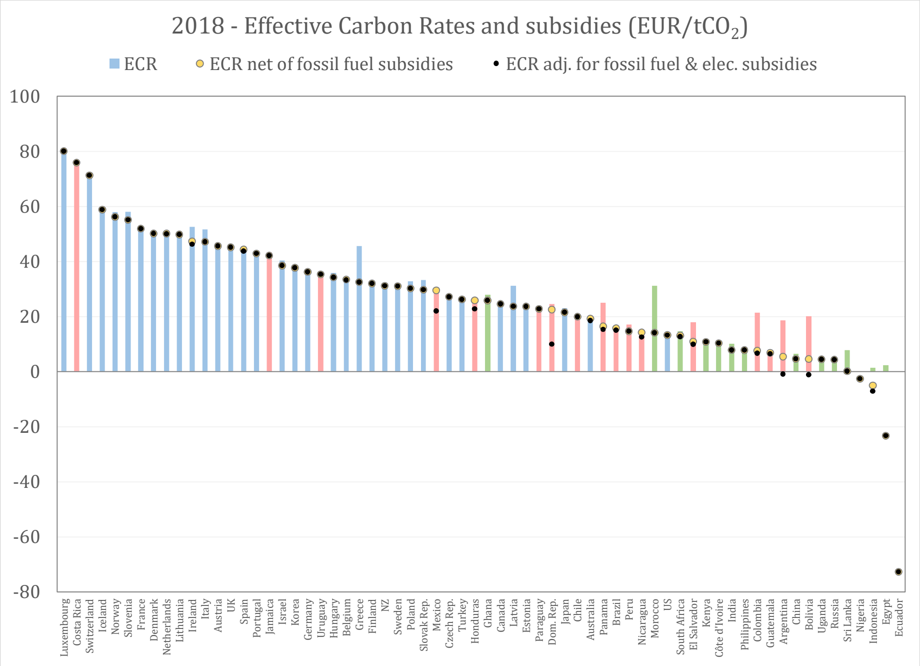
Source: own estimation based on country-level legislation and tax codes, and EIA World Energy Balances.

Figure A1



Note: this hypothetical simulation assumes a static scenario with no fuel substitution effects following relative price changes. Its goal is to depict the magnitude of underlying sectoral exemptions.

Figure A2



Sources: Own estimation and FIEL (2020) for LAC countries. OECD TEU SD. OECD Inventory of Support Measures for Fossil Fuels, considering only budgetary transfers. CO₂ Emissions and local currency exchange rates taken from World Bank, except for emissions for LAC countries, from IEA World Energy Balances.

Table A2

Variable group	Variable name	Description	Source
Country & group variables	**country**	Country name.	
	group	Group where country is assigned. OECD excludes LAC member countries.	
	group_code	Code for group where country is assigned. 0=OECD, 1=LAC, 2=Asia&Africa, 999="LAC B"	
	oecd	Dummy coded =1 if country is OECD member	
	lac	Dummy coded =1 if country is from LAC (does not include "LAC B" countries)	
	asia_africa	Dummy coded =1 if country is from Asia or Africa	
Sector variables	**sector**	Sectoral classification according to primary energy use: Road transport, Off-road transport, Agriculture and fisheries, Industry, Residential and Commercial, Electricity.	
	sector_code	Code for sectoral classification. Economywide=0, Road=1, Off-road=2, Agr. & fish.=3, Industry=4, Res. & com.=5, Electricity=6.	
	economywide	Dummy coded =1 if sector=Economyide	
	road	Dummy coded =1 if sector=Road	
	off_road	Dummy coded =1 if sector=Off-road	
	industry	Dummy coded =1 if sector=Industry	
	agr_fish	Dummy coded =1 if sector=Agr. & fish.	
	res_com	Dummy coded =1 if sector=Res. & com.	
	electricity	Dummy coded =1 if sector=Electricity	
Carbon pricing variables	**ecr**	Effective Carbon Rate (EUR/tCO2) in 2018. ECR includes fuel excises, carbon tax, and marginal permit price for ETS systems, in case these instruments are operative. Data drawn from ECR 2021 was replaced from TEU 2019 uniquely for the Road sector in the particular cases where the sectoral ECR saturated the 120 benchmark.	OECD ECR 2021, OECD TEU 2019, OECD TEU SD
	ets	Dummy variable coded =1 if Emission Trading System was operative in 2018, excluding subnational systems (as for the case of USA, Canada, Japan, China).	https://carbonpricingdashboard.worldbank.org/
	carbon	Dummy variable coded =1 if Carbon Tax was operative in 2018, excluding subnational systems (USA).	https://carbonpricingdashboard.worldbank.org/
	subsidy_fuel	Fossil fuel subsidies (EUR/tCO2) in 2018. LAC country data is from FIEL (2020). TEU SD countries have fuel subsidy data from OECD TEU SD, but do not have electricity subsidy data, so the latter are filled with zero-values. The remainder of the countries in the document have fuel subsidy data from OECD Inventory of Support Measures for Fossil Fuels, taking into acount uniquely Budgetary Transfers, because Tax Expenditures should already be accounted for under TEU methodology. Electricity-based support measures are taken as Electricity subsidies (see below).	
	subsidy_elec	Electricity subsidies (EUR/tCO2) in 2018. Same sources as above.	
	adj_ecr	Effective Carbon Rate net of Fuel Subsidies (EUR/tCO2)	
	adj_ecr_elec	Effective Carbon Rate net of Fuel Subsidies and adjusted for Electricity subsidies (EUR/tCO2). This estimate is done assuming a cost structure where 90% are explained by variable costs, and considering that subsidies on electricity increase the demand for fossil fuels to the extent that electricity generation is fossil-fuel based. Thus, ECR net of fossil fuel subsidies is hereby adjusted by substracting **subsidy_elec** multiplied by 0.9 and by the share of electricity generated using fossil fuels (**1-renew_elec**).	
	ecr_gap_road	Sectoral ECR relative to Road sector ECR. Ecuador and Nigeria, with null ECR values, were completed with zeros.	
	database	Dataset from where ECR value is retrieved.	
Control variables	**gdp**	GDP per capita, 2018, PPP (constant 2017 international $)	World Bank
	gini	Gini index, 2018	World Bank
	sav	Gross savings (% of GDP)	World Bank
	emission	CO2 emissions, 2018 (kg per PPP $ of GDP)	World Bank
	emission_share	Sectoral CO2 emission share. Only available for LAC countries.	IEA World Energy Balances
	emission_transport	Transport sector share in CO2 emissions from enery use. Keep in mind this sectoral definition encompasses Road and Off-Road transport, and takes into account emissions excluding biofuel combustion.	Our World in Data
	oil	Oil rents, 2018 (% of GDP)	World Bank
	energy_imports	Energy imports, net, 2014 (% of energy use).	World Bank
	net_exporter	Dummy coded =1 if country is a net energy exporter (energy_imports<0)	
	fuel_exports	Fuel exports (% of merchandise exports), 2018	World Bank
	fuel_imports	Fuel imports (% of merchandise imports), 2018	World Bank
	renew_energy	Renewable energy consumption, 2018 (% of total final energy consumption)	World Bank
	renew_elec	Renewable electricity output, 2015 (% of total electricity output)	World Bank
	energy_use	Energy use (kg of oil equivalent) per $1000 GDP, 2014 (constant 2017 PPP).	World Bank
	dist_loss	Electric power transmission and distribution losses (% of output), 2014	World Bank
	agr_gdp	GDP share in Agriculture, 2018. Argentina replaced with official National Accounts data because of outlier.	World Bank
	ind_gdp	GDP share in Industry, 2018	World Bank
	agr_e	Employment share in Agriculture, 2018. Argentina replaced with official National Accounts data because of outlier.	ILO
	ind_e	Employment share in Industry, 2018	ILO
	agr_lp	Agriculture labor productivity, 2018 (constant 2015 $ per worker)	World Bank
	ind_lp	Industry labor productivity, 2018 (constant 2015 $ per worker)	World Bank
	agr_lp_gap	Agriculture labor productivity gap, 2018 (relative to Economywide)	
	ind_lp_gap	Industry labor productivity gap, 2018 (relative to Economywide)	
	lp_growth	Economywide labor productivity annual growth rate, 1960 (or first year of available data)-2019, %	PWT 10.0
	ex	Inverse real exchange rate proxy (PPP/XR), price level of USA GDPo in 2017=1	PWT 10.0
	polity	Polity Index, 2018 (10 is full democracy, -10 full autocracy)	Systemic Peace, Polity IV
	regqual	Normalized estimate based on a standard distribution (ranges from aprox -2.5 to 2.5). Reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development. 2018.	Worldwide Governance Indicators
	rulelaw	Normalized estimate based on a standard distribution (ranges from aprox -2.5 to 2.5). Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. 2018.	Worldwide Governance Indicators
	green_tax_rev	Environmentally related tax revenue (% of tax revenue, 2018). Russia, Sri Lanka and Indonesia (missing) replaced extracting revenue from ECR and expressing as a share of total tax revenue.	OECD
	vat	Value Added Tax (%) or most similar tax rate. For USA, State-level Sales & Use tax rates were weighted by total energy consumption shares for 2018 from EIA.	PWC
	mcf	Marginal Cost of public Funds, proxied as (1+VAT)/(1+0.1*VAT)	
	tax	Tax revenues (% of GDP, 2018)	World Bank
	inflation	Inflation rate (GDP deflator), 2010-2019 simple average	World Bank
	debt	Gross Government Debt (% of GDP), 2018	IMF
	deficit_prim	General government primary net lending/borrowing (% of GDP), 2018	IMF
	deficit_fisc	General government net lending/borrowing (% of GDP), 2018	IMF
	deficit_prim_5	General government primary net lending/borrowing (% of GDP), 2014-2018 avg	IMF
	deficit_fisc_5	General government net lending/borrowing (% of GDP), 2014-2018 avg	IMF
	area	Surface area (sq. km)	World Bank
	pop	Population, 2018	World Bank
	pop_density	Population density, 2018 (people per sq. km of land area)	World Bank
	latitude	Latitude value of capital city	https://en.wikipedia.org/wiki/List_of_national_capitals_by_latitude
	latitude_abs	Asbolute latitude value of capital city	
	island	Dummy =1 if country is an island. Australia was listed as island, although it technically is a continent.	https://en.wikipedia.org/wiki/List_of_island_countries
	elevation_avg	Average elevation above sea level (m)	https://en.wikipedia.org/wiki/List_of_countries_by_average_elevation
	elevation_span	Elevation span (distance in m from lowest to highest point)	https://en.wikipedia.org/wiki/List_of_elevation_extremes_by_country
	road_quality	Road quality index, 2017-2018 edition (1 = extremely underdeveloped—among the worst in the world; 7 = extensive and efficient—among the best in the world])	World Economic Forum
	road_km	Total length of the road network in km., last observation	CIA
	paved_road_km	Total length of the paved roads in km., last observation	CIA and World Bank if missing
	road_density	km of road per sq. km	World Bank
	road_paved	Percentage of roads paved (%)	
	transport_infr	Logistics performance index: Quality of trade and transport-related infrastructure (1=low to 5=high). Nicaragua was completed due to missing data using the OLS best fit prediction based on its road_quality value, given that the correlation coefficient between both variables is 0.77.	World Bank
	vehicles	Motor vehicles per 1000 people (2014)	World Bank
	noc_reserves	% of national oil and gas reserves owned by National Oil Companies (NOCs), 2011-2018 average	https://www.nationaloilcompanydata.org/indicator
	noc_production	% of oil and gas production done by NOCs, 2011-2018 average	
	noc_revenue	NOC total revenues as a % of government revenues, 2011-2018 average	
	noc_revenue_gdp	NOC total revenues as a % of GDP, 2011-2018 average	
	noc_debt	NOC debt as a % of government gross debt, 2011-2018 average	
	noc_income_rev	NOC net income as a % of government revenue, 2011-2018 average	
	noc_transfer_inc	NOC transfers to government as a % of NOC net income, 2011-2018 average	
	noc_transfers_exp	NOC transfers to government as a % of total public expenditure, 2011-2018 average	
	noc_transfer_rev	NOC transfers to government as % of NOC revenues, 2011-2018 average	
	noc_transfers_barrel	NOC transfers to government per barrel (USD/barrels of oils equivalent), 2011-2018 average	
	vat_imf	VAT provided by the IMF Fuel Subsidies Template. Although variations respect to vat are minimal, it is taken into account for vat exemption purposes.	IMF Fuel Subsidies Template
	vat_gasoline_ex	VAT exemption magnitude for gasoline.	IMF Fuel Subsidies Template
	vat_diesel_ex	VAT exemption magnitude for diesel.	IMF Fuel Subsidies Template
	vat_gasoline_fraction	% of standard VAT rate applicable to gasoline	
	vat_diesel_fraction	% of standard VAT rate applicable to diesel	
	gasoline_sc	Supply cost for gasoline, 2021 USD/liter (2018)	IMF Fuel Subsidies Template
	gasoline_rp	Retail price for gasoline, 2021 USD/liter (2018).	IMF Fuel Subsidies Template & GIZ IFP for Morocco (missing)
	diesel_sc	Supply cost for diesel, 2021 USD/liter (2018)	IMF Fuel Subsidies Template
	diesel_rp	Retail price for diesel, 2021 USD/liter (2018)	IMF Fuel Subsidies Template
	gasoline_wedge	Difference between retail price and supply cost as a % of retail price, for gasoline	
	diesel_wedge	Difference between retail price and supply cost as a % of retail price, for diesel	
	gasoline_neg_wedge	Dummy =1 if supply cost for gasoline is greater than its retail price	
	diesel_neg_wedge	Dummy =1 if supply cost for diesel is greater than its retail price	
	gasoline_transport	Share of gasoline consumed in transportation	IMF Fuel Subsidies Template
	diesel_transport	Share of diesel consumed in transportation	IMF Fuel Subsidies Template

Appendix B

Adjusting ECR for energy subsidies

This section describes the methodological aspects of quantifying subsidies in a comparable way to how ECRs are computed in OECD TEU. This enables a posterior correction of ECRs based on energy subsidy amounts, considering the economy as a whole (with no sectoral detail). Energy subsidies considered in this document can fall either on fossil fuels or on electricity.

For LAC countries, energy subsidies were taken from FIEL (2020), which details their magnitude in 2018 as a percent of GDP for a set of countries, based on country-level budgetary analysis. These are disaggregated into fossil fuel or electricity subsidies, keeping in mind fossil fuel subsidies do not include fuels used for electricity generation to avoid double accounting issues (this is accounted for in subsidies on electricity). Subsidies were converted into monetary units (2018 Euros) using current price GDP data from the World Bank[17] and reference exchange rates published by OECD[18]. Meanwhile, 2018 carbon emissions were calculated based on IEA World Energy Balances as described in Appendix A. Subsidies were posteriorly applied over this emission base, which by definition is identical to that upon which Effective Carbon Rates fall. In other words, we expressed energy subsidies in comparable units to ECRs (EUR/tCO_2), enabling direct adjustments to carbon pricing through simple subtraction of subsidies from taxes.

OECD TEU-SD (2021) provides fossil fuel subsidy data in comparable units to ECRs, and effectively subtracts the former from taxes to calculate the latter. Thus, for TEU-SD countries in our sample (excluding LAC overlapping ones), fossil fuel subsidy data could be compiled, but not electricity subsidy data. For the remainder of countries, we consulted the OECD Inventory of Support Measures for Fossil Fuels[19], that provides detailed information on policies that encourage consumption or production of fossil fuels. These support measures are divided into Budgetary Transfers and Tax Expenditures, and the latter were not considered in this document because they should be accounted for under Taxing Energy Use (TEU) methodology (i.e.: they are already discounted from ECRs by construction). Additionally, each support measure is targeted to a particular fuel type, and those aimed at fuels used for electricity generation fall under the category of “Electricity-based support”, which we took as reference for electricity subsidies. OECD and World Bank exchange rates used for currency conversion were used. For countries other than LAC, carbon emissions were taken from World Bank data. These do not include emissions from biofuels, and thus may be underestimated under our present methodology, meaning estimated subsidies measured in EUR/tCO_2 may be overestimated for countries with intensive biofuel use. Nonetheless, the fact that LAC countries stand out as those with the higher energy subsidies only emphasizes the relevance of the issue in the region.

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[17] https://data.worldbank.org/

[18] https://data.oecd.org/conversion/exchange-rates.htm

[19] https://www.oecd.org/fossil-fuels/countrydata/

We adjusted ECRs by energy subsidies on two levels. A first stage involved correcting carbon pricing for fossil fuel subsidies. In this case, subsidies on fossil fuels were directly subtracted from ECRs, in a way compatible with TEU-SD methodology. This can be done solely because taxes and subsidies fall on the same base regarding fossil fuels, and it results in an adjusted ECR:

$$adj\_ecr = ecr - subsidy\_fuel$$

A second step involves correcting this further by contemplating subsidies on electricity. This matter is not straightforward: electricity itself does not directly generate carbon emissions, but it does create a derived demand for fossil fuels as inputs in its generation process. To the extent that subsidies on electricity indirectly increase the use of fossil fuels, we can consider them as rival to ECR incentives. Thus, the impact of electricity subsidies on carbon emissions will be dependent on the configuration of electricity production: a hypothetical country where electricity generation is completely renewable means electricity subsidies will not induce an increase in the use of fossil fuels (and therefore, carbon emissions). Additionally, the impact of subsidies on electricity depends on the structure of costs of the Electricity sector: because subsidies can cover fixed as well as variable costs, the share of variable costs (i.e.: fossil fuel inputs) will be determinant on the extent of subsidies that are translated into a higher demand for fossil fuels. Combining these observations, to further correct ECRs by the amount of subsidies on electricity, we subtracted them adjusted by the share of electricity produced based on renewable sources[20], and by an *ad hoc*, conservative estimate of 50% share of variable costs for all countries in our sample:

$$adj\_ecr\_elec = adj\_ecr - 0.5\ subsidy\_elec\ (1 - renew\_elec)$$

We therefore calculated two adjusted versions of ECRs. One of them accounted for subsidies placed on fossil fuels directly, while the other additionally corrected for electricity subsidies considering these only increase carbon emissions to the extent that electricity generation is based on fossil fuel inputs, and that subsidies can also cover fixed costs that are irrelevant in terms of emissions.

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[20] Data on renewable electricity production was taken from IEA, sourced by the World Bank.

Latin American countries' insertion into the hydrogen technology value chain

- **Introduction:** Latin American countries have a comparative advantage for developing an economy of hydrogen based on their availability of renewable energy sources. They can produce hydrogen to supply their industry demands and export a vast amount to other countries in the future. According to the Paris Agreement, governments are expected to compromise with the transition to a low carbon economy by 2050. Latin American countries have the challenge of creating local/regional conditions for the formation of an integrated value chain to support this clean industry development. Although they have abundant renewable resources, technological development is crucial to accomplish cost-competitive clean energy production. Innovation is also necessary to the adaptation of technologies to local specific conditions in each country and for new applications. We aim to identify the technological capacities of Latin American countries in the hydrogen economy in the value chain stages using patent data. Parallel with that, we show the international collaborations between inventors of Latin American countries and foreign inventors in constructing this knowledge base.

- **Metodology:** The construction of the Hydrogen economy knowledge base considers the complete set of patents related to hydrogen production and commercial use as fuel, storage, fuel cells, and electric vehicles. We used the OECD, REGPAT database, version of July 2021 with patent applications ('international applications') filed under the Patent Cooperation Treaty (PCT) at the international phase. The search for patents related to hydrogen used CPC (Cooperative Patent Classification) class symbols was based on the methodology of EPO (2016) for the production, storage and use of hydrogen, fuel cells and electric vehicles, and for hydrogen fuel based on fossil sources of EPO and IEA (2021).

- **Expected results:** The indicators on Latin American countries’ hydrogen technologies development compose the analysis of the region's previous capabilities and local competences for industry diversification. The Latin American countries that developed capabilities in hydrogen technologies were Argentina, Brazil, Chile, Colombia and Mexico. The network analysis demonstrates the unequal “complex transnational linkages” and the increasing gap between countries. A small group of developed countries appear in the core of the hydrogen technologies international collaboration network. Latin American countries have few patents and connect poorly with the developed countries that are core to the collaboration network. Also, Latin American countries do not connect directly indicating weak regional cooperation. This aims to point out the strengths and weaknesses of these countries in catching up in the hydrogen economy.

- **Conclusions:** Latin American Countries have developed competences in hydrogen technologies, but they are not among the main patent holders, nor are their companies, nor do they collaborate with these companies. They have a peripheric role in hydrogen technology development. This will have important implications for the future development of the hydrogen sector locally, limiting local capacity of innovating. Importing hydrogen technologies for production, storage, and many applications may be a possible path, but one that has limited positive internal impacts. Identifying the technological potential and national bottlenecks can contribute to more targeted policies at this stage of developing national plans for the hydrogen economy.

- **References**

Hidalgo, C. A., et al. "The product space conditions the development of nations." *Science* 317.5837 (2007): 482-487.

IEA (2021). Net Zero by 2050. A Roadmap for the Global Energy Sector. IEA, Paris. https://www.iea.org/reports/net-zero-by-2050

IEA, "The Future of Hydrogen". IEA, Paris, 2019. https://www.iea.org/reports/the-future-of-hydrogen

IRENA, "Geopolitics of the Energy Transformation: The Hydrogen Factor ", International Renewable Energy Agency, Abu Dhabi, 2022.

Lebrouhi, B. E., et al. "Global hydrogen development-A technological and geopolitical overview." International Journal of Hydrogen Energy (2022).

Lee, K., and Lim, C. "Technological regimes, catching-up and leapfrogging: findings from the Korean industries." *Research policy* 30.3 (2001): 459-483.

Suurs, R. A., Hekkert, M. P., & Smits, R. E. (2009). Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. International Journal of Hydrogen Energy, 34(24), 9639-9654.

Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., & Luderer, G. (2021). Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nature Climate Change, 11(5), 384-393.

Factibilidad para proyectos de hidrógeno verde en Colombia a partir de energía eólica

Introducción

El hidrógeno verde, está ganando terreno como elemento clave para lograr la transición energética por su versatilidad como vector energético con la capacidad de atender aplicaciones intensivas en energía de las industrias petrolera, siderúrgica y vidrio, entre otras, que son difíciles de electrificar (Hanley, E. S., Deane, J., & Gallachóir, B. Ó., 2018; i-deals, 2021), y la posibilidad de ser un sistema de almacenamiento de energía eléctrica (Berrío Castro, E. J., 2021). En los últimos años, Colombia por su ubicación geográfica y avances en políticas públicas, se viene posicionando como destino de inversión para la implementación de proyectos de energías renovables; pero debido al carácter intermitente de éstas y el desfase con la demanda, es necesario explorar alternativas que permitan aprovechar de la mejor manera la energía producida; por esto la producción de hidrogeno mediante electrólisis se visualiza como una oportunidad (i-deals , 2021).

Metodología

En el presente trabajo se evalúa la factibilidad de producir hidrógeno a partir de energía eólica en Colombia; se identifican los métodos de producción de hidrógeno a partir de electricidad, los mercados actuales, la disponibilidad de recurso eólico y los parámetros para la generación de hidrógeno usando energía eólica; con esto se selecciona una ubicación en Colombia, donde se evalúa el recurso eólico en diferentes alturas, se identifican posibles mercados y su distancia con respecto al origen de producción; finalmente se construye un modelo para evaluar el costo nivelado del hidrogeno a partir de energía eólica en Colombia, y se realizan análisis de sensibilidad.

Resultados:

A partir del modelo elaborado, se identifican barreras técnicas y económicas, donde dado que dentro del CAPEX de una planta de producción de hidrogeno, alrededor del 30 % corresponde a costos directos asociados al electrolizador, en cuanto a infraestructura: eléctrica, control y automatización, civil e hidráulica para el acceso a fuentes de agua. Al ser estas variables en su mayoría dependientes de la ubicación del proyecto, por la cercania a fuentes de agua y la proximidad a la demanda; al lograr una disminución significativa en los costos de estos, se obtiene un precio menor final por kilogramo de hidrógeno.

Por esto, al analizar el recurso eólico en diferentes regiones para la ubicación de estos proyectos, se obtiene un modelo con elementos para realizar análisis detallados, que conduzcan a orientar de manera más eficiente y certera, los esfuerzos para el desarrollo de estos proyectos en Colombia.

Conclusiones

Se identifican factores claves para la estructuración de proyectos de hidrógeno a partir de energía eólica con respecto a su ubicación, disponibilidad del recurso eólico, cercanía a redes de transmisión nacional, acceso a puertos y proximidad con la demanda. Pues esto repercute de forma directa en la variabilidad de la generación eléctrica por medio de energía eólica, y la cercanía a redes de transmisión nacional permite aumentar la producción diaria de hidrogeno, por otro lado la distancia con respecto a la demanda impacta de forma directa en el CAPEX de la infraestructura necesaria para llevar el hidrogeno a la demanda.

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Referencias

Berrío Castro, E. J. (2021). *Viabilidad del uso del hidrógeno como sistema de almacenamiento de energía eléctrica en el contexto colombiano.* [Trabajo de grado - Maestría, Universidad Nacional de Colombia]. https://repositorio.unal.edu.co/handle/unal/80165

Blanco, M. I. (2009). The economics of wind energy. *Renewable and Sustainable Energy Reviews*, *13*(6), 1372-1382. https://doi.org/10.1016/j.rser.2008.09.004

Castiblanco, O., & Cárdenas, D. J. (2020). Producción de hidrógeno y su perspectiva en Colombia: Una revisión. *Gestión y Ambiente*, *23*(2), 299-311. https://doi.org/10.15446/ga.v23n2.86466

GIZ, ARIEMA Energía y Medioambiente S.l, & TCI Gecomp SpA. (2021). *Estudios de prefactibilidad técnica y económica de la producción de hidrógeno a escala local* [Estudios de prefactibilidad técnica y económica]. https://www.4echile.cl/publicaciones/estudio-de-prefactibilidad-tecnica-y-economica-de-la-produccion-de-hidrogeno-verde-mediante-electrolisis-para-la-entidad-gna/

Hanley, E. S., Deane, J., & Gallachóir, B. Ó. (2018). The role of hydrogen in low carbon energy futures–A review of existing perspectives. *Renewable and Sustainable Energy Reviews*, *82*, 3027-3045. https://doi.org/10.1016/j.rser.2017.10.034

i-deals. (2021). *Hoja de Ruta del Hidrógeno en Colombia* [Hoja de ruta]. Ministerio de energia. https://www.minenergia.gov.co/enlaces-ruta-hidrogeno

Levelized Cost of Green Hydrogen Production in the Antofagasta Region

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Overview

As part of its nationally determined contribution (NDC) to reduce emission levels under the Paris Agreement, Chile is committed to fully decarbonizing its energy matrix by 2050. Even though the plan for the retirement of all coal-fired power plants was a voluntary agreement between the private sector and the government, it is an ambitious goal not easy to achieve. One difficulty to accelerate this process is that new renewable technologies, mostly solar PV and wind, have intermittence and variability, so as the deployment increases, the system ends up with several periods with low and high costs of electricity. In this context, with a higher variance in prices, investors owning or developing renewable energy projects see with concern the evolution of the market as their projects face major curtailments and become riskier. One alternative to reduce the risk and uncertainty of the projects is to provide a use to all energy generated by renewable plants increasing, for this purpose, the demand at the hours when that energy is available and low cost with the production of fuels such as hydrogen.

Hydrogen is the most abundant chemical element in the universe and has the great power of being a very powerful fuel to be used in an ever-increasing number of processes, including transportation and industrial uses. Because it is not available to be taken and used directly from nature, hydrogen must be produced. The production of hydrogen from renewable energies is called green hydrogen and is considered an opportunity for improving the global economic growth and simultaneously help to combat climate change. In this study, we estimate and analyze the levelized cost of green hydrogen production in northern Chile, since it has a great solar potential and ideal conditions to produce it.

The specific area of analysis is the Antofagasta Region, which is a mining region in northern Chile, with plenty of demand for green hydrogen and the port infrastructure to export to other countries. An additional and relevant advantage is that he region has very high irradiation levels and significant wind resource. However, one drawback of the area is that it has no freshwater, so any hydrogen production has to start by water desalination (World Bank, 2019).

In the paper we present a methodology to calculate the Levelized Cost of Hydrogen (LCOH) according to different parameters such as distance to the power grid, distance to ports, and height from sea level.

Methods

The first step in methodology of this study consists of analyzing in detail all of the most cost-effective technologies for the region, including the electrolyzer, the corresponding stack, the desalination plant, transmission lines, pumping and piping equipment and the balance of plant (International Energy Agency, 2020; Huehmer, R., *et al*, 2011). In the second step, considering all the main technical characteristics of each technology and the specific conditions in the Antofagasta Region, a PEM-type electrolysis unit (Peterson, D., *et al*, 2020) and a reverse osmosis desalination unit (SWRO) capable of producing 447,500 tons per year were chosen as the best option to evaluate. The methodology then calculates the capital and operation costs, CAPEX and OPEX, respectively, for various locations within the region. These cost obviously vary due to considerations such as distance to ports and transmission grids and also reflect the height of the plant reflecting the need to pump water to it. Once all the components -technical and geographical- are explicitly taken into account the LCOH is calculated per location.

Results

The result of the evaluation shows costs of around 2.33 US$/kg H2 as LCOH in the area near Antofagasta City. This area was selected over other zones that were analyzed in the region, as at this site hydrogen production is more convenient bases on all parameters, including the distance to the coast and the electrical system.

Conclusions

The research shows that it is feasible to calculate the LCOH in different geographical areas to allow developers to find the optimal location for their investment. In the case of the Antofagasta Region, LCOH change slightly depending on the specific location: the farther from the coast and the higher the plant is located above sea level, the higher the capital and operating costs are. In particular, the most suitable place in the Antofagasta Region is by the ocean and near Antofagasta city.

References

World Bank, (2019) ´The Role of Desalination in an Increasingly Water-Scarce World´. World Bank.

Huehmer, R., Gomez, J., Curl, J., and Moore, K. (2011) ´Cost Modeling of Desalination Systems´, Desalination Global Technology Leader, CH2M HILL, USA.

International Energy Agency (2020) “IEA G20 Hydrogen report: Assumptions”, https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf

Peterson, D., Vickers, J., and DeSantis, D., (2020) ´Hydrogen production cost from PEM electrolysis—2019´. DOE Hydrogen Fuel Cells Program Record 19009 2020.

MEASURING ENERGY POVERTY IN BRAZIL: A PROPOSAL BASED ON THE MULTIDIMENSIONAL ENERGY POVERTY INDEX

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Overview

In Brazil there is no an indicator about energy poverty, which limit the implementation of programs and adequate policies for its mitigation. This research proposes an energy poverty metric that synthesizes the factors that contribute or harm the well-being of Brazilian families based on the capabilities approach of Amartya Sen (1993) and on the Multidimensional Energy Poverty Index (MEPI), developed by Nussbaumer *et al*. (2011; 2012). Using survey data from the last edition of the Brazilian Consumer Expenditure Survey (2017-2018), the proposed index includes indicators on the usage of fuels for cooking, quality of electricity supply, availability of electricity service, and variables related to ownership of appliances and affordability of energy services. The results show that 11,5% of the households analyzed in Brazil are in energy poverty condition. The intensity of deprivations was 31,9% and the MEPI reached values of 4,6%. In rural areas, energy poverty rates are high when compared to urban areas.

Key-words: energy poverty, fuels for cooking, electricity quality, electricity access, affordability.

Methods

This research proposes an energy poverty metric based on the Multidimensional Energy Poverty Index (MEPI) developed by Nussbaumer et al. (2011; 2012). The MEPI for Brazil includes indicators on cooking fuel use, perceived quality of electricity supply, availability of electricity service, ownership of household appliances, and ability to pay energy bills. For each indicator arbitrary weights were defined, with the objective of making a weighted sum of the indicators and obtaining a single number as the energy poverty index. A household is identified as poor if the combination of deprivations in a household exceeds a pre-established threshold. The MEPI is the product of the count rate (proportion of people identified as poor) and the average intensity of the deprivations of the households identified as energy poor. Data from the 2017-2018 Household Budget Survey (POF) of the Brazilian Institute of Geography and Statistics (IBGE) were used.

Results

The results indicate that the incidence or proportion of households in multidimensional energy poverty in Brazil is 11.5%. The intensity of the deprivations is 31.9%, that is, families in energy poverty have deprivations, on average, of 39.6% of the indicators analyzed. The MEPI value was 4.6%, indicating the proportion of households in multidimensional energy poverty adjusted by the intensity of the deprivation that the households face. In rural areas, energy poverty rates are significant compared to urban areas. Brazilian households are vulnerable in the "ability to pay" dimension, especially in the urban area. In rural areas, the "use of cooking fuels" is the indicator with the greatest contribution to energy poverty. Moreover, it was found that one of the factors of energy vulnerability in Brazil is income, since the households identified as energy poor have the lowest levels of income per capita.

Conclusions

In this research, the concepts and ways of measuring energy poverty in the international literature were initially discussed. It was identified that concepts vary by region. In developed countries it is common to find definitions of energy poverty related to the financial inability to heat households adequately at an acceptable cost. However, in developing countries it has been found that other indicators are used to examine energy poverty from other perspectives that are not limited to, yet include, economic factors. this research proposed a definition of energy poverty based on the capability theory of Amartya Sen and Martha Nussbaum. An energy poor household is one that simultaneously lacks several of the essential energy services, negatively affecting the realization of different secondary capabilities (cooking food, access to information, washing clothes, among others) and thus lacks a person's basic capabilities (physical health, food, leisure, among others). Furthermore, a Multidimensional Energy Poverty Index (MEPI) was constructed, adapted from the index developed by Nussbaumer et al. (2011).

References

NUSSBAUMER, P.; BAZILIAN, M.; MODI, V. (2012) Measuring energy poverty: Focusing on what matters. Renewable and Sustainable Energy Reviews, v. 16, p. 231-243, 2012.

NUSSBAUMER, P.; BAZILIAN, M.; MODI, V.; YUMKELLA, K. (2011). Measuring Energy Poverty: Focusing on What Matters. (O. P. (OPHI), Ed.), OPHI Working paper No. 42, 2011.

PAIVA, J. Pobreza Energética: um Indicador baseado na capacidade de pagamento por serviços de energia elétrica no Brasil. 2019. PhD thesis (PhD in *Planejamento de Sistemas Energéticos*) - Faculdade de Engenharia Mecânica. Universidade Estadual de Campinas, Campinas, 2019.

PEREIRA, M.; FREITAS, M.; SILVA, N. (2011). The challenge of energy poverty: Brazilian case study. Energy Policy, 39, p. 167–175, 2011.

POF-PESQUISA DE ORÇAMENTOS FAMILIARES. Instituto Brasileiro de Geografia e Estatística. 2017-2018. Microdados. https://www.ibge.gov.br/estatisticas/sociais/saude/24786-pesquisa-de-orcamentos-familiares-2.html?=&t=downloads

SADATHA, A.; ACHARYAB, R. (2017) Assessing the extent and intensity of energy poverty using Multidimensional Energy Poverty Index: Empirical evidence from households in India. Energy Policy, 102, p. 540-548, 2017.

SEN, A. (1993). Capability and Well-Being. In: NUSSBAUM, M; SEN, A. The Quality of Life. Oxford, 1993. https://www.oxfordscholarship.com/view/10.1093/0198287976.001.0001/acprof-9780198287971-chapter-3. Acces: 20 fev. 2020.

SEN, A. (2000). Pobreza como privação de capacidades. In SEN, A. Desenvolvimento como liberdade. Traduction from Laura Teixeira Motta. São Paulo: Companhia das Letras, 2000.

SEN A; NUSSBAUM, M. (Eds). (1993). The Quality of Life. Oxford University Press, 1993. https://oxford.universitypressscholarship.com/view/10.1093/0198287976.001.0001/acprof-9780198287971. Access: 20. Fev. 2020.

VILLALOBOS, C.; CHÁVEZ, C.; URIBE, A. (2021). Energy poverty measures and the identification of the energy poor: A comparison between the utilitarian and capability-based approaches. Energy Policy, 152, 2021.

ENERGY SHARING AS A BUSINESS MODEL FOR BOLIVIAN RURAL COMMUNITIES: POLICIES AND MARKET INCENTIVES

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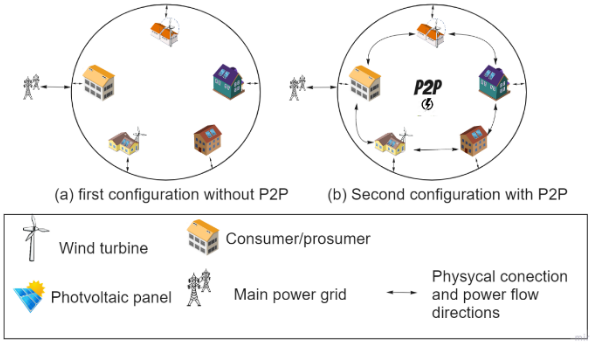
Introduction

Raising oil prices and stronger awareness of the impacts of climate change has led the Bolivian government to consider developing polices aimed at supporting the adoption of decentralized energy sources. In this context, local energy markets (LEM) and Peer-to-Peer (P2P) trading have emerged as new mechanisms to incentivise the installation of renewable resources (e.g., solar PV panels). LEMs are defined as trading platforms for energy-related services within consumer and prosumer communities. For instance, asset owners can recover part of their investments by selling surplus power to their neighbours. Local markets are a promising way to deal with technical and socio-economic issues. For example, Luth et al. (2018) analysed LEM benefits for end-users in England by estimating savings up to 31% on their electricity bill when co-optimizing local electricity trading, compared to a case with no trading. Other related works have reported similar economic benefits and prospects. In this paper, we apply this innovative local electricity markets frameworks to the Bolivian context. This paper assesses the value of cooperation between Bolivian prosumers in a closed micro-grid to determine: how do heterogeneous prosumers and consumers cooperate and interact in a micro-grid setting to achieve high levels of self-sufficiency?

Given the energy transition challenges in Bolivia, we look at to remove energy subsidies for diesel generators and incentivise Solar PV-Battery systems. Hence, in the case study we assume that consumers aim at being independent of electricity supply from the grid. We consider a cooperative community of prosumers and consumers confined in a microgrid system and we model the trade between each neighbouring household to analyse scenarios of decarbonization, role of subsidies, and energy system costs.

Methods

We developed a techno-economic bottom model based on linear programming that optimizes the operations of batteries and other energy units for each individual prosumer or consumer. It is a linear optimisation problem that simulates all the end-users part of a community. It has a centralised approach that minimises the total energy cost of the community members by prioritising self-sufficiency, storage use, and energy sharing.


(a) first configuration without P2P (b) Second configuration with P2P

We setup and compare two cases: the first case considers a large battery installed for an array of buildings and in the second case each individual prosumer installs a battery for self-balancing and trading purposes. The analysis is implemented to a real-life community located in Santa Cruz, Bolivia. The El Espino Community has a microgrid built in 2015 in Bolivia (Balderrama et. al. 2019). We use 40 profiles of houses and buildings to test the deployment of Solar PV combined with batteries. Various configurations on the energy system are analysed to determine revenues that might stimulate adoption of renewables. These are compared to various subsidies schemes focused on the development of local markets. The data and period analysed covers one year.

Expected Results

The results from studying the two control system strategies show that the difference favours clearly the energy sharing case. Local markets improve community and individual self-sufficiency. Preliminary results indicate savings in the order of 10% when LEM is implemented. Batteries play a central role, but the capacity to achieve self sufficiency is quite high. That is, solar PV would require a substantial subsidy (capacity increase) to be able to induce a surplus that can be shared with other community members. In the El Espino Community, results and analysis determine that some members will not be able to adopt some of the technologies due to costs and low electricity consumption. Hence, the optimal combination is to install central community units (e.g., solar farm or large battery) combined with decentralized prosumers that can supplement with surplus energy. This combination seems the more pragmatic policy option. A central open question in this local market configuration would be determining the local electricity price.

Conclusions

Local energy markets create new business models by creating new energy services to customers. Also, LEM open opportunities for end-users to better understand their energy use (consumption intensity, community energy sharing, and others). The local market benefits prosumers and consumers (seller and buyer) by offering more competitive buy-back rates for prosumers and lower electricity prices for consumers. Also, including end-users in an energy sharing market facilitates the integration of flexibility assets (e.g., demand response or storage). As a result, end-users are more aware of the importance of flexibility patterns and hence potentially reducing communal energy peaks. For example, prosumers from a P2P market study in Switzerland have reported that they have started shifting their load to sunshine hours after installing PV panels (Ableitner et al., 2020). In the Bolivian community, we see that the clear role of subsidies can pave the way for adoption of Solar-PV battery systems. Despite of the advantages and economic incentives of the energy sharing schemes, automatization and internet-of-things might hinder its implementation in developing countries. LEM require smart meters and other smart grid communications developments which might also require a set of energy policies.

Bolivia is an urgent need to phase out subsidies on gasoline and oil, LEM provide some economic incentives to stimulate this transition.

References

Ableitner, L., Tiefenbeck, V., Meeuw, A., Wörner, A., Fleisch, E., & Wortmann, F. (2020). User behavior in a real-world peer-to-peer electricity market. Applied Energy, 270, 115061.

Lüth, A., Zepter, J. M., Crespo Del Granado, P., & Egging, R. (2018). Local electricity market designs for peer-to-peer trading: The role of battery flexibility. Applied Energy, 229, 1233-1243.

Balderrama, Sergio & Lombardi, Francesco & Riva, Fabio & Canedo, Walter & Colombo, Emanuela & Quoilin, Sylvain. (2019). A two-stage linear programming optimization framework for isolated hybrid microgrids in a rural context: The case study of the “El Espino” community. Energy. 188. 116073. 10.1016/j.energy.2019.116073.

Assessing solar communities in Colombia: A multi-level assessment framework

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Abstract

Energy communities are associations of citizens that band together to develop renewable energy sources while making the most of their local resources. These communities use various strategies based on a range of variables, including the legislative framework for promoting renewable energy, the considered renewable technology, the intended activity (production, supply, etc.), the economic capacities of the community, the number of their members, etc. Depending on all these variables a viable energy community project might be established. Consequently. in this study, based on a pilot community project in El Salvador- Medellín[1], we introduce a multi-level assessment framework to evaluate the viability and potential benefits of community solar solutions for the Colombian context.

The work is presented in four parts: First, we illustrate the context of energy communities in the Colombian energy sector. Second, we introduce a two-directional descriptive and cross-sectional research design as our methodology to analyse the qualitative as well as the quantitative perspectives accordingly. Third, our results sections present the key economic, technical, social, and legal factors that determine the qualitative viability of such projects. Finally, our assessment framework proposes a quantitative model to assess the financial viability of solar community projects.

The proposed assessment framework aims at overcoming the numerous difficulties connected to solar community projects in Colombia and allows to be used as reference for the creation of many solar communities in the future. However, our results suggest that further evidence from applying this framework to other projects is needed to validate and enhance the proposed assessment method.

Keywords: Energy community, Energy transition, Energy sharing, Renewable energy cooperative, Sustainable energy communities, Financing models

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Contribuições para o desenvolvimento de uma Economia do Hidrogênio no Brasil

1. Introdução

A transição energética é um processo estrutural e irreversível de transformação da matriz energética global, majoritariamente fóssil e emissora de gases de efeito estufa (GEE), para uma matriz limpa e renovável. A busca por alternativas tecnológicas, renováveis ou de baixo carbono, capazes de integrar fontes renováveis intermitentes e os setores de difícil redução de emissões torna-se, assim, um fator estratégico capaz de atender, simultaneamente, as metas climáticas e a segurança energética.

Neste contexto de descarbonização, o hidrogênio verde ou de baixo carbono emerge como potencial vetor energético fundamental para a transição em curso (PARRA *et al.*, 2019; IEA, 2021). Em escala mundial, a centralidade do H_2 deriva da movimentação dos países em direção às metas estabelecidas no Acordo de Paris, assinado em 2016, cujo principal objetivo é limitar o aumento da temperatura a 1,5ºC. A economia do H_2 é objeto de um conjunto de estratégias e políticas públicas identificadas a nível global, sobretudo nos últimos anos. Ressalta-se, inclusive, desde que o levantamento se iniciou em 2021, o número de projetos e investimentos propostos cresceram em ritmo muito rápido, e diversas novas iniciativas surgiram trazendo novas oportunidades e desenhos de mercado.

Desta forma, a economia do H_2 vem se estruturando como um novo paradigma econômico baseado no uso em larga escala do H_2 como vetor energético central para atender a demanda crescente por energia e reduzir as emissões de GEE (CGEE, 2010; PANDEV *et al.*, 2017). Atualmente, cerca de 35 países em todo o mundo apresentam estratégias de H_2 e/ou roteiros regulatórios para apoiar o desenvolvimento de uma economia do H_2 verde e de baixo carbono. Além disso, a cada dia, novos projetos demonstram a redução de preços em toda cadeia de valor – com destaque para redução do custo da energia renovável e dos eletrolisadores – a disponibilidade de produtos comerciais seguros e, o aumento da aceitação pública e do apoio político em relação à importância de ações em prol do desenvolvimento sustentável.

Em consonância com as iniciativas globais, o Brasil tem apresentado avanços significativos no que concerne à estruturação de uma economia de H_2. Em 2020, a Empresa de Pesquisa Energética (EPE) publicou o Plano Nacional de Expansão de Energia (PNE) 2050, apresentando o H_2 como uma tecnologia disruptiva e estratégica para o setor energético brasileiro. Em 2021, o governo apresentou diretrizes para um Programa Nacional do Hidrogênio (PNH2). Paralelamente, assiste-se ao surgimento de diversos memorandos de entendimento e projetos no território nacional, seguindo uma abordagem gradual de inserção deste vetor.

Por apresentar características singulares para o desenvolvimento da economia do H_2, haja vista sua capacidade de expansão e operação de energias renováveis e a presença de uma infraestrutura de transporte terrestre, de dutos e marítima, o Brasil é considerado um *player* com elevado potencial de exportação de H_2 verde, bem como para o desenvolvimento de seu mercado interno. Diante deste contexto e considerando que o Brasil ainda está em estágio de desenvolvimento de sua estratégia nacional o presente artigo tem como objetivo central contribuir com a formulação de ações e políticas, através das boas práticas internacionais, que subsidiem a consolidação de uma economia do H_2 no Brasil.

2. Metodologia

O artigo se debruça sobre os resultados consolidados através de uma revisão sistemática da literatura (RSL) com análise bibliométrica, que possui como objetivo apresentar o estado da arte e a experiência internacional, com ênfase nas boas práticas que compõem o conjunto de atividades e iniciativas acerca da produção, armazenamento, transporte e uso do H_2. O estudo de levantamento bibliográfico da economia do H_2 verde e de baixo carbono, se baseou nas seguintes vertentes de análise: econômico-regulatória e ambiental; e tecnológica.

Na primeira, a RSL objetivou identificar os modelos econômicos e regulatórios, as variáveis socioambientais e as políticas públicas associadas ao desenvolvimento da economia do hidrogênio no contexto internacional. A análise tecnológica, por outro lado, possuiu como enfoque central o levantamento dos principais métodos e tecnologias inseridas nos processos de produção, armazenamento e transporte do H2, bem como suas principais aplicações.

Para tal, o estudo realizou um amplo levantamento de medidas e ações direcionadas à promoção do hidrogênio em determinados países com estratégias nacionais consolidadas para o desenvolvimento de uma economia do H_2. Os países foram selecionados de acordo com seu posicionamento diante da economia do H_2 e a disponibilidade de documentos como estratégias nacionais, *roadmaps*, inovações regulatórias, normatização e certificação, dentre outros.

Posteriormente, buscou-se identificar de que forma esses países poderiam contribuir com o desenvolvimento e estruturação deste setor energético no Brasil, seja por meio de inspirações para o desenvolvimento da exportação ou do mercado interno – como é o caso do Chile, Austrália e Reino Unido –, ou para o estabelecimento de cooperações internacionais capazes de viabilizar a exportação de hidrogênio, notadamente a Alemanha e a União Europeia como um todo. Nas seções seguintes, o estudo de caso de cada um dos países selecionados será abordado em detalhes.

3. União Europeia

A União Europeia produz apenas metade da energia que consome e cerca de 77% das suas necessidades energéticas são satisfeitas com petróleo, gás e carvão, o que resulta em uma matriz energética 50% composta de combustíveis fósseis (IEA, 2022). Em função das suas preocupações com as mudanças climáticas e o alcance das metas do Acordo de Paris, a região publicou, em 2019, o *European Green Deal* e o *Hydrogen Roadmap Europe*, estabelecendo meta de emissão zero de carbono, até 2050.

Em 2020, a Comissão Europeia (CE) publicou os documentos *A hydrogen strategy for a climate-neutral Europe* e *EU Strategy for Energy System Integration*, definindo estratégias para a transição do sistema elétrico europeu para um sistema neutro em emissão de GEE, até 2050. Nestes documentos, o hidrogênio é apontado como investimento prioritário para os objetivos de neutralidade climática do *European Green Deal* (EC, 2020b; FCH 2 JU, 2019).

Através do pacote de recuperação econômica, *Next Generation EU*, a Estratégia Europeia de H_2, lançada logo após o início da pandemia de Covid-19, evidencia o objetivo da região de impulsionar a produção de hidrogênio verde e de baixo carbono como medida fundamental para a recuperação da UE, à medida que viabiliza a geração de empregos e o crescimento sustentável no período pós-pandemia, destacando-os como investimento prioritário. De forma mais recente, o *REPowerEU*, também incluiu o H_2 como um acelerador do processo de transição energética na Europa, impulsionada pela guerra da Rússia-Ucrânia. Destaca-se que o orçamento europeu de financiamento público previsto para aumentar a capacidade de produção do hidrogênio é elevado e amplo, no qual serão investidos cerca de 180 a 470 bilhões de euros, até 2050. Em especial, o objetivo de expandir a geração de energia por fontes renováveis e os investimentos diretamente voltados para à produção de H_2 são estimados entre 3 e 18 bilhões de euros.

Investimentos adicionais têm sido realizados através dos Projetos de Interesse Comum (*Projects of Common Interest* – PCIs), voltados para a promoção do crescimento e desenvolvimento da infraestrutura, suportados, em geral, pelos *EU's Cohesion Fund, European Regional Development Fund (ERDF), European Investment Bank (EIB) e European Fund for Strategic Investments* (EFSI) (EC, 2020). Segundo a IRENA, a região possui também o maior número de projetos e a maior quantidade de investimentos em projetos de P&D, em uma ampla variedade de atividades da cadeia de valor, desde a produção de hidrogênio renovável e de baixo carbono até sua distribuição e aplicação na indústria e para mobilidade, entre outros usos finais. Além disso, os projetos podem obter financiamento de vários instrumentos em combinação, desde que não haja duplo financiamento dos mesmos custos (IRENA, 2021).

As políticas da União Europeia visam criar incentivos que permitam reduzir o *gap* de custos entre o hidrogênio verde e o hidrogênio de base fóssil, estimulando o *take-off* da cadeia de valor do H_2 verde e de baixo carbono. Para tal, os planos estratégicos na União Europeia são delineados a partir de objetivos estratégicos baseados em três principais etapas, abrangendo o período de 2020 e 2050. Na primeira etapa, o objetivo é a descarbonização de setores existentes, expansão da produção e infraestrutura local e inserção de novas aplicações finais; na segunda, o estabelecimento de um mercado de H2 eficiente, com infraestrutura transnacional e acordos entre países; e por fim, o alcance da maturidade tecnológica e econômica do H_2 verde, com aplicação em larga escala e a produção de atividades de zero carbono (EU Hydrogen Strategy, 2020).

Para alcançar esses objetivos, dois instrumentos financeiros merecem destaque: o EU- *Emissions Trading System* (ETS) e o *Carbon Contracts for Difference* (CCfD). O primeiro é um sistema de comércio de emissões baseado no princípio *cap and trade*, que atua na redução de emissões através do estabelecimento de um limite – constantemente revisado e reduzido - de GEE emitido pelas instalações (EC, 2021b). O segundo, um contrato de longo prazo, com contrapartida pública, que remunera o investidor ao pagar a diferença entre o preço de exercício do CO_2 e o preço real no ETS, cobrindo a lacuna de custos e fornecendo o incentivo para o desenvolvimento inicial. Dessa maneira, há um custo associado à emissão de CO_2, levando a um incentivo econômico para que as empresas reduzam sua participação nas emissões e, indiretamente, invistam em tecnologias limpas como o H2V (OIES, 2020).

No que diz respeito às medidas regulatórias europeias, podemos citar como principais iniciativas: (i) a possibilidade de implementação de quotas mínimas de participação de hidrogênio renovável em certos usos e aplicações através da revisão da *Renewable Energy Directive* (RED); (ii) a introdução de um sistema de certificação harmonizado para as tecnologias e combustíveis de baixo carbono; (iii) a revisão da *Energy Taxation Directive* com o intuído de evitar a dupla taxação do hidrogênio; (iv) aiscussão e revisão de diretivas que abarcam a questão do hidrogênio, sendo as mais relevantes: a *Alternative Fuel Infrastructures* (AFID); *Clean Vehicle Directive* (CVD); *Renewable Energy Directive* (RED II); *CO2 emission standards for light-duty vehicles* (LDVs); e *Heavy-duty vehicles* (HDVs); (v) a revisão das regulações TEM-E, TEM-T e do AFID e revisão do escopo do TYNDP e da legislação interna do mercado de gás para garantir uma coordenação no planejamento da infraestrutura e apoio às estações de abastecimento; (vi) o desenvolvimento de uma agenda de investimento e a construção de um projeto de pipeline através do *European Clean Hydrogen Alliance*; (vii) o estímulo à produção de hidrogênio renovável com base em fertilizantes através do *Horizon Europe Program*; e(viii) o fomento a reestruturação da infraestrutura de rede de transmissão e distribuição de gás através da iniciativa *European Hydrogen Backbone* (EHB).

De forma complementar, em 2021, a UE propôs a *European Climate Law*, que visa transformar em lei os objetivos de do *Green Deal* e garantir que todas as políticas da UE contribuam para reduzir as emissões de GEE em 55% até 2030, incluindo os setores da economia (EC, 2021b). Além disso, lançou o *Fit for 55*, um conjunto de propostas que visa fortalecer oito tópicos legislativos existentes com equilíbrio entre preços, metas, padrões e medidas de apoio, utilização de receitas e regulamentações para promover a inovação e mitigar os impactos para os vulneráveis (EC, 2021a). Ademais, inclui novos requisitos e metas para a descarbonização da indústria, com mecanismos de apoio para a incorporação de novas tecnologias, inclusive a inclusão de novos setores no sistema ETS e a majoração da meta de redução de emissões dos setores já cobertos pela EU-ETS para 61% em 2030, em comparação com os níveis de 2005. O pacote prevê também, a criação do Mecanismo de Ajuste da Fronteira de Carbono - *Carbon Border Adjustment Mechanism* (CBAM), que garante que o preço do carbono dos produtos importados será pago pelos próprios produtores, evitando o chamado "vazamento de carbono". Através do mecanismo, todas as emissões de CO_2 – incluindo aquelas incorporadas nas importações – podem ser precificadas de acordo com os preços dos certificados no EU-ETS.

A cooperação internacional e desenvolvimento de projetos de H_2 verde em países vizinhos e regiões estratégicas também é um elemento central dos objetivos de longo prazo da UE (EC, 2020). Nesse sentido, países como a Austrália, Brasil e o Chile, que possuem elevada capacidade de geração de energia por meio de fontes, vêm estabelecendo acordos de cooperação e se posicionando como potenciais exportadores de H_2 verde para a UE. Em linhas gerais, percebe-se que ao longo dos últimos anos a região vem trabalhando em iniciativas pautadas no desenvolvimento de um mercado que englobe seus setores industriais de forma ampla e no menor prazo possível, estabelecendo o H_2 verde como prioridade, através de mecanismos financeiros e incentivos, focada em reduzir as emissões de GEE e diversificar suas fontes energéticas, inserindo formas de produção com baixa emissão de carbono, que desempenharão um papel importante no curto e médio prazo.

A experiência internacional da União Europeia neste mercado pode contribuir diretamente para a formulação de normas, regulamentos e boas práticas quanto ao uso do H_2 em outras regiões do mundo. Vale salientar ainda que cada estado-membro possui ambições próprias e preferências, além de potencialidades particularidades que se refletem em cada uma das estratégias nacionais publicadas por seus governos.

4. Alemanha

A Alemanha ainda apresenta uma matriz energética muito dependente de combustíveis fósseis, com a maior parcela proveniente do carvão de linhita, com elevada intensidade de carbono. Vale destacar a relevância das importações na matriz energética alemã (77%), sendo mais de 95% proveniente de petróleo, seus derivados e gás natural e mais de 85% do antracito que consome (EU Comission, DG Energy, 2020).

Nos últimos anos, percebe-se um significativo crescimento das energias renováveis. Particularmente, quando se trata de energia elétrica, a participação de energias de baixo carbono na matriz elétrica atingiu 60%, em 2020, incluindo nuclear, sendo 53% de fontes renováveis. Destaca-se ainda que, na União Europeia, a Alemanha tem sido líder em energia eólica e solar *offshore*, tendo aumentado suas metas para 20 GW de eólica *offshore* até 2030 e 40 GW até 2040.

Desde 2010, o país iniciou um grande plano, o *Energiewende*, para tornar seu sistema de energia mais limpo e eficiente até 2050, incluindo como estratégia uma acelerada eliminação da energia nuclear até 2022. Para alcançar as metas propostas, o uso do carvão será eliminado gradualmente até 2038 e a maior parte do fornecimento de energia será transferida para fontes de energia renovável.

Diante do contexto de descarbonização e da dependência energética alemã, o H_2 vem sendo adotado como vetor energético do processo de transição energética em curso, a fim alcançar as metas de neutralização de emissão de GEE, conquistar maior segurança energética e, ainda, estimular a economia a reagir aos efeitos da pandemia do Covid-19. A meta é atingir 5 GW de capacidade de produção de H_2 por meio da eletrólise até 2030.

O incentivo à indústria do H_2 vem ocorrendo desde 2010, com investimentos do governo em torno de 700 milhões de euros para o desenvolvimento de tecnologia, dentre as quais se destacam as células a combustível. Em 2019, foi posta em prática a Lei Nacional do Clima (*National Climate Law*), que aprofundou os compromissos da Alemanha, fixando metas de redução das emissões em 55% para 2030, busca pela neutralidade de GEE até 2050 e a criação de uma comissão de especialistas em clima. O mesmo instrumento também estabeleceu o Plano de Ação 2030, que estipulou medidas para atingir as metas de 2030 em cada setor, incluindo programas de suporte, como a modernização das construções, sistemas para a precificação de CO_2 em transportes e construções, medidas de alívio à indústria e cidadãos e ainda, medidas regulatórias.

Em 2020, foi previsto um pacote de recursos de 7 bilhões de euros para serem aplicados em desenvolvimento de mercado e 2 bilhões de euros para estimular parcerias internacionais, tendo em vista que a Alemanha reconhece que terá que importar H_2 verde e não terá condições de produzir internamente a totalidade desse vetor sustentável. Ainda em 2020, foi lançado o Plano de Ação “Estratégia Nacional do

Hidrogênio” (BMWI.DE, 2020), trazendo uma política industrial extensa, com o objetivo de desenvolver a infraestrutura de H_2 necessária à visão de longo prazo alemã.

Dentre as diretrizes e metas da Estratégia de H_2, destacam-se: (i) H_2 verde como o único vetor para a neutralidade energética em 2050, considerando H_2 azul ou turquesa no período de transição; (ii) criação de um mercado interno para possibilitar a penetração e a exportação das tecnologias de H_2; iii) produção de H_2 verde em escala industrial crescente; (iv) cobrança sobre as emissões de CO_2, já vigente; (v) implantação de infraestrutura de transporte e aproveitamento da rede de gasodutos existente; (vi) suporte financeiro para investimentos em eletrolisadores e possíveis leilões para produção de H_2 verde; (vii) investimento em Pesquisa, Desenvolvimento e Educação; (viii) incentivo ao desenvolvimento de normas, padrões e certificações de origem de energias renováveis e de H_2 verde; (ix) parcerias internacionais, estimulando o comércio de H_2 verde e a compra de tecnologia alemã ou europeia; e (x) desenvolvimento de infraestrutura de abastecimento de FCEVs (TJARKS, 2020).

Na economia do H_2, o governo alemão estima uma demanda de 90 a 110 TWh de H_2 em 2030, e pretende implantar 5 GW de capacidade de produção local até 2040 e intensificar a parceria com outros membros da UE que têm capacidade de produzir H_2 verde, principalmente os mais próximos ao Mar do Norte e ao Mar Báltico, com grande potencial de geração eólica *offshore*, e os países do sul da Europa, com grande potencial para energia solar. Além disso, o país planeja parcerias com outros países por meio do estabelecimento de contratos de compra de H_2 de longo prazo, como por exemplo, pelo mecanismo criado pelo H2Global.

No que se refere ao setor industrial, estima-se uma demanda de 80 TWh, em 2050, para a indústria siderúrgica e 22 TWh para refinarias e amônia (BMWI.DE, 2020). O H_2 atualmente consumido é predominantemente H_2 cinza, havendo 7% de H_2 verde produzido por eletrólise alcalina (Global CCS Institute, 2020). Destaca-se ainda que, atualmente, existem 34 plantas de PtX, com capacidade instalada de 29 MW (WEC, 2020).

No que diz respeito à infraestrutura, a Alemanha possui uma rede de gás natural capilarizada, com unidades de armazenamento de gás a ela conectadas. Para sua utilização no transporte de H_2 serão desenvolvidos arcabouço regulatório e especificações técnicas a serem atendidas para garantir a segurança da operação.

Percebe-se, assim, que, no mercado do H_2, a Alemanha se configura estrategicamente como um país importador, com a previsão de massivos investimentos em desenvolvimento tecnológico e na sua aplicação comercial como sustentação de política industrial. Isso é feito por meio de cooperação entre o Estado, a academia e empresas. Além disso, prevê um movimento concertado com a UE, no sentido de criar mercados, compartilhar conhecimentos e experiências e equalizar normas e padrões, capacitar mão-de-obra e desenvolver projetos conjuntos.

5. Reino Unido

Em 2009, apenas 4% do fornecimento energético do Reino Unido era proveniente de energias renováveis (SMARTER BUSINESS, 2018). No setor elétrico, o cenário também era majoritariamente fóssil, em 2010, cerca de 70% da geração de eletricidade era de fontes fósseis, em especial carvão e gás natural, sendo que dos 30% restantes, 18% eram referentes à energia nuclear (BEIS, 2021). Porém, desde 2011, com a reforma do mercado de eletricidade, o país vem assegurando uma maior inserção de fontes renováveis. Em 2020, a geração de energia a partir do carvão foi praticamente extinta, sendo o novo mix de geração de energia composto de 38% de gás natural, 25% de energia eólica, 17% de energia nuclear, 12% de bioenergia, 4% de energia solar, 2% de recursos hídricos, e 2% de outras fontes. Ou seja, a geração de eletricidade passou a ser cerca de 60% limpa, sendo 44% renovável com destaque para a energia eólica (IRENA, 2022).

A ambição e o potencial do Reino Unido para um Revolução Industrial Verde são apresentados no *Energy White Paper* de 2020 e no *Ten Point Plan* do Primeiro-Ministro, que engloba as seguintes tecnologias: eólica *offshore*, hidrogênio, nuclear, captura de carbono e medidas de eficiência energética. Essas medidas reforçam os planos de transformar os sistemas de energia e aquecimento para apoiar a meta de emissões líquidas zero de CO_2, até 2050. Destaca-se que o Reino Unido foi a primeira grande economia a se comprometer, por lei, a reduzir as emissões de GEE para zero líquido, decisão feita em 2019 (K&L GATES, 2020).

De forma geral, as projeções revelam que, ao longo do processo de descarbonização, o H_2 apresentará um importante papel. Segundo dados do *Department for Business, Energy and Industrial Strategy* (BEIS), estima-se uma demanda de 250 a 460 TWh de H_2, em 2050, equivalentes a 20%-35% do consumo final de energia do país. Porém, atualmente, a maior parte do H_2 é proveniente de combustíveis fósseis sem captura de CO_2, desta forma, para se alcançar neutralidade de emissões, toda a produção atual e futura precisará ser de baixo carbono (HM GOVERNMENT, 2020).

Neste sentido, em novembro de 2020, o Reino Unido anunciou um plano ambicioso para combater a crise climática e desenvolver o mercado de H_2 de baixo carbono, o "*Green Industrial Revolution*", com dez pontos estratégicos, dos quais destacam-se: a implantação de 5 GW de capacidade de produção de H_2 de baixo carbono até 2030; *hubs* de geração renovável de H_2 e CCUS para rotas emissoras de GEE, bem como a disponibilização de £240 milhões de fundos para *Net Zero Hydrogen*, a mobilização de £4 bilhões de investimento privado e a criação de 250 mil empregos.

Em agosto de 2021, consolidando a visão apresentada, o Reino Unido lançou sua Estratégia de Hidrogênio, estabelecendo como meta se tornar um líder global em H_2, impulsionando a descarbonização, apoiando novos empregos e o crescimento sustentável da economia (HM GOVERNMENT, 2021). A geografia, geologia, infraestrutura e experiência do Reino Unido se revelam como vantagens competitivas para desenvolver rapidamente a economia de H_2, com potencial para se tornar um líder global e autossuficiente, garantindo oportunidades econômicas em todo o país (HM GOVERNMENT, 2021). Assim, embora o Reino Unido tenha recursos e capacidade de futuramente exportar H_2, esse não é um de seus objetivos principais, já que sua estratégia se encontra focada na descarbonização, integração de energias renováveis e crescimento econômico. No que tange aos setores alvo para o H_2 destacam-se a indústria, o setor elétrico e o aquecimento residencial (K&L GATES, 2020).

No contexto atual, é sugerido que o uso do H_2 de baixo carbono seja capaz de proporcionar a redução de emissões de cerca de 41 MtCO2, entre 2023 e 2032. Isso contribuirá para o alcance da Contribuição Nacionalmente Determinada (NDC), firmada no Acordo de Paris, de redução das emissões em 68%, até 2030 (HM GOVERNMENT, 2021). Ademais, de acordo com a *UK Hydrogen Strategy*, as evidências atuais sugerem que o desenvolvimento de uma economia de H_2 no Reino Unido também poderia sustentar mais de 9.000 empregos até 2030 e até 100.000 empregos até 2050 (HM GOVERNMENT, 2021; EQUINOR, 2021).

Na prática, a economia do H_2 já iniciou sua estruturação, mesmo que seja por meio de projetos pilotos e acordos de parceria. Neste sentido, alguns projetos e acordos colaborativos já estão tomando espaço no cenário do H_2, como por exemplo, o Projeto HyDeploy que está relacionado à aplicação de aquecimento residencial e que, em escala de produção piloto, demonstrou e comprovou a eficiência de mistura de 20% de H_2 com gás natural, sem necessitar de alterações significativas, para atender o abastecimento residencial. Salienta-se que em decorrência dos resultados, o governo revelou que a rede de gás da Grã-Bretanha estará pronta para fornecer uma mistura de 20% de H_2 para residências em todo o país em 2023.

Em suma, foram atribuídos na *UK Hydrogen Strategy* os princípios que guiarão o país nas futuras decisões políticas e ações governamentais, proporcionando clareza sobre a direção futura da política para investidores e usuários. Além disso, não adotar especificamente uma única rota tecnológica mantêm as opções em aberto, de forma que o país possa se adaptar à medida que o mercado se desenvolve. Assim, observa-se que o Reino Unido é um país que tem avançado na economia do H_2 utilizando uma abordagem ampla, apoiando o desenvolvimento de toda a cadeia de valor e em diversas rotas de produção do H_2, sem deixar de criar mecanismos de apoio para rotas mais maduras como a do H_2 produzido a partir da eletrolise da água, cuja energia é oriunda, notadamente das eólicas *offshore* que estão em constante expansão no país.

6. Austrália

A Austrália possui abundância em recursos energéticos renováveis e não renováveis, se caracterizando como um país exportador de energia, em especial de gás natural e carvão. Em 2021, as fontes renováveis representaram 8% da matriz energética, já os combustíveis fósseis (carvão, petróleo e gás) 92% da energia primária (ENERGY.GOV.AU, 2020). Na geração de eletricidade, em 2021, os combustíveis fósseis contribuíram com 71% da geração total, incluindo carvão (51%), gás (18%) e petróleo (2%), frente a parcela das energias renováveis, com participação de solar (12%), eólica (10%) e hídrica (6%).

Atualmente, a Austrália é o segundo maior exportador mundial de carvão. No entanto, em contraste com o início do século, quando a participação deste combustível era superior a 80% na geração de eletricidade, sua contribuição vem reduzindo na matriz elétrica. Assim, dado os avanços e novas perspectivas de inserção de fontes renováveis, salienta-se que a Austrália está em transição para um futuro de baixo carbono. Em 2016, quando ratificou o Acordo de Paris, comprometeu-se a uma redução de 26 a 28% nas emissões de GEE abaixo dos níveis de 2005, até 2030 (K&L Gates, 2020).

Embora a redução das emissões de carbono seja um dos seus objetivos estratégicos, a principal motivação da Austrália se concentra na abertura de novos mercados, à medida que a demanda pelas exportações de combustíveis fósseis caírem. Dessa forma, o H_2 é identificado pelo governo como uma das alternativas com maior poder de transição energética e, para promover o desenvolvimento deste novo mercado, diversas políticas públicas vêm sendo traçadas.

Em 2018, o Conselho de Energia do governo australiano, CSIRO (*Commonwealth Scientific and Industrial Research Organisation*), formulou uma visão para o desenvolvimento da indústria do H_2, que se consolidou com o lançamento do “Roadmap Nacional do Hidrogênio” (CSIRO, 2022). Definida a visão geral do tema, ainda em 2018, foi criado um Grupo de Trabalho dedicado ao desenvolvimento da economia do H_2, com o intuito de estruturar uma estratégia nacional para o H_2. Em novembro de 2019, o governo australiano publicou a "Estratégia Nacional de Hidrogênio da Austrália", cujo objetivo é delinear as ações políticas, econômicas, produtivas, de consumo e desenvolvimento humano para a economia do H_2 (WEC, 2020).

Do lançamento da estratégia nacional até meados de 2022, é perceptível o avanço do país no desenvolvimento da economia do H_2, tanto à nível nacional, como também no desenvolvimento de projetos e cooperações de âmbito internacional, de forma que este é um país que merece destaque de análise. A Austrália possui características geográficas, energéticas e políticas públicas de incentivo que a posicionam como *hub* da economia mundial do H_2, a nível nacional e mundial por meio da exportação.

Para sustentar uma estratégia ampla como esta, a Austrália vem concentrando esforços na produção de H_2. Neste sentido, será adotado um processo gradual, com uso de fontes fósseis, até 2030, e a partir de 2031, o uso exclusivo de fontes renováveis e fósseis combinadas com CCS, haja vista as metas de redução das emissões de carbono e a demanda internacional pelo H_2 verde ou de baixo carbono (WEC, 2020). Vale ressaltar que esta estratégia gradual dá a Austrália a vantagem de iniciar projetos pilotos capazes de trazer experiências para outros segmentos da cadeia, notadamente o de transporte e armazenamento de H_2. Nesse sentido, cita-se o projeto piloto *Hydrogen Energy Supply Chain Pilot*, firmado entre a Austrália e o Japão, onde o processo de desenvolvimento de elos da cadeia de valor e da exportação são de grande relevância. Neste projeto, o H_2 produzido por meio da gaseificação do carvão marrom é liquefeito de forma criogênico (-253°C), em Hastings, na Austrália, e enviado para Kobe, Japão, por meio do navio Suiso Frontier, desenvolvido especificamente para o projeto (WEC, 2020).

Desta forma, seguindo uma estratégia gradual, a Austrália pretende se tornar o principal *player* global na produção e comércio de H_2 de baixo carbono no horizonte de 2050 e considera o H_2 sua “próxima grande *commodity* exportação” (COAG, 2019). De forma complementar, estima-se que a indústria australiana de H_2 tenha capacidade de gerar cerca de 7.600 empregos e US$11 bilhões em PIB em 2050 com base no cenário de implementação global. Em uma análise mais otimista, em que o cenário considera o H_2 como a energia do futuro, as estimativas aumentam para cerca de 17.000 empregos e US$26 bilhões em PIB (COAG, 2019).

Em relação às políticas de apoio ao desenvolvimento da economia do H_2, a Austrália está entre os países com estratégias mais detalhadas e avançadas. Neste sentido, conta com as principais políticas de incentivo ao desenvolvimento da economia do H_2, tanto a nível nacional, como estadual, a destacar o desenvolvimento de medidas regulatórias, normativas e de certificação, o incentivo à P&D, o financiamento e investimento em toda cadeia produtiva, a difusão de conhecimento e, finalmente, a governança com base na estratégia nacional proposta (WEC, 2020). No que tange aos incentivos financeiros e investimentos, desde 2015, a Austrália já comprometeu mais de AUD$ 570 milhões (TAYLOR, 2020), com destaque para os AUD$ 13,5 milhões destinados ao desenvolvimento da Estratégia Nacional.

Em relação ao desenvolvimento de aspectos normativos e de certificação, foi constituído o comitê de Tecnologias de Hidrogênio ME-093 da Standards Australia, que é responsável por colaborar para desenvolver os padrões técnicos e as orientações necessárias para a indústria de H_2, permitindo a entrega de resultados de desempenho técnico e de segurança (STANDARDS AUSTRALIA, 2019). No que diz respeito aos padrões e normas aplicáveis à exportação, a Austrália considera a certificação de origem em sua Estratégia Nacional como uma prioridade, pois é a única forma de dar transparência aos compradores e de se diferenciar no mercado.

Portanto, analisando o processo de desenvolvimento da economia do H_2 proposto pela Austrália, é possível identificar a importância das políticas públicas para fomentar o desenvolvimento de toda cadeia produtiva desta tecnologia. Além disso, metas temporais e financiamentos a projetos de larga escala colocam a Austrália no radar dos principais atores da indústria global, indicando, aos potenciais importadores, o pioneirismo e a maturidade do desenvolvimento das infraestruturas para exportação do país.

7. Chile

Historicamente, a matriz energética chilena foi estruturada em uma base de suprimento a partir da importação de fontes fósseis. Todavia, entre 2011 e 2021, a capacidade instalada das energias renováveis cresceu cerca de onze vezes, saindo de 540 MW para 6113 MW. Espera-se que, até 2030, 70% da matriz elétrica seja renovável e as emissões de GEE sejam reduzidas em 30% em comparação aos níveis de 2007. Para 2050, o Chile objetiva atingir a neutralidade climática (IEA, 2018; CHILE, 2020), com base em três pilares: disponibilidade de recursos energéticos, objetivos globais de descarbonização e oportunidade de desenvolvimento econômico. Ademais, o Chile apresenta uma das melhores condições naturais tanto para a geração solar, especificamente em função do deserto de Atacama, ao norte, quanto para a eólica, representada ao sul pela Patagônia (IRENA 2020b).

De acordo com o *Bloomberg New Energy Finance Climate Scope*, o Chile tem se destacado como o país emergente com condições mais atrativas para investimento em energias renováveis, em função de políticas energéticas expressivas voltadas para a descarbonização e o compromisso de descontinuar as plantas de geração à carvão (BNEF, 2020). Nesse sentido, estima-se que o Chile possua o potencial de produzir cerca de 160 milhões de toneladas de H_2 verde por ano, tendo, inclusive, a perspectiva de produção aos menores custos no futuro (IEA, 2019; IRENA, 2022).

Em 2015, o governo do Chile publicou sua política energética de longo prazo, denominada “Energía 2050”, com o objetivo central de estabelecer uma visão sistêmica para um setor energético confiável, sustentável, inclusivo e competitivo até 2050. A política aponta, dentre outros elementos, o uso massivo de H_2 no setor de transporte e a eletrificação da economia como oportunidades para o Chile (CHILE, 2015). Dessa maneira, a política energética de longo prazo do Chile pode ser considerada um primeiro enquadramento do H_2 verde enquanto vetor energético estratégico para o país. Em novembro de 2020, o país publicou sua Estratégia Nacional de Hidrogênio Verde, evidenciando dois *drivers* centrais para a consolidação do país como um *hub* de exportação de H_2 verde: a crise climática e a disponibilidade de recursos energéticos renováveis no país (CHILE, 2020). Esse segundo vetor, que viabiliza a redução de custos de produção do H_2 verde, está no centro da estratégia chilena. De fato, é com base em seu potencial de geração renovável – cerca de 70 vezes a capacidade instalada atual do país - que a estratégia está voltada exclusivamente para o H_2 verde e direcionada à exportação (IRENA, 2020b).

Ademais, o Chile tem se destacado com o menor custo global até 2030, produzido a partir das gerações solar, proveniente da região do Atacama, e eólica, da região de Magallanes. Em função dos custos reduzidos associados à geração renovável, o H_2 produzido no Chile a partir da eletrólise da água pode ser considerado competitivo em relação ao gás natural e a produção de H_2 a partir de combustíveis fósseis, até mesmo em casos em que tecnologias de CCUS não são utilizadas. Dessa maneira, uma das características centrais da estratégia chilena é o foco em metas ambiciosas de redução de custos, tendo como objetivo o preço de US$ 1,5/kg de H_2 até 2030 (IEA, 2019).

Somada à dotação natural de recursos energéticos renováveis, a preços relativamente baixos, a Estratégia analisa que a redução de custos dos eletrolisadores, a crescente disponibilidade do chamado “financiamento verde”, os compromissos rígidos de descarbonização e a presença de benefícios fiscais em regiões remotas também serão determinantes para o modelo de negócios competitivo (CHILE, 2020). Em função do contexto apresentado, o Chile identifica o H_2 verde como uma oportunidade de reposicionamento estratégico do país no cenário internacional em transformação.

Em relação ao mercado, a Estratégia Nacional identifica o H_2 verde como uma indústria limpa com potencial de atingir os níveis do setor de mineração chileno, com geração de oportunidades para criação de ecossistemas dinâmicos e capacidades nacionais associadas ao futuro do setor energético (CHILE, 2020; IEA, 2018). Para atingir os objetivos propostos na estratégia, três fases principais foram definidas. A primeira fase objetiva desenvolver a infraestrutura de H_2 para exportação, acelerando o desenvolvimento na economia do H_2 no mercado interno, a partir de aplicações selecionadas, como refino de petróleo, produção de amônia, mineração, transporte pesado e de longas distâncias e integração à rede de gás natural. Na segunda fase, são desenvolvidos consórcios para a exportação de H_2 verde, a partir de aprimoramentos na base doméstica. Por fim, a partir de 2030, são identificadas oportunidades para a exportação em larga escala. Essa *commodity* movimentaria $ 24 bilhões em 2050 e teria como principais centros importadores são a Europa, Japão e Coréia do Sul, seguidos pela China, Estados Unidos e América Latina (CHILE, 2020).

Para viabilizar a estruturação de sua economia do H_2, identifica-se que um dos pilares essenciais da nova política energética do Chile é o papel da iniciativa privada como motor do desenvolvimento energético. O Estado, por outro lado, atuaria no atendimento às necessidades nacionais, na articulação dos agentes na visão compartilhada de longo prazo e na orientação do desenvolvimento energético. Na Estratégia para o H2 verde, a abordagem de políticas orientadas por missões atribui ao setor público um papel central enquanto facilitador, coordenador e promotor do estabelecimento da nova indústria de H2, através de esforços multisetoriais. Neste sentido, a estratégia propõe um plano de ação em que políticas públicas e ajustes regulatórios destacam-se nos quatro pilares, quais sejam (CHILE, 2020): (i) promoção dos mercados doméstico e de exportação, reduzindo incertezas e criando economias de escala e escopo; (ii) normas, segurança e projetos pilotos, fundamentando o desenvolvimento da economia do H_2 chilena e promovendo segurança aos investidores; (iii) desenvolvimento social e local, criando sinergias entre as regiões e novos usos potenciais do H2; e (iv) desenvolvimento de competências e inovação, com a promoção da pesquisa e desenvolvimento e de atividades inovadoras.

Observa-se que o plano evidencia a coordenação entre diferentes agentes (ex. indústria, academia e centros de pesquisa e desenvolvimento) para criação de competências nacionais, associados à implementação de um *Roadmap* de P&D construído pelos setores público e privado (CHILE, 2020). Consoante a isso, dentre as políticas associadas aos mercados interno e externo de H_2, estão a criação de um financiamento de cerca de $50 milhões para apoio à projetos de H_2 verde, com foco na garantia à competitividade econômica da produção a partir de renováveis; o estabelecimento de discussões público-privadas em torno de políticas de precificação de carbono; e, por fim, a criação de redes de acordos comerciais e técnicos. A cooperação internacional é um objetivo fundamental da Estratégia (CHILE, 2020). Nesse sentido, o Chile e a Alemanha assinaram, em abril de 2019, uma declaração de intenções, com a criação da Parceria Energética Alemanha-Chile.

Com isso, ainda que recente, a Estratégia Chilena tem se demonstrado ambiciosa e coordenada aos objetivos internacionais de descarbonização. Além disso, a centralidade do H_2 verde na reestruturação enquanto economia exportadora, marcada pela transição da exploração de recursos não renováveis para produção de vetores energéticos limpos e produtos de baixo carbono, evidencia o potencial do H_2 enquanto recurso energético central.

8. Boas Práticas e Recomendações para a Economia do Hidrogênio no Brasil

Através do levantamento das estratégias nacionais, principais iniciativas e mecanismos financeiros dos países selecionados, podemos destacar lições e inspirações da experiência internacional para o desenvolvimento da economia do H_2 no Brasil, considerando as particularidades, potencialidades e desafios do cenário brasileiro. Desta forma, foi possível tanto posicionar o Brasil nessa trajetória de desenvolvimento de uma economia do H_2, quanto elaborar um conjunto de recomendações e proposições de ações que auxiliem o Brasil na estruturação e consolidação de sua estratégia nacional.

De forma geral, o estudo identificou os principais setores para estimular o consumo doméstico de hidrogênio: indústria química (principalmente amônia e metanol), petroquímica (principalmente refino e combustíveis sintéticos), mobilidade, indústria siderúrgica (substituição do carvão na redução direta do minério de ferro), substituição de geração de calor em setores difíceis de descarbonizar, o chamado *hard-to-abate*, como produção de minerais, cimento, vidro e cerâmica. A questão da mistura de hidrogênio com o gás natural em gasodutos também tem sido estudada, em especial na Europa, haja vista que esta oferece a vantagem de utilizar a infraestrutura de transporte já existente.

Os países estudados apresentam diferentes interesses e potenciais: para produzir e consumir (Reino Unido), produzir e exportar (Chile e a Austrália), ou utilizar o hidrogênio para descarbonizar sua matriz energética, seja como transportador de energia ou como matéria-prima para a indústria (UE e Alemanha). O desenvolvimento do arcabouço regulatório e a estruturação do mercado do hidrogênio seguem velocidades e ritmos de inserção distintos para cada país, de acordo com as particularidades econômicas, geopolíticas e socioambientais. A exemplo do Brasil, o Chile e a Austrália possuem grande potencialidade de expansão de geração de energia através de fontes renováveis e estão interessados em desenvolver uma nova indústria, através de exportações, devido essa abundância. A União Europeia e a Alemanha, por usa vez, veem o hidrogênio como uma forma de descarbonizar sua economia, enquanto o Reino Unido pretende, além de descarbonizar sua economia, suprir sua própria demanda interna, principalmente através da expansão de infraestrutura, seja na rede de gás, seja no setor de mobilidade.

A UE vem apoiando projetos de P&D de tecnologias limpas e hidrogênio há cerca de duas décadas e, notadamente, a partir de seus resultados, passou a construir metas de avanço na produção e uso, com reformulação de diretivas e criação de mecanismos dedicados. O Reino Unido já investe em estudos para descarbonizar as redes de gás há alguns anos, além de investir na infraestrutura do setor eólico *offshore,* a qual servirá para expansão do seu mercado. De posse dessa experiência, o país criou diversas iniciativas para impulsionar o setor privado a também investir nessas duas vertentes. A Alemanha apresenta uma longa experiência na implementação do mercado do hidrogênio com grandes investimentos em desenvolvimento tecnológico e inovação e está desenvolvendo um mecanismo de compra de hidrogênio, através de países exportadores. A Austrália possui uma vasta experiência no mercado de exportação e tem se valido disso para estabelecer acordos comerciais os quais devem auxiliar o país a garantir a sustentabilidade do seu mercado. Em países onde a economia do hidrogênio só começou a ganhar força recentemente, como é o caso do Chile, é notório que as políticas, diretrizes e planos sejam pautados em iniciativas que mostrem resultados concretos e mensuráveis e projetos que apresentem grande potencial de ganhar escala.

Dentre deste contexto, podemos enfatizar que Brasil se destaca como fornecedor de hidrogênio, devido ao conjunto de características geográficas, econômicas e técnicas, favoráveis à produção de energia eólica e solar fotovoltaica. Além de possuir um grande potencial de expansão de geração de energia renovável intermitente, o país apresenta um extenso sistema de transmissão e uma infraestrutura logística e portuária que permite a exportação do hidrogênio em larga escala, com destaque à região Nordeste do Brasil.

Dessa forma, algumas recomendações, mediante lições aprendidas, podem ser citadas:

- Para um rápido avanço das tecnologias de hidrogênio deve ser traçado um conjunto de políticas, estruturas de financiamento e mecanismos estabelecidos ao longo dos anos, voltados para o desenvolvimento de tecnologias limpas. Dessa forma, além de projetos de inserção de energias renováveis já estimulados no Brasil, outros mecanismos devem ser inseridos para o desenvolvimento de um mercado de produção de H_2 verde, a exemplo de um mercado de carbono;
- A implementação e o desenvolvimento de uma estratégia nacional, com metas, planos de ações, estrutura de financiamento e arcabouço político e regulatório adequados são condições fundamentais a curto prazo, para desenvolver esse mercado internamente;
- Os setores atuais de maior consumo de hidrogênio produzem elevadas taxas de emissão de carbono, como o setor petroquímico e o de produção de fertilizantes nitrogenados, e devem ser incentivados (seja através de incentivos financeiros ou apenas através do estabelecimento de quotas) para substituição do hidrogênio de combustível fóssil pelo H_2 verde ou de baixo carbono;
- O apoio financeiro à indústria, focando no aumento de demanda, criação de mercado consumidor, criação de mecanismos de apoio fiscal às empresas que pretendam produzir o hidrogênio verde ou de baixo carbono, incentivos para expansão da infraestrutura de abastecimento e criação de *hubs*, devem existir para diminuir os custos iniciais de implantação e ganhar escala. Esses *hubs* podem se localizar estrategicamente em portos, cidades ou em áreas regionais ou remotas, fornecendo à indústria um baixo custo logístico.
- Programas de incentivo à formação de recursos humanos, projetos de pesquisa, piloto e de demonstração, devem fazer parte da estratégia de um país que pretende se estabelecer neste mercado;
- A normatização e certificação devem estar padronizadas e adotar normas internacionais para toda cadeia de valor, como forma de potencializar e acelerar o desenvolvimento da economia do hidrogênio, em consonância com o mercado mundial, proporcionando segurança ao setor privado e fortalecendo o desenvolvimento de experiências em comum.

Por fim, pode-se afirmar que através do estudo foi possível trazer referências internacionais como inspiração para o desenvolvimento do mercado brasileiro, ainda em estágio incipiente, e posicionar o Brasil como potencial exportador na economia do hidrogênio. O hidrogênio verde pode vir a se consolidar como uma importante *commodity* e o país possui diversos recursos para desenvolver este mercado, todavia, necessita de um arcabouço regulatório adequado e estabelecer uma série de mecanismos financeiros, incentivos e instrumentos para integrar diversos setores a esse mercado, fornecendo flexibilidade operacional, segurança e benefícios sistêmicos, através da sua redução das emissões de GEE.

9. Conclusões

A título de conclusão, torna-se importante destacar que os países analisados têm seguido uma estrutura de planejamento pautada na valoração de especificidades regionais. Assim, a necessidade de redução da dependência energética e, simultaneamente, a visualização de vantagens estratégicas em um mercado em formação, são elementos basilares da visão de longo prazo dos países.

Considerando o estado emergente da Economia do H_2 no Brasil, observa-se que sua estruturação tem sido feita a partir da organização de programas, *roadmaps*, cooperação internacional, pesquisa e inovação, seguidos de projetos piloto e de demonstração de H_2. Ainda assim, percebe-se a necessidade de estabelecer políticas públicas para o desenvolvimento e consolidação de uma cadeia de valor do H_2 no país, com destaque para a definição de políticas públicas e diretrizes voltadas ao H_2, no âmbito regulatório, incluindo o estabelecimento de metas, normas e padrões bem definidos.

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Referências Bibliográficas

BNEF - BLOOMBERG NEW ENERGY FINANCE. Climatescope- Emerging Markets Outlook 2020. 2020. Disponível em: https://global-climatescope.org/downloads/climatescope-2020-report-en.pdf. Acessado em 15 mar. 2021.

CGEE, Centro de Gestão e Estudos Estratégicos. Hidrogênio energético no Brasil: Subsídios para políticas de competitividade, 2010-2025. Série Documentos Técnicos, n. 07. Brasília: 2010.

COAG - COUNCIL OF AUSTRALIAN GOVERNMENTS. AusH2 - Australia's Hydrogen Opportunities Tool. 2021. Disponível em: https://portal.ga.gov.au/persona/hydrogen. Acessado em 11 fev. 2021.

COAG - COUNCIL OF AUSTRALIAN GOVERNMENTS. Australia's National Hydrogen Strategy. 2019. Disponível em: https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy. Acessado em 18 fev. 2021.

EC, EUROPEAN COMISSION, 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, 2021a. Disponível em: chapeau_communication.pdf (europa.eu). Acessado em 09 fev. 2021

EC, EUROPEAN COMISSION. A hydrogen strategy for a climate-neutral Europe. COM (2020b) 301. Disponível em https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

EC, EUROPEAN COMISSION. Europe Climate Law, 2021b. Disponível em: https://ec.europa.eu/clima/policies/eu-climate-action/law_en. Acesso em: 30 de agosto de 2021.

EC, EUROPEAN COMISSION. Europe's moment: Repair and Prepare for the Next Generation. COM (2020a) 456. Disponível em <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590732521013&uri=COM:2020:456:FIN. Acessado em 09 fev. 2021

EQUINOR, H2H Saltend. 2021. Disponível em: https://www.equinor.com/en/what-we-do/h2hsaltend.html. Acessado em 12 fev. 2021

EU ETS – acesso em 09/02/2021 em EU Emissions Trading System (EU ETS) | Climate Action (europa.eu)

FCH 2 JU. Hydrogen Roadmap Europe: A sustainable pathway for the european energy transition, 2019

GLOBAL CCS INSTITUTE. Global status of CCS 2020. 2021. Disponível em: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf. Acessado em 17 mar. 2021.

HM GOVERNMENT, Energy White Paper - Powering Our Net Zero Future. 2020. Disponível em: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945893/201215_BEIS_EWP_Command_Paper_Large_Print_Web.pdf. Acessado em 12 fev. 2021.

HM GOVERNMENT. UK Hydrogen Strategy. 2021. Disponível em: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf. Acessado em 09 ago. 2021.

IEA - INTERNATIONAL ENERGY AGENCY. Energy Policies Beyond IEA Countries: Chile. 2018. Disponível em: https://iea.blob.core.windows.net/assets/8c16efa0-41b1-47be-b12a-a29483a0c635/EnergyPoliciesBeyondIEACountriesChile2018Review.pdf. Acessado em 10 fev. 2021.

IEA - INTERNATIONAL ENERGY AGENCY. The Future of Hydrogen Report - Seizing today’s opportunities. 2019. Disponível em: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf. Acessado em 12 fev. 2021.

IEA. Global Hydrogen Review 2021. Paris: International Energy Agency, 2021.

IRENA. Energy Profile - United Kingdom. 2022. Disponível em: https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/United%20Kingdom_Europe_RE_SP.pdf

IRENA - INTERNATIONAL RENEWABLE ENERGY AGENCY. Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°C Climate Goal. 2020b. Disponível em: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf. Acessado em 17 jun. 2021.

IRENA, Green hydrogen supply: A guide to policy making, International Renewable Energy Agency, Abu Dhabi. ISBN: 978-92-9260-344-1.

IRENA, Making the breakthrough: Green hydrogen policies and technology costs,. International Renewable Energy Agency, Abu Dhabi.

K&L GATES. The H2 handbook: legal, regulatory, policy and commercial issues impacting the future of hydrogen, 2020. Disponível em: https://www.klgates.com/The-Hydrogen-Handbook. Acessado em 17 jun. 2021.

MINISTERIO DE ENERGÍA. Energía 2050 - Política Energética de Chile. 2015. Disponível em: https://www.energia.gob.cl/sites/default/files/energia_2050_-_politica_energetica_de_chile.pdf. Acessado em 11 mar. 2021.

MINISTERIO DE ENERGÍA. National Green Hydrogen Strategy.2020. Disponível em: https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf. Acessado em 25 fev. 2021.

PANDEV, M.; LUCCHESE, P.; MANSILLA, C.; LE DUIGOU, A.; ABRASHEV, B.; VLADIKOVA, D. Hydrogen Economy: the future for a sustainable and green society. Bulgarian Chemical Communiations, v. 49, p. 84-92, 2017.

PARRA, D.; VALVERDE, L.; PINO, F. J.; PATEL, M. K. A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. Renewable and Sustainable Energy Reviews, v. 101, p. 279-294, 2019.

STANDARDS AUSTRALIA. ME-093 Hydrogen Technologies: Strategic Work Plan. 2019.

TAYLOR, H. Exploring Australia’s hydrogen future with Germany. 2020. Disponível em: https://www.minister.industry.gov.au/ministers/taylor/media-releases/exploring-australias-hydrogen-future-germany. Acesso em: 30 jun. 2021.

TJARKS, G. The German Approach towards a Hydrogen Economy. 2020. Disponível em: https://www.renewable-ei.org/pdfdownload/activities/09_GeertTjarks.pdf. Acessado em 07 set. 2021.

WEC - WORLD ENERGY COUNCIL GERMANY. International hydro-gen strategies: A study commissioned by and in cooperation with the World Energy Council Germany, 2020. Disponível em: https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf. Acessado em 07 jun. 2021.

Pricing for Chance-Constrained Electricity Markets

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I. Overview

In a commodity market, market-clearing prices refer to prices that allow the commodity producers and consumers (or buyers and sellers) to trade the commodity so no surplus or deficit occurs. Classical economic theory studies exchanges of goods and services, with common terms for all participating agents seeking equilibrium between supply and demand. Sometimes these common terms take the form of centralized auctions. Centralized auction mechanisms have been used for allocation in a wide range of areas, including envisioned electricity markets before their actual implementation, electromagnetic spectrum license allocations, emissions of sulfur dioxide; and power exchanges in wholesale electricity markets.

Obtaining appropriate market-clearing prices for electricity markets is a challenging problem due the way in which electricity is produced, transmitted and consumed, as well as the fact that electricity, loosely speaking, cannot yet be economically stored. Thus, in many electricity markets (e.g., California ISO, PJM Interconnection, New York ISO, New England ISO, ERCOT, and Nordpool), a market administrator is tasked with the central administration of the market that is referred as the independent system operator (ISO). One of these challenges arises from the increasing penetration of variable renewable energy sources (VRES); like solar, wave, and wind generators, in electricity markets, following efforts to move towards a low carbon economy. Namely, the uncertain and intermittent nature of the power generated by the VRES generating units introduces uncertainty in the market-clearing model used to compute the desired market-clearing prices.

II. Methods

In economic dispatch models for electricity markets, the most popular way to schedule resources and determine prices is by developing stochastic market-clearing models. That is, models in which the market uncertainties are modeled by considering their distribution to be given by a finite set of scenarios with corresponding probabilities of occurrence. We develop a chance-constrained market-clearing model and corresponding chance-constrained pricing scheme that ensures revenue adequacy for the market administrator in expectation, and cost recovery in expectation for all the conventional and VRES generators in the market. Typically, market-clearing models for electricity markets are formulated as two-stage models with matching settlements. In the market's scheduling (first) stage, usually timed a day-ahead before the market's real-time (second) stage, conventional and VRES generators make offers, and the market administrator chooses scheduled (or pre-dispatch) quantities of electricity generation. Then, in the market's real-time stage, when delivery of power occurs, new sets of generation bids are submitted (e.g., by VRES generators), which can deviate (i.e., be redispatched) from the scheduled dispatch levels to clear the market. As considered here, in the real-time stage, the market administrator might also curtail the market loads (demands), subject to compensation to consumers. The market administrator's objective in setting the scheduled dispatches, and the real-time dispatches and curtailments, is to maximize the social welfare. Our methods built on recent literature with chance-constrained market-clearing models.

III. RESULTS

We show that there is a fundamental difference between stochastic and chance constrained pricing schemes. Namely, stochastic pricing schemes derive prices for the real-time participants' actions that might change depending on the realization of the market's uncertain parameter(s) (e.g., VRES generation). We also show that the use of the dual variables associated with the market-clearing model beyond those related to the scheduling and real-time stage balancing constraints, allow to obtain distributions of the revenues throughout the network that can be significantly different to the ones resulting from a stochastic market-clearing pricing scheme.

IV. CONCLUSIONS

Our results show that a fundamental difference between revenue adequate, stochastic market-clearing prices and revenue adequate, chance-constrained market-clearing prices is that the former prices are dependent on the real-time outcome of the uncertainties in the market for actions taken in the real-time stage. In contrast, the latter real-time prices are uncertainty uniform in the sense that they do not depend on the real-time uncertainty outcomes. Our method also has much better solution times than traditional stochastic methods.

NOTES

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Evaluating the Impact of a Carbon Tax on GDP in a Global Context

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1. Introduction

Climate change is an ongoing problem for the world caused by the over-consumption of fossil fuels and the resulted high level of carbon emissions. Despite the fact that carbon tax is introduced as a cost-effective instrument, politiciations are hestiant to employ this policy due to their concern regarding its effect on the GDP (COP26,2021).

There is a limited number of empirical studies about the economic impact of the carbon tax policy. Yamazaki (2017), Bernard et al. (2018), and Metcalf (2020) studied the economic impact of the carbon tax policy implication on the GDP of the Canadian province of British Colombia. In the VAR model used by Bernard et al. (2018) no statistically significant effect was detected but the difference-in-difference model employed by the Metcalf (2020) showed that the GDP of this province has increased by 7 per cent during the eight years of policy implication, 2008 that the policy was adopted to 2016, and Yamazaki's (2017) research confirmed the implication of the carbon tax has increased employment in this province. Metcalf et al. (2019) applied the structural VAR model to estimate the impact of the carbon tax policy on the economy of the carbon tax adopter countries in Europe and no statistically significant effect was detected.

To the knowledge of the author, it is the first study that has estimated the real-world effect of the carbon tax policy implementation on ten members of OECD countries via the newly introduced difference-in-difference approach for a panel with multiple treatment timing. This is the first study that estimates the aggregated group-time average treatment effect of the carbon tax policy implementation in the OECD countries to depict the impact of the carbon tax policy exposure on the GDP per capita of the whole panel of countries.

2. Methodology

This study is a natural experiment right around an exogenous shock caused by imposing a carbon tax policy on a panel consisting of ten members of OECD countries, each starting the policy in a different year and having a distinct length of exposure to the carbon tax policy.

To provide an unbiased estimate in the difference-in-difference analysis, the new approach proposed by Callaway and Sant'Anna (2021) is employed, in which groups are formed based on the year they first get treated and the group-time average treatment effect is calculated. The presence of the parallel trend is conditioned on control variables too. To overcome the obstacle caused by variation in the treatment timing, instead of the average treatment effect of the treated (ATT) the group-time average treatment effect $(ATT(g,t))$ is estimated. The group-time average treatment effect presents the impact of the policy intervention on the variable of interest in each group and the aggregated effect shows the impact of the policy imposition on the whole panel of countries.

As this study is a global study, 10 countries are selected as the treatment group and 10 are selected as control group. We restrict our study to members of OCED. Finland, Norway, Sweden, Denmark,Switzerland, Ireland, Japan, Spain, France, Portugal are considered as treatment countries. Belgium, Costa Rica, Germany, Greece, Italy, New Zealand, UK, Luxembourg, and Austria are chosen as the control group. To control for heterogeneity caused by other factors on the GDP per capita, five control variables are chosen to limit the heterogeneity caused by them on the outcome of interest.

3. Results

Study confirms that the impact of the carbon tax policy on only two groups is statistically significant, and positive. After conditioning the model on five control variables, the statistically significant effect of the carbon tax policy intervention in group 2010 and group 2015 is statistically significant. This effect is not statistically significant on the GDP per capita of group 1990, group 1991, group 1992, group 2008, group 2012, and group 2014. The aggregated effect of the policy on the GDP per capita of the whole panel is statistically insignificant too.To test for the robustness of the model, the dynamic average treatment effect is estimated which aproves the results.

4. Conclusion

By employing the empirical evidence and applying the novel approach for the difference-in-difference method in case of variation in the treatment timing, the impact of the carbon tax imposition on the GDP per capita of groups 2010 and 2015 turns out to be positive and significant. Applying the carbon tax after conditioning the model to five control variables has resulted in increase in the GDP per capita of groups 2010 and 2015. This study can provide a baseline for further research based on empirical evidence to provide a broader understanding of the economic impact of the carbon tax on the economy.

References

1- Callaway, B., Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics*, *225*(2), 200-230.

2- Metcalf, G. (2019). "On the Economics of a Carbon Tax for the United States." Brookings Papers on Economic Activity, (Spring), 405-458.

3- Metcalf, G., Stock, J. (2020). Carbon tax policy, measuring the macroeconomic impact of carbon taxes. AEA, 110, 101-106.

4- Six Assessment Report of Intergovernmental Panel on Climate Change (IPCC-AR6). (2022).

5- Bernard, J., Kichian, M., Islam, M. (2018). Effects of B.C.'s carbon tax on GDP. USAEE research paper series No 18-329.

6- Yamazaki, A. (2017), Jobs And climate policy: Evidence from British Colombia's revenue-neutral carbon tax. Journal of Environmental Economics and Management. 83, 197-216.

7- UN Climate Change Conference (COP26). (2021).

ECONOMICS REGULATION OF RENEWABLE DISTRIBUTED GENERATION IN ARGENTINA, BRAZIL, CHILE, COLOMBIA AND MEXICO: DIFFERENCES AND SIMILARITIES

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Overview

In the last decade, many Latin America and Caribbean (LAC)' countries in particular countries have been modifying the way electricity is being provided. Instead of massive investments on large generation premises, it is being observed a growth in small capacity located near de consumers. Countries such as Argentina, Brazil, Chile, Colombia, and Mexico are playing an increasingly important role in the global energy sector. These countries have been showing high relevance not only in the local market, but also worldwide, thus contributing to the development of renewable sources in the region with impacts worldwide.

According to the Organización Latinoamericana de Energía (OLADE) [1], the installed capacity of electricity from new renewable energy sources grew by more than 65 GW between 2015 and 2020, reaching the mark of 261 GW in LAC. This conquest is due to abundance of natural resources and their geographic localization which provides high levels of solar irradiation during all the year and constant winds from either Atlantic and Pacific Ocean.

Since 2015 the numbers for the Solar Photovoltaic (PV) market have been surprising in the region. As shown by the Global Market Outlook for Solar Power 2022-2026 [2], between 2015 and 2021 the PV installed capacity in LAC had a growth of 4,229%, from 0.7 GW to 30.3 GW in 2021. A significant part of these numbers is due to the insertion of distributed solar generation in LAC and the improvement in regulations that aim to encourage this type of investment.

Methods

This article starts from a survey of the regulatory situation for new renewables, with focus on distributed generation in Argentina, Brazil, Chile, Colombia, and Mexico. The evolution of distributed generation in these countries is placed in perspective in relation to the regulatory changes of the last ten years that provided an effective increase, especially in the photovoltaics.

The analysis takes into consideration convergences and divergences involving these countries. The aim is to understand how each country individually has created its legal-regulatory framework and what has been the market's response to the various changes the electricity industry has undergone. The path that these countries have taken to achieve the installed capacity of distributed solar generation that they have nowadays will be presented, as well as government policies such as subsidies and incentives that have attracted new investments in these markets. In addition, it is also analysed the participation of some stakeholders, such as distribution companies, which are crucial for distributed generation to succeed. Finally, it is tackled the current regulatory situation of the selected countries as well as the status of the installed capacity with its nuances.

Results

International experience has shown that policies to encourage new renewable sources, especially with regard to distributed solar generation, are the key to the growth and strengthening of this type generation. At the same time, it is observed that distribution concessionaires need to be prepared to deal with this new arena and provide an agile, easy and efficient connection between the generation plants and the grid. It is being observed that the countries have had significant increases in the installed capacity of the photovoltaics generation after they had developed regulatory policies that boosted the distributed generation sector.

Furthermore, countries have encountered different difficulties over the past decade to establish a competitive and stable market. The status of distributed generation varies from one country to another. Their distinct laws and regulations differentiate for instance the maximum powers that projects can have to fit in and receive government benefits. All these factors have been crucial for the development of this market in LAC.

Conclusions

Analysing the situation of new renewable sources growth profile in LAC, especially photovoltaic solar generation amongst Argentina, Brazil, Chile, Colombia and Mexico, it is clear the importance of regulations that encourage investments on this source to provide a less carbonized future, as well as to provide a safer and more efficient national electricity industry.

The analysis of the distributed generation growth in distinct countries in LAC made it clear that regulatory changes have encouraged small and medium consumers to invest in their own energy generation on the roof of their homes and small businesses.

References

[1] OLADE. Panorama Energético 2021. **Organización Latinoamericana de Energía**. Primera Edición – Noviembre del 2021. ISBN: 978-9978-70-138-6, 2021

[2] SPE. Global Market Outlook For Solar Power 2022 - 2026. **Solar Power Europe.** ISBN: 9789464518610, 2022.

[3] EPE, Empresa de Pesquisa Energética (Brazil). **Balanço Energético Nacional 2021: Year base 2020** / Empresa de Pesquisa Energética. – Rio de Janeiro : EPE, 2021.

REFORMAS REGULATÓRIAS NO MERCADO DE REFINO E IMPACTOS NOS PREÇOS DA GASOLINA NA CHINA

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Overview

Para decidir se um sistema de regulação é bom, aceitável ou precisa ser reformado, é necessário ter clareza sobre os *benchmarks* que são relevantes para o alcance dos objetivos traçados (BADWIN, CAVE e LODGE, 1999). As teorias normativas buscam estabelecer a regulação ideal de uma perspectiva econômica e são prescritivas. Elas geralmente são baseadas nos conceitos de eficiência econômica e de falhas de mercado, e fornecem uma versão econômica de uma teoria de interesse público de regulação. Já a economia positiva é o ramo explicativo e empírico da economia da regulação. Ela procura explicar a natureza e o desenvolvimento da regulamentação e seu impacto por meio de análises estatísticas e, às vezes, avaliações de custo-benefício (BADWIN, CAVE e LODGE, 1999). No campo positivo, Stigler fundou a Teoria Econômica da Regulação (antes havia hipóteses, não teorias), que visa a explicar quem arcará com o ônus e os benefícios da regulação e seus efeitos sobre a alocação de recursos.

O objetivo geral do artigo é determinar se as reformas regulatórias no mercado de refino na China conseguiram estabelecer preços módicos de gasolina no mercado interno, ao mesmo tempo em que preservaram o alinhamento dos preços internos aos do mercado internacional. Conforme supracitado, para se decidir se uma regulação é boa, é necessário estabelecer seus benchmarks. No caso, os benchmarks selecionados para a verificação se as reformas do mercado de refino permitiram preços de mais baixos são os preços de gasolina de outros países, de renda semelhante (G7). Pelo lado normativo, a busca pela eficiência econômica prescreve medidas pelo lado da defesa da concorrência e do controle de preços (regulação reativa), a fim de se aumentar a competição e reduzir preços. O pressuposto de que preços competitivos aumentam o excedente do consumidor é medido pela verificação do alinhamento de preços ao mercado internacional. Pelo lado positivo, fica claro que esse arcabouço é insuficiente para descrever todo o rol de razões que justificam a regulação. Assim, optou-se por incluir um aspecto ligado a objetivos sociais, a fim de se medir o sucesso dessa regulação. O uso de objetivos não estritamente ligados às falhas de mercado é essencial por demonstrar que uma melhor regulação não significa menos regulação ou, necessariamente, menos Estado.

Desde a entrada da China para OMC, diversos mercados passaram por um processo gradual de abertura, dentre esses o de combustíveis (ELLIOT at al, 2020).

A reforma dos preços e taxas do petróleo refinado em dezembro de 2008 estabeleceu o atual mecanismo de fixação de preços de produtos refinados. Nos últimos anos, o mecanismo geral de preços tem sofrido alterações com o intuito de aprimorar seu funcionamento, de forma a garantir o abastecimento, ao mesmo tempo em que promove o aumento da concorrência no mercado. A operação do mecanismo de reajuste vem sendo aprimorada para resolver problemas com o ciclo de reajuste de preços excessivamente longo e aumentar a sua transparência (CNE, 2019).

Desde 2018, o mercado de refino na China é formalmente aberto, inclusive para investidores estrangeiros, cujas restrições à entrada foram formalmente eliminadas. De lá para cá, diversas empresas entraram no mercado de refino e distribuição de combustíveis, muitas vezes atuando em parceria com empresas chinesas.

A participação de refinarias privadas no total de refino na China tem aumentado, sendo que elas foram as principais responsáveis pelo crescimento da capacidade de refino de petróleo em 2018 (DELLOITE, 2018, pg. 3). No entanto, cabe analisar a eficácia dessas medidas, a fim de estabelecer um mercado relativamente competitivo, com preços alinhados aos internacionais e capaz de oferecer combustíveis a um preço módico à população.

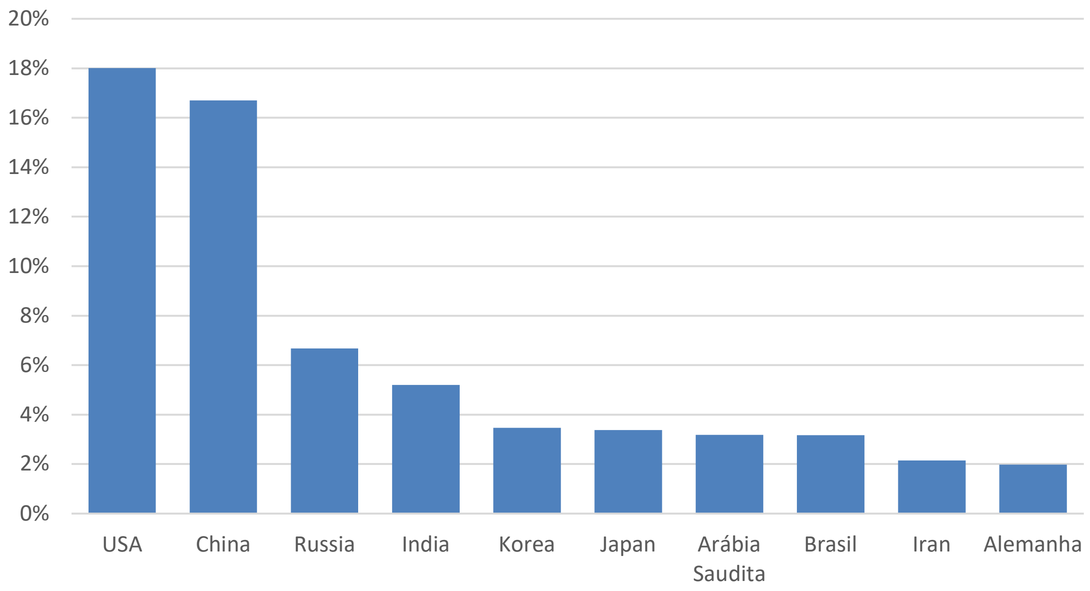
A liberalização das licenças de importação de petróleo continua a alimentar a dinâmica de produção das refinarias privadas. Já o mercado de revenda de combustíveis por meio de postos de gasolina é razoavelmente diversificado com 46% sobre o controle das *National Oil Companies* (NOC), 50% de empresas privadas e 4% de empresas estrangeiras (DELOITTE, 2018).

1. Caracterização do Mercado de Refino

1.1. Oferta Mundial

De acordo com a Agência Internacional de Energia, o mercado de refino mundial atingiu a capacidade de pouco mais de 102 milhões de barris/dia (MM b/d) em 2020 (IEA, 2021). Nesse sentido o maior produtor mundial é os Estados Unidos com pouco mais de 18 MM b/d de capacidade, seguidos pela China com pouco mais de 17 MM b/d.

Gráfico 1 - Capacidade de Refino MM b/d



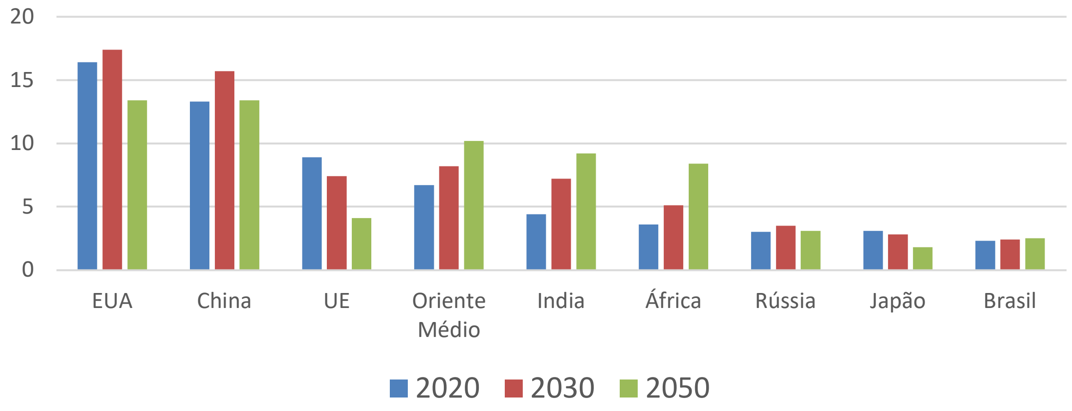
Fonte: elaboração própria com dados da IEA 2021.

1.2. Demanda Mundial

De acordo com a IEA (2021) a demanda por petróleo no cenário de referência da Agência, *State Policy Scenario* (STEPS) sai de 87,9 MMb/d em 2020 e atinge 103 MM b/d em 2020, permanecendo nesse patamar em 2050. E a demanda por produtos refinados sai de 75 MM b/d em 2020, para 88,4 MM b/d em 2030 e 88,6 MM b/d em 2050.

A China que em 2020 tinha uma demanda por petróleo de 13,3 MM b/d contra 16,4 MM b/d dos EUA em 2020, iguala sua demanda à dos EUA em 2050, atingindo o patamar de 13,4 MM b/d no STEPS, conforme gráfico abaixo.

Gráfico 2 - Demanda por petróleo MM b/d

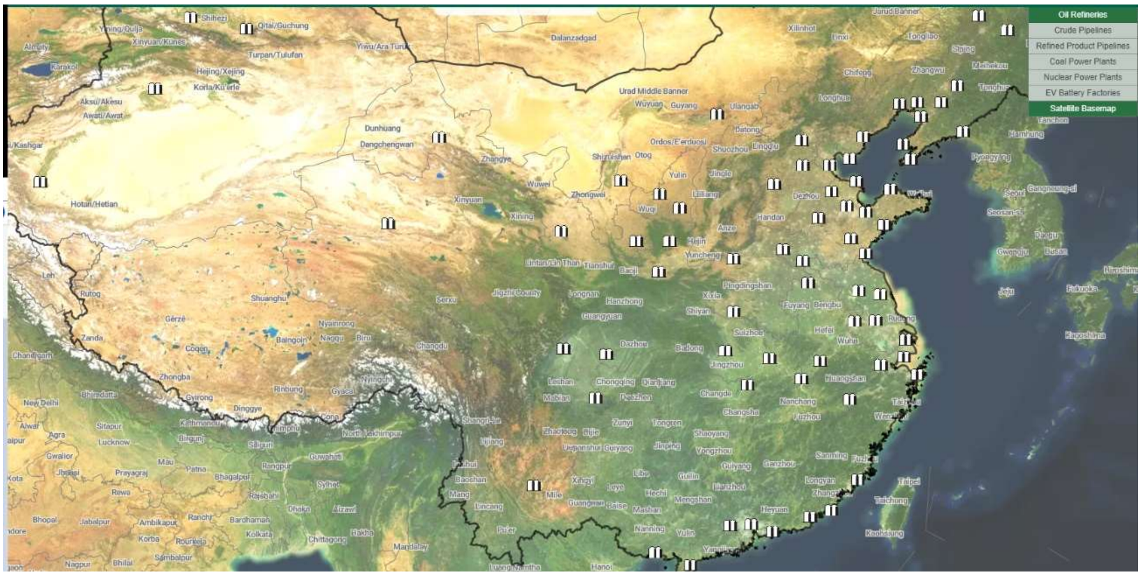


Fonte: Elaboração própria com dados da IEA 2021

1.3. Refino na China

Conforme supracitado, a China é o segundo maior país em termos de capacidade de refino, com 17 MM b/d. Outras fontes, no entanto, apontam que a capacidade de refino da China, em 2021, já estaria em 22,7 milhões de barris/dia De acordo com essa fonte, o número total de refinarias em 2021 é de 210 plantas (BAKER INSTITUTE).

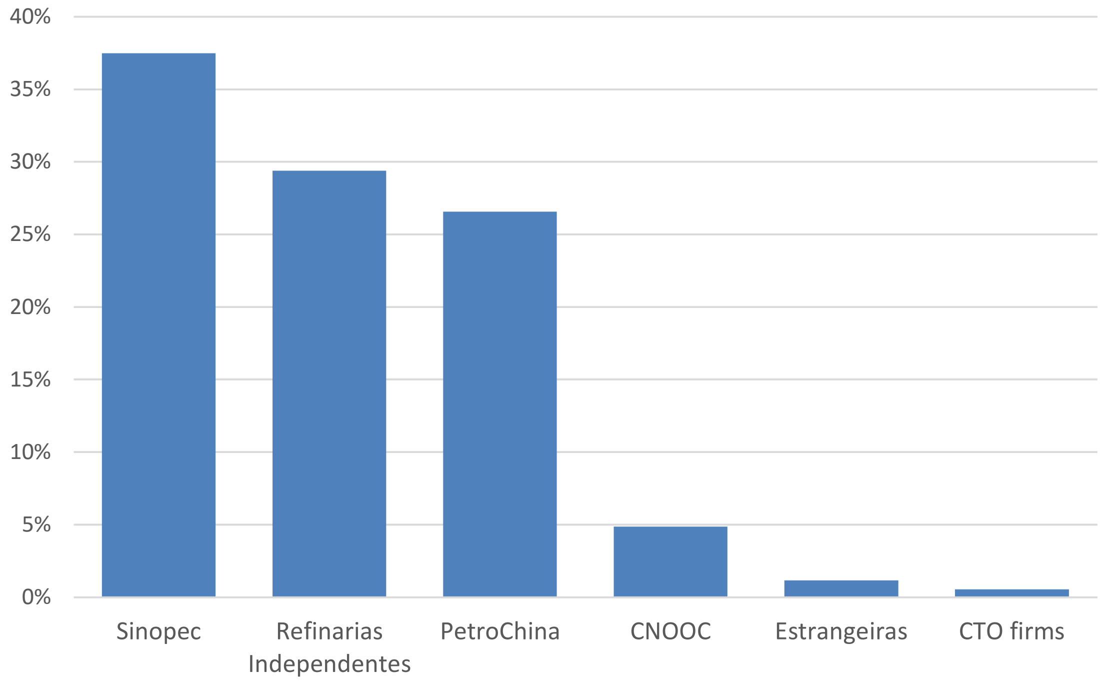
Figura 1 - Distribuição das refinarias na China



Fonte: Baker Institute

Na produção, o mercado é dominado por duas grandes estatais de petróleo Sinopec e PetroChina, com 37% e 27% de *market share*, respectivamente. Além disso, conta com *players* privados, nacionais e estrangeiros. Pelo lado dos refinadores privados nacionais, a China conta com pequenas empresas que atuam de forma independente, as chamadas *tea pots*[1], conforme gráfico abaixo.

Gráfico 3 - Capacidade de Refino na China

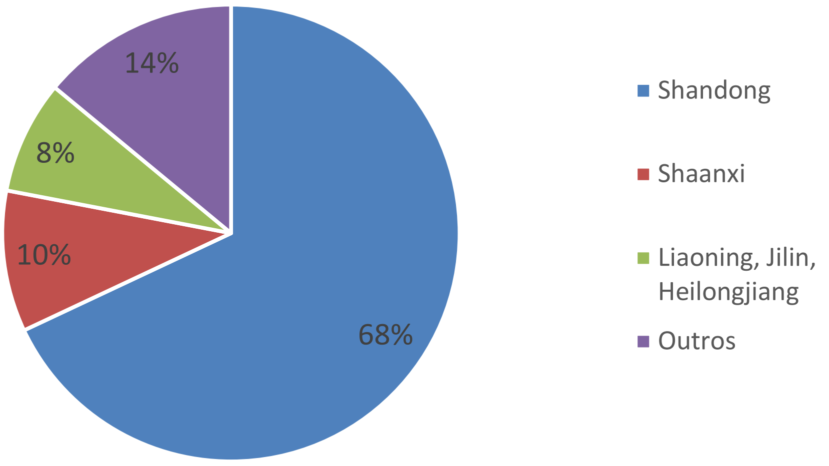


Fonte: elaboração própria com dados da International Petroleum Economists.

1.3.1. As *Tea Pots*

As chamadas *tea pots* são as pequenas refinarias independentes, localizadas, em grande parte, na província de Shandong, que foram autorizadas a adquirir e a refinar petróleo por conta própria em 2015, são chamadas por esse nome em virtude de seu *design* inicial em forma de forno de barro e por seu tamanho em relação às gigantes *National Oil Companies*. Em termos de tamanho, sua média de capacidade é de 70.000 bd, sendo algumas com apenas 20.000 bd (DOWNS, pg. 10, 2017). Sua distribuição geográfica pode ser observada no gráfico abaixo.

Gráfico 4 - Distribuição geográfica das tea pots em 2015



Fonte: DOWNS 2017

Em 2009, a Comissão Nacional de Desenvolvimento e Reforma (NDRC) estipulou que até 2011 refinarias com capacidade inferior a 20.000 bpd deveriam ser fechadas e que refinarias com capacidade de 20.000 – 40.000 bpd deveriam ser fundidas ou atualizadas. Como resultado, a capacidade das refinarias independentes aumentou substancialmente. Em outubro de 2013, a Administração Nacional de Energia (NEA) divulgou para comentários públicos uma proposta para alocar refinarias independentes 200.000 bpd de petróleo importado por ano.

Em 2015, o governo central tomou a decisão de permitir que as *tea pots* passassem a importar diretamente petróleo, por meio do estabelecimento de quotas. O objetivo foi consolidar o setor de refino independente e expor as NOC à competição para se tornarem mais eficientes. O governo concedeu sua primeira cota de importação a uma refinaria independente sob o novo regime de comércio de petróleo em julho de 2015.

Até o final de 2016, a agência havia concedido cotas anuais de importação de petróleo bruto a 19 refinarias, totalizando 1,48 MM bpd, e o Ministério do Comércio havia concedido licenças de importação de petróleo bruto a 13 das 19 refinarias, totalizando 1,1 MM bpd. A queda nos preços do petróleo levou o governo central em dezembro de 2015 a suspender sua prática de ajustar os preços do diesel e da gasolina a cada dez dias úteis de acordo com as flutuações nos preços globais do petróleo. Em seguida, o governo central anunciou que não haveria mudanças nos preços do diesel e da gasolina enquanto o petróleo fosse negociado abaixo de US$ 40/bbl. O objetivo era limitar as perdas a montante das NOC, cujos custos de produção estavam ligeiramente acima de US$ 40/bbl, de acordo com o NDRC. No entanto, as refinarias independentes também se beneficiaram do piso dos preços do petróleo, embora não tenham operações a montante.

O maior acesso ao petróleo importado combinado com o piso do preço do petróleo estimulou uma reversão da sorte para as refinarias independentes, especialmente no início de 2016, quando os preços do petróleo eram inferiores a US$ 40. As taxas de utilização das refinarias independentes estavam em torno de 30% em 2014. No final de 2016, suas taxas de utilização aumentaram drasticamente. Os independentes continuaram sendo o principal impulsionador do crescimento de 13,8% da China nas importações de petróleo bruto no primeiro semestre de 2017 em relação ao mesmo período de 2016.

Nos últimos anos, os produtos petrolíferos refinados do país enfrentaram o desafio do sério excesso de capacidade e a lucratividade das empresas de refino de petróleo diminuiu. Além disso, o mercado diminuiu e a concorrência no setor se intensificou.

Por muito tempo, PetroChina e Sinopec foram absolutamente dominantes na indústria de refino de petróleo, e o mercado de petróleo refinado também estava em uma situação de duas potências competindo pela hegemonia. Com a implementação do "Aviso da Comissão Nacional de Desenvolvimento e Reforma sobre Questões Relativas ao Uso e Gestão do Petróleo Bruto Importado", as empresas locais independentes de refino de petróleo tornaram-se gradualmente maiores, e outras empresas centrais também entraram rapidamente na indústria de refino de petróleo. Para o novo padrão de concorrência - entre as duas principais empresas de refino de petróleo e independentes -, formou-se um padrão básico de diversificação do corpo principal do mercado de petróleo refinado, que promoveu efetivamente o nível geral de concorrência na indústria e o nível geral de ambiente de consumo foi muito melhorado.

Empresas privadas representadas por Hengli, Rongsheng, Tongkun, Shenghong, etc., entraram no refino e na indústria química com a ajuda da política Dongfeng. A abertura do mercado chinês para empresas de capital estrangeiro está em constante expansão, e gigantes petroquímicos internacionais como ExxonMobil, BASF e SABIC estão competindo ativamente no mercado petroquímico. Grandes refinarias como Sinopec, PetroChina e Sinochem também estão acelerando seu refino e transformação química e modernização.

A tradicional indústria privada de refino e química acelera a integração, transformação e atualização da indústria de *layout*. A indústria de refino de petróleo da China está no "período doloroso" de excesso de capacidade causado pelos dividendos da política de liberalização do mercado. A maior remodelação da história está chegando, e a transformação e modernização serão aceleradas no futuro para avançar em direção ao desenvolvimento de alta qualidade.

1.4. Políticas de Petróleo na China

1.4.1. Histórico e Dinâmica de Formaçao de Preços de Combustíveis

Desde 1998 o governo central começou a introduzir uma série de mudanças na regulamentação sobre os preços de petróleo na China, de forma a aprimorar o mecanismo de preços de mercado e a concorrência no setor.

Anteriormente a 1998, o preço de venda dos combustíveis era definido pelo governo chinês. A partir desse ano, foi criada uma regra formal para a definição do preço de combustíveis. Esta passou a ser atrelada a uma cesta de preços internacionais de petróleo, que são utilizadas para se definir um preço teto do varejo. Abaixo desse teto, os *players* passaram ater liberdade para definir os preços de acordo com o mercado (ELLIOT at al, 2020, pg. 7).

De 1998 a 2001, o governo chinês utilizou os preços do petróleo *spot* de Cingapura como *benchmark.* Ajustes adicionais eram feitos quando o *gap* entre preços domésticos e internacionais se tornavam grandes demais. De 2001 a 2005 a métrica era uma média ponderada do WTI *spot* (60%), Cingapura *spot* (30%) e Brent *spot* (30%). Em 2006 a métrica mudou novamente e esse preço passou a ser calculado por uma média ponderada do Brent *spot* (40%), Ásia Dubai Fatech *spot* (30%) e Minas da Indonésia *spot* (30%) (CHEN, HUAN, MA pg. 6).

Em 2009, CNDR emitiu o documento “Medidas para a Administração dos Preços do Petróleo” para implementação experimental, que em seu artigo 7º estabelecia que quando o preço médio móvel do petróleo bruto no mercado internacional por 22 dias úteis consecutivos sofrer variação superior a 4%, o preço doméstico do petróleo refinado poderá ser ajustado em conformidade. Além disso, estabelecia que quando o preço do petróleo bruto no mercado internacional fosse inferior a US$ 80 por barril, o preço do petróleo refinado será calculado de acordo com a taxa normal de lucro de processamento. Quando fosse superior a US$ 80 por barril, a margem de lucro do processamento seria deduzida até que o preço do petróleo refinado seja calculado com base no lucro zero do processamento. Quando o preço for superior a US$ 130 por barril, de acordo com o princípio de levar em conta os interesses dos produtores e consumidores e manter o funcionamento estável da economia nacional, são adotadas políticas fiscais e tributárias adequadas para garantir a produção e o abastecimento de óleo refinado, e os preços da gasolina e do diesel não são elevados ou menos elevados em princípio (CNDR, 2009). Em 2013, o esquema de precificação de produtos refinados mudou novamente, permitindo que os preços do petróleo bruto fossem estabelecidos conjuntamente pela Sinopec e PetroChina, com base nas condições locais. Os varejistas de serviços podem definir seus próprios preços, desde que estejam abaixo de um preço máximo estabelecido pela NDRC para cada províncias (ELLIOT at al, 2020, pg. 7).

Em 2016, a CNDR emitiu documento chamado com atualizações relativas à melhoria do mecanismo de formação de preços do petróleo refinado. Este documento, determinava a fixação de um limite inferior para regulação do preço do óleo refinado de de US$ 40/bbl. Assim, quando o preço do petróleo bruto no mercado internacional for inferior a US$ 40/bbl, o valor não regulado dos preços do petróleo refinado será totalmente incorporado às reservas de risco, depositadas em contas especiais, utilizadas com a aprovação do Estado , e principalmente utilizado na conservação de energia e redução de emissões, melhoria da qualidade do petróleo, garantia da segurança do abastecimento de petróleo, entre outros aspectos.

As "Medidas de Gestão de Preços do Petróleo" passou por diversos aprimoramentos até que chegou à versão atual, em que os preços domésticos de produtos refinados estão ancorados nos preços internacionais do petróleo. Dessa forma, o documento estipula que os preços domésticos da gasolina e do diesel são ajustados a cada 10 dias úteis de acordo com as alterações nos preços do petróleo bruto no mercado internacional, e o reajuste do preço terá efeito às 24:00 do dia do reajuste do preço é liberado. Quando a faixa de ajuste de preço for inferior a 50 yuans por tonelada, nenhum ajuste será feito e será acumulado ou compensado no próximo ajuste de preço. O documento também estipula preços diferenciados para diversas cidades e regiões, levando-se em conta diferenças tributárias e de taxa de retorno das empresas. A tabela com os preços de gasolina e diesel para 17/02/2022 está abaixo:

Tabela 1 - O preço de teto do varejo de gasolina e diesel nas províncias, regiões autônomas e cidades centrais

17/02/2022	**¥/ton**	
	Gasolina (produto padrão)	**Diesel (produto padrão)**
1. Regiões onde é implementado um preço por província		
Pequim	9.760	8.720
Tianjin	9.725	8.685
Província de Hebei	9.725	8.685
Província de Shanxi	9.795	8.740
Província de Liaoning	9.725	8.685
Província de Jilin	9.725	8.740
Província de Heilongjiang	9.725	8.685
Xangai	9.740	8.685
Província de Jiangsu	9.780	8.685
Província de Zhejiang	9.780	8.690
Província de Anhui	9.775	8.725
Província de Fujian	9.800	8.740
Província de Jiangxi	9.780	8.735
Província de Shandong	9.735	8.750
Província de Hubei	9.750	8.745
Província de Hunan	9.790	8.695
Província de Henan	9.745	8.710
Província de Hainan	9.870	8.705
Chongqing	9.940	8.820
Província de Guangdong	9.805	8.895
Região Autônoma de Guangxi	9.870	8.755
Região Autônoma de Ningxia	9.730	8.820
Província de Gansu	9.710	8.685
Região Autônoma de Xinjiang	9.505	8.705
2. Regiões sem preço específico por província		
Hohhot	9.740	8.700

Chengdu	9.945	8.920
Guiyang	9.905	8.845
Kunming	9.935	8.875
Xi'an	9.710	8.695
Xining	9.690	8.730

Nota: 1. Os preços constantes da tabela incluem o imposto de consumo, o imposto sobre o valor acrescentado, o imposto sobre construção urbana e a sobretaxa de educação.

Fonte: http://www.gov.cn/shuju/2022-02/17/content_5674375.htm

Ademais, diversos autores identificaram assimetrias de preços nos moldes das descritas por Noel. Isso significa que os preços da gasolina aumentam mais rapidamente quando os preços do petróleo bruto estão subindo do que caem quando os preços do petróleo bruto estão caindo**.** Na China, como em outros países, aumentos e diminuições nos preços internacionais do petróleo têm efeitos assimétricos nos preços no atacado da gasolina e do diesel. Em particular, os preços da gasolina e do diesel na China aumentam rapidamente quando os preços internacionais do petróleo aumentam, mas diminuem lentamente quando os preços internacionais do petróleo diminuem (CHEN, HUAN, MA pg. 17).

2. Método

A metodologia utilizada será a Análise Envoltória de Dados, que permite comparar uma eficiência revelada (tida como otimizada) com a eficiência das unidades analisadas. A fim de se medir a aderência dos preços da gasolina aos preços internacionais de petróleo, será testado se o preço teto para a gasolina, estabelecido pelo governo chinês, mantém correlação significativa com os preços do barril de petróleo tipo Brent.

Para se fazer a comparação absoluta dos preços da gasolina na China contra os preços dos demais países, todos os preços foram convertidos para US$/litros. Em seguida foi feita a comparação dos preços da gasolina comum contra a média dos preços da gasolina dos países do G7 (*benchmarking*), e a comparação contra os preços dos países individualmente, a fim de se estabelecer um *ranking*.

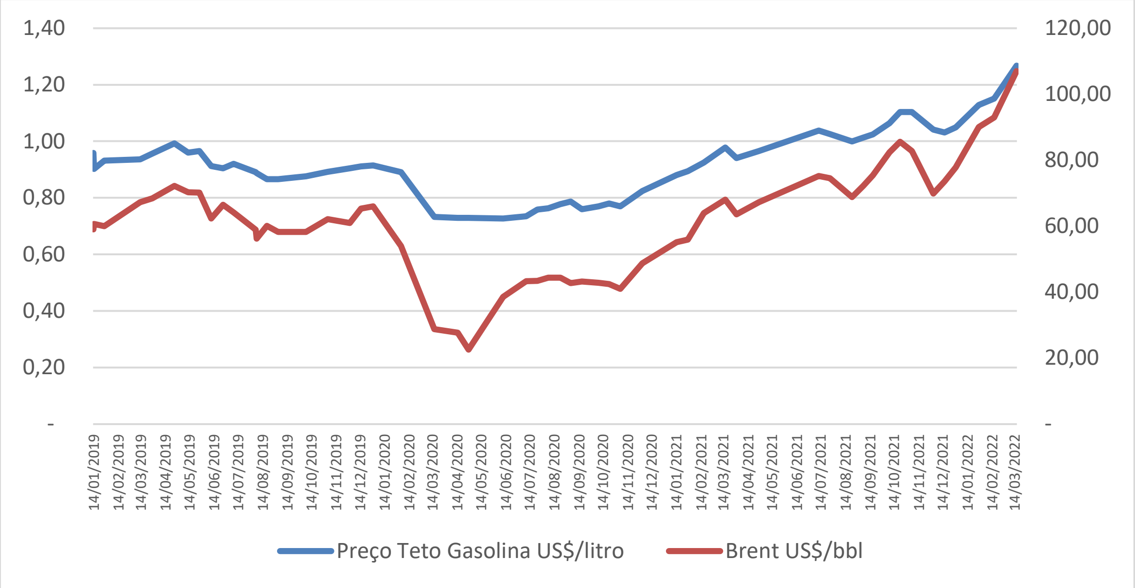
Para se fazer a comparação relativa dos preços da gasolina na China, contra o preço da gasolina nos demais países, foi construído o indicador renda per capita (em paridade do poder de compra – PPP) dividido pelo preço da gasolina em US$/mil litros. Em seguida, foi feita a comparação desse indicador para a China contra a média desse indicador para os países do G7 (*benchmarking*), e a comparação contra o indicador para cada um dos países, a fim de se estabelecer um *ranking*.

2.1. Indicadores de Eficiência Econômica

A fim de se medir a aderência dos preços da gasolina aos preços internacionais de petróleo, comparamos no gráfico abaixo os preços de gasolina para a cidade de Xangai contra os preços do petróleo Brent. Os preços originais da gasolina foram obtidos em Renminbi (RMB)/tonelada e convertidos para US$/litros, a fim de facilitar a comparação. A tabela com os valores originais, bem como com as conversões se encontram no Anexo 1.

Pode-se facilmente constatar a elevada correlação entre ambos, de 97%. O que corrobora a tese de que, numa análise preliminar, o governo chinês tem tido relativo sucesso em manter uma a aderência dos preços domésticos aos preços internacionais de petróleo, conforme gráfico abaixo.

Gráfico 5 - Brent x Preço teto da gasolina em Pequim



Fonte: elaboração própria com dados do CNDR.

A fim de comparar os efeitos dessa política de preços, em termos de oferecer preços módicos ao consumidor, estabelecemos a comparação dos preços da gasolina na China com um leque de países selecionados. O critério para a escolha dos países foi, basicamente, os países do Grupo dos Sete (G7), com exceção do Japão, ao qual não foi possível obter uma cotação específica para seus preços de gasolina. Ademais, acrescentamos os preços da gasolina no Brasil a fim de facilitar nossa comparação dos preços.

Foram utilizadas as médias anuais das cotações apresentadas a seguir. O detalhamento de cada série de preços está na tabela abaixo:

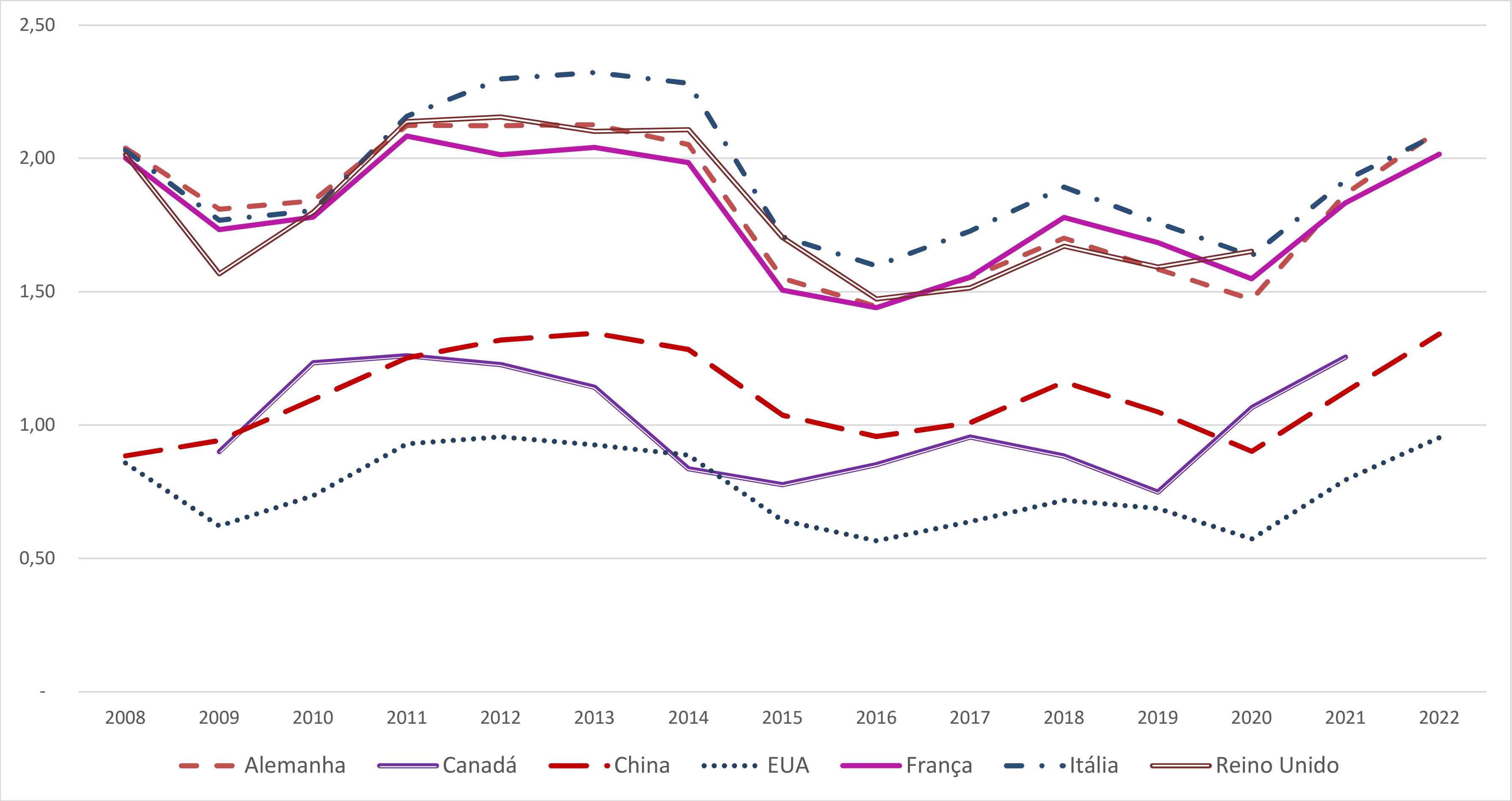
Tabela 2 - Detalhamento das séries de preços

País	Descrição	Unidade Original
EUA	US retail automotive gasoline total regular average. Fonte: US Department Energy Frequência: semanal às segundas-feiras	US$/galão
Alemanha	Germany Euro-super 95 gasoline price inclunding tax Fonte: European Commission Frequência: semanal às sextas-feiras	€/quilolitro
França	France Euro-super 95 gasoline price inclunding tax Fonte: European Commission Frequência: semanal às sextas-feiras	€/quilolitro
UK	UK Euro-super 95 gasoline price inclunding tax Fonte: European Commission Frequência: semanal às sextas-feiras	€/quilolitro

Itália	Italy Euro-super 95 gasoline price inclunding tax Fonte: European Commission Frequência: semanal às sextas-feiras	€/quilolitro
Canadá	Canada regular gasoline avarage retail pump price inclunding tax Fonte: Natural Resources of Canada Frequência: diário	Cad/litro
China	China State Retail 95 Run Gasoline price Beijing Fonte: CNDR Frequência: diário	¥/litro

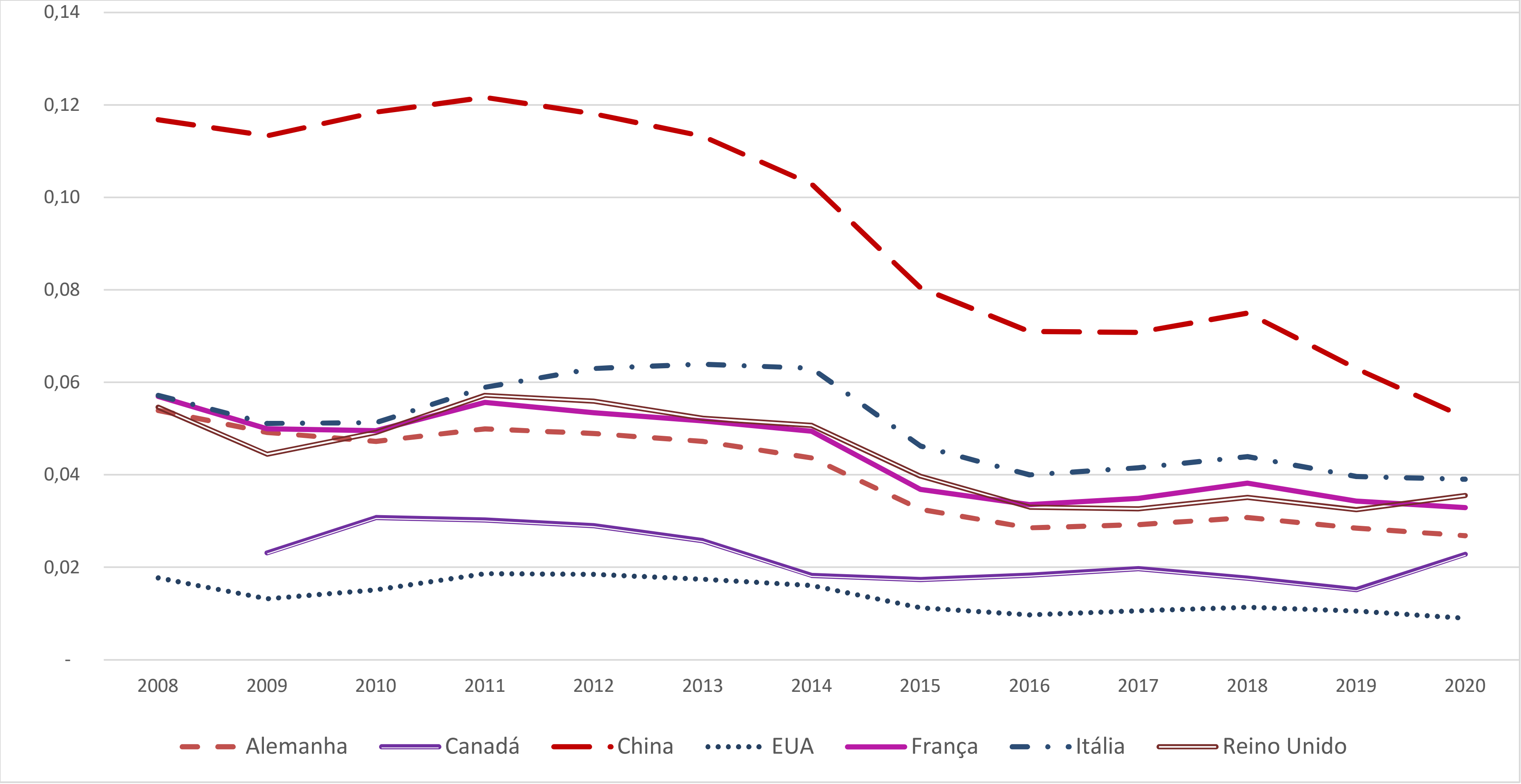
Os resultados obtidos estão no gráfico abaixo. Nele podemos verificar que os preços da gasolina na China em US$/litro são substancialmente menores do que os dos países da Europa, mas estão em patamares mais altos do que os dos países da América do Norte. O patamar atual de preços no Brasil é bem próximo daquele praticado na China, conforme gráfico abaixo.

Gráfico 6 - Preço da Gasolina US$/litro



Por fim, cabe avaliar quanto a gasolina na China custa em termos relativos. Assim, elaboramos uma comparação da renda relativa, para os mesmos países, entre o PIB per capita em Paridade do Poder de Compra (PPP) e o valor de 1.000 litros de gasolina (apenas para equalizar as ordens de grandeza). Os resultados estão no gráfico abaixo:

Gráfico 7 - Preço da Gasolina x PIB per capita PPP



No gráfico acima, podemos observar que os preços da gasolina na China, que pareciam ter preços ao consumidor mais módicos - quando comparados em termos de renda per capita - ocupam os maiores patamares, dentre os países analisados. Isso significa, que *ceteris paribus*, desconsiderando diferenças nos padrões de consumo, uma unidade de gasolina, custa proporcionalmente mais do que em outros países do G7.

Resultados

Foi constatado que a política de preço-teto para os preços de gasolina foi capaz de manter a aderência aos preços internacionais de petróleo tipo Brent. Ademais, os preços da gasolina na China em valores absolutos, medidos em US$/litro, são substancialmente menores do que os dos países europeus testados, mas estão em patamares mais altos do que os dos países da América do Norte. Por fim, pode-se observar que os preços da gasolina na China, quando comparados em termos de renda per capita - ocupam os maiores patamares, dentre os países analisados. Isso significa que, *ceteris paribus*, desconsiderando diferenças nos padrões de consumo, uma unidade de gasolina, custa proporcionalmente mais do que em outros países do G7.

Conclusões

A evidência analisada demonstra que a política do Governo Central tem sido relativamente bem-sucedida em termos de manter a aderência dos preços domésticos aos preços internacionais. No entanto, em termos de fornecer preços módicos ao consumidor, isso não está tão claro. Em uma primeira análise - quando comparamos os preços internacionais em dólar - os preços da gasolina na China parecem mais módicos em relação àqueles praticados em determinados países da Europa. No entanto, quando comparamos esses preços, em termos da renda per capita em PPP, podemos constatar que o cidadão chinês faz um esforço proporcionalmente maior do que seus pares europeus e norte-americanos.

Nos últimos anos, as regras para a venda de gasolina na China têm estado em constante evolução, a fim de aumentar o grau de competição no mercado e tornar as empresas mais eficientes e aumentar a modicidade dos preços.

O estudo sugere a necessidade de continuar a pesquisa, aprofundando-se com o uso de técnicas quantitativas mais complexas e talvez com um rol maior de países.

ANEXO 1 – Preço da Gasolina em Pequim

Beijing	Pequim		Teto	Brent	Câmbio
Data	¥/tonelada	¥/litro	US$/litro	US$/bbl	¥/US$
30/11/18	8.520	6,40	0,92	58,71	6,95
14/01/19	8.235	6,19	0,92	58,99	6,76
15/01/19	8.130	6,11	0,90	60,64	6,77
28/01/19	8.375	6,30	0,93	59,93	6,76
14/03/19	8.550	6,43	0,96	67,23	6,72
29/03/19	8.550	6,43	0,96	68,39	6,72
26/04/19	8.900	6,69	0,99	72,15	6,74
13/05/19	8.800	6,62	0,96	70,23	6,91
27/05/19	8.875	6,67	0,97	70,11	6,91
11/06/19	8.410	6,32	0,91	62,29	6,93
26/06/19	8.290	6,23	0,90	66,49	6,89
09/07/19	8.440	6,34	0,92	64,16	6,90
06/08/19	8.280	6,22	0,88	58,94	7,05
07/08/19	8.360	6,28	0,89	56,23	7,09
20/08/19	8.150	6,13	0,87	60,03	7,07
03/09/19	8.265	6,21	0,87	58,26	7,18
08/10/19	8.265	6,21	0,87	58,24	7,16
04/11/19	8.345	6,27	0,89	62,13	7,03
02/12/19	8.470	6,37	0,90	60,92	7,04
16/12/19	8.285	6,23	0,89	65,34	6,99
31/12/19	8.285	6,23	0,89	66,00	6,96
04/02/20	8.285	6,23	0,89	53,96	6,99
17/03/20	6.855	5,15	0,73	28,73	7,03
15/04/20	7.075	5,32	0,75	27,69	7,07
29/04/20	7.075	5,32	0,75	22,54	7,07
11/06/20	7.075	5,32	0,75	38,55	7,08
10/07/20	7.075	5,32	0,76	43,24	7,01
24/07/20	7.075	5,32	0,76	43,34	7,02
07/08/20	7.160	5,38	0,77	44,40	6,97
22/08/20	7.160	5,38	0,78	44,35	6,92

04/09/20	6.845	5,15	0,75	42,66	6,84
18/09/20	6.845	5,15	0,76	43,15	6,78
09/10/20	6.845	5,15	0,77	42,85	6,69
22/10/20	6.925	5,21	0,78	42,46	6,67
05/11/20	6.765	5,09	0,77	40,93	6,61
03/12/20	7.165	5,39	0,82	48,71	6,54
15/01/21	7.595	5,71	0,88	55,10	6,48
29/01/21	7.670	5,77	0,89	55,88	6,45
18/02/21	7.945	5,97	0,92	63,93	6,46
17/03/21	8.440	6,34	0,98	68,00	6,49
31/03/21	8.215	6,18	0,94	63,54	6,56
28/04/21	8.315	6,25	0,97	67,27	6,48
12/07/21	8.885	6,68	1,04	75,16	6,44
26/07/21	8.785	6,60	1,03	74,50	6,44
23/08/21	8.535	6,42	1,00	68,75	6,42
06/09/21	8.675	6,52	1,01	72,22	6,44
18/09/21	9.200	6,92	1,07	75,34	6,43
09/10/21	9.110	6,85	1,06	82,39	6,44
22/10/21	9.410	7,07	1,10	85,53	6,41
06/11/21	8.885	6,68	1,04	82,74	6,41
03/12/21	8.885	6,68	1,04	69,88	6,41
17/12/21	8.755	6,58	1,03	73,52	6,38
31/12/21	8.895	6,69	1,05	77,78	6,37
29/01/22	9.550	7,18	1,13	90,03	6,36
17/02/22	9.760	7,34	1,15	92,97	6,37
17/03/22	10.770	8,10	1,27	107,00	6,38

Referencias

BAKER INSTITUTE. Disponível em: <https://www.bakerinstitute.org/chinas-energy-infrastructure/> Acesso em: 13.03.2022.

BALDWIN, R; CAVE, M. e LODGE, M. Understanding Regulation. Theory, Strategy and Pratice. 2012.

CHEN, Y., HUANG, G. e MA, L. Rockets and Feathers: The Asymmetric Effect between China's Refined Oil Prices and International Crude Oil Prices. 2017.

COMITÊ CENTRAL DO PARTIDO COMUNISTA (CCPC). Propostas do Comitê Central do Partido Comunista da China sobre a Formulação do Décimo Quarto Plano Quinquenal de Desenvolvimento Econômico e Social Nacional e Metas de Longo Prazo para 2035. Disponível em: <https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202103/t20210323_1270124.html?code=&state=123> Acesso em: 23 de março de 2021.

____. Action plan for carbon dioxide peaking before 2030. Disponível em: < https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html> Acesso em: 27 de utubro de 2021.

COMITÊ NACIONAL DE DESENVOVIMENTO E REFORMA DA REPÚBLICA POPULAR DA CHINA (CNDR). Disponível em: < http://www.gov.cn/shuju/jiage/youjia.htm> Acesso em: 22/03/2022.

CONSELHO NACIONAL DE ENERGIA (CNE). Disponível em: <http://www.nea.gov.cn/2011-10/09/c_131180188.htm>. Acesso em 3 de março de 2022.

DELOITTE. China gasoline retailing development trends report 2019. 2019.

DOWNS, E. The rise of China's Independent refineries. Columbia SIPA – Centre on Global Energy Policy. 2017.

ELLIOT, R., SUN P. e, ZHU. Shell shocked: The impact of foreign entry on the gasoline retail market in China. 2020.

INTERNATIONAL ENERGY AGENCY (IEA). Key World Energy Statistics 2021.

REDE DE INTELIGÊNCIA HUAJING (RIH). Disponível em: < https://xueqiu.com/1973934190/160574720>. Acesso em 3 de março de 2022.

STIGLER, G. The Theory of Economic Regulation. The Theory of Economic Regulation. 1971.

WORLD BANK. Disponível em: <https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?end=2020&start=1990&view=cha>. Acesso em 12 de março de 2022.

WORLD BANK. Disponível em: < https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?end=2020&start=1990&view=cha>. Acesso em 12 de março de 2022.

EXTRACTIVES: CHALLENGES AND OPPORTUNITIES FOR THE SOUTH IN THE ENERGY TRANSITION

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Abstract

While the transition to a sustainable energy system will rely on a combination of additional deployment of existing technologies, deployment of new technologies, and development of innovative technologies, all will require an abundant, secure, and sustainable supply of minerals. The International Energy Agency noted that lithium, nickel, cobalt, manganese, and graphite are crucial to battery performance, longevity, and energy density. Rare earth elements are essential for permanent magnets for wind turbines and EV motors. Electricity networks need a considerable amount of copper and aluminum, with copper being a cornerstone for all electricity-related technologies. And iron and steel are critical for the renewal and improvements of infrastructure.

Countries with abundant mineral resources have a significant economic and workforce development opportunity as they contribute to the energy transition, the Paris Agreement's objectives, and the UN's Sustainable Development Goals. And at the same time, the challenge is to make mining and processing of extractives a sustainable industry that meets the growing demand for minerals with lower environmental impacts (lower emissions, lower water use, less waste).

Latin America is an important producer of critical minerals (copper, lithium, cobalt, and nickel), considering its current production levels and participation in the global reserves of copper, lithium, cobalt, and nickel.

Chile, Peru, and Mexico hold approximately 38% of the world's copper reserves, with additional reserves found in Argentina, Brazil, Colombia, and Ecuador. Approximately 60% of the world's identified lithium deposits are found in Latin America, mainly in Bolivia, Argentina, and Chile, and some in Mexico, Peru, and Brazil. Latin America also has significant nickel reserves, where Brazil hosts 17% of the world's nickel reserves and Cobalt in Mexico and in small quantities in Brazil.[3]

This paper analyses the challenges and opportunities that LAC, a region with abundant natural resources, will have in supporting a sustainable energy transition, a role that goes beyond enhancing its own energy matrix, the one with the lowest levels of CO2 emission, and is in its protagonist to sustainably deliver the critical minerals and cleaner fuels that the world needs to sustain the energy transition.

The presence of regionally abundant natural resources – both minerals and opportunities for expanded deployment of renewable energy (solar and wind) technologies for energy and clean fuels generation - can be a driver to transform the LAC into a Natural Laboratory for the innovation of clean technologies and improved processes, which in combination can make extractives more sustainable. Through the

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deployment of innovative technologies and integration of workforce development efforts, the region can address the main challenges confronted by extractives in the region, including the conflict related to resource governance, the distribution of socioeconomic benefits, and the environmental impacts, CO2 emissions, waste and water use, consultation with affected communities. Examples of how some countries are confronting these issues making extractives cleaner minerals sources to support the energy transition. Where, using science and the development of technologies, progress is made in giving greater added value to its natural resources, the country can climb in global supply chains and contribute to the objectives of the Paris Agreement and Sustainable Development of the UN.

References

- International Energy Agency (2021). World Energy Outlook Special Report, "*The Role of Critical Minerals in Clean Energy Transition*".
- ANAC (2020). Automotive Market Report, December.
- Associated Universities, Inc. (2021). www.aui.edu
- Bipartisan Policy Center (2021). Webinar "*Critical Minerals are Key in the Energy Transition*", July 27, Washington DC USA https://bipartisanpolicy.org/event/minerals-energy-transition/
- Carolina Llanos (2020), Natural laboratories: comparative advantages for Chile. A challenge for diplomacy and science. https://academiadiplomatica.cl/laboratorios-naturales-ventajas-comparativas-para-chile-un-desafio-para-la-diplomacia-y-la-ciencia/
- Center for Climate and Energy Solutions (2021). revised https://www.c2es.org/content/international-emissions/ 22/11/2021
- Centro de Desarrollo Energético Antofagasta CDEA (2021). https://www.cdeaua.cl/instalaciones/plataforma-solar-del-desierto-de-atacama-psda/
- Mining Council (2021). Updated mining figures.
- Council for Science, Technology and Innovation between Chile and the United States (2019). "*Report first year of work*". https://www.ecosisteam.cl/wp-content/uploads/2019/10/Informe-del-Consejo-CTI-Chile-Estados-Unidos-2019.pdf
- Corfo (2021). Center for the Development of Electromobility. https://www.corfo.cl/sites/cpp/convocatorias/centro_para_el_desarrollo_de_la_electromovilidad
- Corfo (2021). Macrozona Norte Circular Economy Center. https://www.corfo.cl/sites/cpp/convocatorias/centro_de_economia_circular_macro_zona_norte
- Corfo (2021). Call for Clean Technologies Institute, RFP phase https://www.corfo.cl/sites/cpp/convocatorias/instituto_de_tecnologias_limpias_fase_rfp
- Corfo (2021). https://www.corfo.cl/sites/Satellite?c=C_NoticiaNacional&cid=1476727520687&d=Touch&pagename=CorfoPortalPublico%2FC_NoticiaNacional%2FcorfoDetalleNoticiaNacionalWeb
- Chile's Fourth Biennial Update Report on Climate Change (2020), Ministry of the Environment – MMA -, Chile. https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/574160_Chile-BUR4-1-Chile_4th%20BUR_2020.pdf

- Dan Senor and Saul Singer (2011), "*Start-up Nation: The Story of Israel's Economic*". Council of Foreign Relations, Twelve Hachette Group Book, NY – USA
- Renewable Energies: The Journalism of Clean Energies (2021). Four consortia are proposed to develop the Chilean Institute of Clean Technologies https://www.energias-renovables.com/panorama/cuatro-consorcios-se-proponen-para-desarrollar-el-20200403https://www.energias-renovables.com/panorama/cuatro-consorcios-se-proponen-para-desarrollar-el-20200403
- Renewable Energies: The Journalism of Clean Energies (2021). An American university consortium in which MIT participates is awarded the Institute of Clean Technologies. https://www.energias-renovables.com/panorama/un-consorcio-universitario-estadounidense-del-que-participa-20210105
- European Southern Observatory (2021). The Extremely Large Telescope. https://elt.eso.org/
- Explora Comisión Nacional de Investigación Científica y Tecnológica (CONICYT) (2020). Chile's leading role in international astronomy. https://www.explora.cl/blog/el-rol-protagonico-de-chile-en-la-astronomia-internacional/
- Felipe Larrain (2018). Natural laboratories for Chile, newspaper La Tercera. https://www.latercera.com/pulso/noticia/laboratorios-naturales-chile/227792/
- Global Data (2020). Global lithium demand to more than double by 2024, as electric vehicle battery production quadruples. https://www.globaldata.com/global-lithium-demand-double-2024-electric-vehicle-battery-production-quadruples/
- GMTO Corporation (2021). Giant Magellan Telescope. https://www.gmto.org/
- World Bank Group (2020). Climate Smart Mining Facility, "*Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*".
- World Bank Group (2021). "*Potential solar energy by country"* https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country
- World Bank Group (2021). Open Data. https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm
- World Bank Group (2021). Open Data. https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS
  hydroelectric from Arica to Chile, Santiago.
- https://www.corfo.cl/sites/cpp/convocatorias/instituto_de_tecnologias_limpias_fase_rfp
- Hydrogen Council November (2017), "*A sustainable pathway for the global energy transition: Hydrogen scaling up*". https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf
- IDTechEx (2017). The Electric Vehicle Market and Copper Demand. https://copperalliance.org/wp-content/uploads/2017/06/2017.06-E-Mobility-Factsheet-1.pdf
- IEA (2020). "Energy Technology Perspectives 2020", Paris.
- IEA (2021). "Global EV Outlook 2021", Paris.
- IEA (2021). "The Role of Critical Minerals in Clean Energy Transitions", Paris. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions
- InvestChile (2021). Natural laboratory to test new technologies and sustainable businesses. https://investchile.gob.cl/es/porquechile/tendencia/

- José Miguel Aguilera R (2018). "*Laboratorios Naturales para Chile: Ciencia e innovación con ventaja*", ASIN: B07GNP22H9, Ediciones UC, Chile.
- Justin Miller and Lisa Viscidi (2016). "Innovation in Clean Energy in Latin America", Inter-American Dialogue and CAF - Development Bank of Latin America. http://www.thedialogue.org/wp-content/uploads/2016/02/Innovaci%C3%B3n-en-energ%C3%ADa-limpia-en-Am%C3%A9rica-Latina-3.pdf
- Lindsay Delevingne, Will Glazener, Liesbet Grégoir, and Kimberly Henderson (2020). "*Climate risk and decarbonization: What every mining CEO needs to know*". McKinsey Sustainability. https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know
- Minerals Council of Australia and Commodity Insights (May 2021). "*Commodity Demand Outlook 2030*": https://www.minerals.org.au/sites/default/files/Commodity%20Outlook%202030.pdf
- Chilean Mining (2018.) https://www.mch.cl/reportajes/los-detalles-del-acuerdo-corfo-sqm/ #
- Ministry of Energy of Chile (2017). National Electromobility Strategy. https://energia.gob.cl/electromovilidad
- Ministry of Energy of Chile (2020). National Green Hydrogen Strategy. https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf
- Ministry of Energy of Chile (2021). "*Solar Explorer Ministry of Energy Chile*": https://solar.minenergia.cl/mediciones
- Ministry of Energy of Chile (2021). Anuncio del cierre anticipado de plantas de generación de carbón. https://energia.gob.cl/noticias/nacional/ministro-juan-carlos-jobet-tras-historico-anuncio-de-cierre-adelantado-de-centrales-carbon-este-nuevo-hito-nos-acerca-cada-vez-mas-hacer-de-chile-un-pais-de-energias-limpias
- Ministry of Energy of Chile (2021). National Electromobility Strategy. https://energia.gob.cl/electromovilidad
- Ministry of Energy of Chile (2021). Law 21305 on Energy Efficiency. https://www.bcn.cl/leychile/navegar?idNorma=1155887
- Ministry of Energy of Chile / GIZ (2014). Renewable energies in Chile. The wind, solar and hydroelectric potential from Arica to Chile, Santiago.
- United Nations (2015). General Assembly resolution 70/1. Sustainable Development Goal. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E
- United Nations (2020). General Assembly resolution 74/225. https://undocs.org/en/A/RES/74/225
- OLADE (2019). At cop25 10 countries in Latin America and the Caribbean are committed to contribute to reach 70 of renewable energy in the region. http://extranet.olade.org/noticias/at-cop25-10-countries-in-latin-america-and-the-caribbean-are-committed-to-contribute-to-reach-70-of-renewable-energy-in-the-region/?lang=en
- Mining Portal (2015) Plataforma Solar Desierto de Atacama inaugurates the first stage of the project. http://www.portalminero.com/display/NOT/2015/08/19/Plataforma+Solar+Desierto+de+Atacama+inaugura+primera+etapa+del+proyecto
- Senate of Chile (2020). Draft law establishing the Framework Law on Climate Change. https://www.senado.cl/appsenado/templates/tramitacion/index.php?boletin_ini=13191-12

- National Electric System SEN. (2021) , http://energiaabierta.cl/visualizaciones/factor-de-emision-sic-sing/
- USGS (2021). Lithium Statistics and Information.

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[*PAPER TITLE*]

DETERMINING FACTORS OF ROAD TRANSPORT COSTS IN BRAZIL AND ASYMMETRY IN PRICE TRANSMISSION

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Overview

In Brazil, the fuel pricing process gained prominence with the New Pricing Strategy adopted by Petrobras in October 2016. Until then, there was some stability in the prices of oil derivatives and readjustments were infrequent. From this period on, Petrobras changed its methodology for pricing derivatives at its refineries, seeking to align short-term prices with the international market. As of July 2017, the readjustments became almost daily. This great volatility, added to successive increases in the price of derivatives, given the devaluation of the real against the dollar, culminated in the truck drivers' strike in May 2018, which spread across the country and blocked highways. The strike caused significant losses for the Brazilian economy, negatively impacting fuel supply, production, distribution of goods and provision of services.

The diesel crisis significantly impacted the national road freight market, highlighting the vulnerability in its structure and the importance of this market for the Brazilian economy, since Brazil is a country of continental dimensions and the road modal is the predominant transport system for the movement of people and goods. Of all the cargo transported in the country, approximately 65% is done by road, and the number of passengers transported represents approximately 46.7 million in 2020 (CNT, 2022). Furthermore, the cost of diesel represents more than 40% of the total cost of long-distance loads (CNT, 2022). Furthermore, the logistical dependence on diesel is significant and fuels play an important role in the country's tax collection, representing the largest source of taxes for the states.

The road transport sector faced difficulties due to the slowdown in economic activity, with a lower volume of cargo transported, and an excess supply of trucks, after several years of credit incentives given by the government (ANFAVEA, 2018). The overcapacity in the supply of road freight and the escalation of the price of diesel, which in less than a week accumulated a 5.85% increase in the price sold by Petrobras at its refineries, triggered the truck drivers' strike that lasted 10 days. In order to contain the negative impacts on social and economic activity, and to put an end to the strike, the government adopted a set of measures, including the diesel price subsidy program; tax reductions to ensure a reduction of R$ 0.46 in the price of diesel; exemption from charging for the suspended axle of empty trucks at tolls, valid for the entire national territory; guarantee that the Supply Company (CONAB) contracts 30% of its freight with self-employed truck drivers and the creation of a minimum price list for road freight. In addition, the National Treasury made R$9.5 billion available for the diesel subsidy program.

The scenario of difficulties in the business environment arising from the covid-19 pandemic, which began in 2020, the sequence of high fuel prices that accompanied the soaring price of oil in the international market and the devaluation of the Real (Brazilian currency) in 2021 , together with the economic issues arising from the Russian military invasion of Ukraine in February 2022, significantly impacted the fuel market through the increase and volatility of derivatives prices.

The scenario of difficulties in the business environment arising from the covid-19 pandemic, which began in 2020, the sequence of high fuel prices that accompanied the soaring price of oil in the international market and the devaluation of the Real (Brazilian currency) in 2021 , together with the economic issues arising from the Russian military invasion of Ukraine in February 2022, significantly impacted the fuel market through the increase and volatility of derivatives prices. In this sense, the fuel price crisis always motivates new discussions about the final price of derivatives to the consumer and highlights the way in which fuel prices are transmitted, especially diesel, which is an important input in national logistics being the higher cost of road freight transport.

The theoretical-empirical literature (BREMMER AND KESSELRING, 2016) points to the existence of price asymmetry in the fuel market and this asymmetry follows the “rock and balloon” pattern. That is, when the price of diesel drops at the pump, the price of freight starts to fall faster (rock effect). At the same time, when the price of diesel rises at the pump, the price of freight rises little (balloon effect). Therefore, this article aims to investigate how the asymmetry process occurs in Brazil in the transmission of diesel prices from the gas station (final price of diesel) to the road freight market for grains - corn and soybeans (freight price), in the period from January 2012 to June 2022. For this, the NARDL (*Nonlinear Autorregressive Distributed Lag*) methodology will be used.

Methods

The methodology used to investigate price transmission is the NARDL (*Nonlinear Autorregressive Distributed Lag*) model (SHIN, YU, GREENWOOD-NIMMO, 2014). Thus, in order to study the long-term relationships and the short-term dynamics between freight and diesel prices, in which there may be momentary departures resulting from the shocks of the long-term trajectory, the NARDL Model (p,q) can be expressed in the form of the Error Correction Model (MEYER and VON CRAMON TAUBADEL, 2004), as can be seen in Equation (1):

$$\Delta P_t^f = \rho P_{t-1}^f + \theta^+ P_{t-1}^{d+} + \theta^- P_{t-1}^{d-} + \sum_{j=1}^{p-1} \alpha_j \Delta P_{t-j}^f + \sum_{j=0}^{q-1} (\beta_j^+ \Delta P_{t-j}^{d+} + \beta_j^- \Delta P_{t-j}^{d-}) + \varepsilon_t \quad (1)$$

where: Δ indicates the first difference operator; P^f is the price of road freight; P^d is the price of diesel; α_j are the autoregressive coefficients; β_j^+ e β_j^- are the asymmetric coefficients with distributed lag; and ε_t is the error term.

In addition, the following tests will be performed:
If $\beta^+ > \beta^-$, positive asymmetry, there is a rocket and feather effect (BACON, 1991; TAPPATA, 2009);
If $\beta^+ < \beta^-$, negative asymmetry, there is a rock and balloon effect (BREMMER AND KESSELRING, 2016); and,
If $\beta^+ = \beta^-$ has no asymmetry.

Results

Diesel is a relevant component in the formation of the cost of freight transport. In this sense, it is expected to find negative asymmetry and the balloon effect, which shows the difficulty of truck drivers in passing on positive diesel price adjustments in a complete and instantaneous way, because there are many competitors in the road freight market (excess supply). If the truck driver passes on the entire price increase, he will lose customers to his competitor. Thus, the balloon effect motivated the 2018 truck drivers strike.

Conclusions

There are several components that make up the cost of road transport, such as distance, toll and operating costs (fuel, tire, maintenance, labor, truck insurance, depreciation, etc.). Thus, it is difficult to identify and measure all costs related to transport activities, so passing on the increase in input prices to the value of freight is not an easy task. In this sense, it is complex to clearly and objectively accommodate all the variables that determine the price of road freight, together with their particularities, in a table of minimum prices for road freight, while such a table, in addition to generating distortions in the freight market, ends up not solving the source of the problem, which is the excess capacity of road freight transport. In addition, the analysis is important to assist in the construction of specific public policies for the sector aimed at reducing the cost of transport and the consequent increase in competitiveness.

Finally, to solve the truck drivers problem, the government must adopt specific public policies, reduce the oversupply of trucks, which is the main problem in the road freight market, and adopt flexible taxation to accommodate the volatility of fuel prices. . By accommodating volatility, you end up accommodating readjustments, and by mitigating readjustments, you end up mitigating balloon effects as well.

References

ANFAVEA – Associação Nacional dos Fabricantes de Veículos Automotores (2018). Anuário da Indústria Automobilística 2018. São Paulo: ANFAVEA. Available in: http://www.virapagina.com.br/anfavea2018/. Accessed in: july, 2022.
BACON, R. W. (1991). Rockets and feathers: the asymmetric speed of adjustment of UK retail gasoline prices to cost changes. Energy Economics, 13, issue 3, pp. 211-218.
BREMMER, D. S.; KESSELRING, R. G. (2016). The relationship between US retail gasoline and crude oild prices during the Great Recession: "rockets and feathers" or "ballons and rocks"? Energy Economics, v. 55, pp. 200-210.
CNT – CONFEDERAÇÃO NACIONAL DO TRANSPORTE (2022). Boletins Técnicos CNT. Available in: https://www.cnt.org.br/. Accessed in: july, 2022.
MEYER, J., VON CRAMON-TAUBADEL, S. (2004). Asymmetric price transmission: a survey. Journal of Agricultural Economics, Oxford, v. 55, n. 3, p. 581-611.
SHIN, Y., YU, B., & GREENWOOD-NIMMO, M. (2014). Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ardl framework. In Festschrift in Honor of Peter Schmidt (pp. 281–314). Nova York: Springer.
TAPPATA, M. (2009). Rockets and feathers: understanding asymmetric pricing. The RAND Journal of Economics, v.40, n. 4, pp. 673-6.

Artigo 8ELAEE

Impacto da criminalidade na implantação de um serviço de e-Carsharing em cidades latino-americanas: o caso do Rio de Janeiro

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Resumo:

O presente estudo tem como objetivo analisar a interferência da criminalidade urbana no processo de seleção das áreas mais indicadas para a prestação do serviço de e-Carsharing. Com esta finalidade, este trabalho utiliza a metodologia SMARTER para classificar os bairros da cidade do Rio de Janeiro quanto a implementação de um serviço de e-*Carsharing*. Os resultados apontam para uma concentração dos melhores bairros em uma região específica da cidade (Área de Planejamento 2), concentração esta, que é amplificada quando leva-se em conta o critério de criminalidade. Portanto, conclui-se que, no Rio de Janeiro, a criminalidade poderá impactar a escolha das áreas para a instalação de bases operacionais de um serviço de *e-Carsharing*. Como desdobramento, isto poderá reduzir a viabilidade econômica do empreendimento ou até mesmo inviabilizá-lo.

Palavras-chaves: e-Carsharing; Criminalidade Urbana; Rio de Janeiro

Abstract:

The present study aims to analyze the interference of urban crime in the selection process of the most suitable areas for the provision of the e-Carsharing service. For this purpose, this work uses the SMARTER methodology to classify the neighborhoods of the city of Rio de Janeiro regarding the implementation of an e-Carsharing service. The results point to a concentration of the best neighborhoods in a specific region of the city (Planning Area 2), a concentration that is amplified when the crime criterion is taken into account. Therefore, it is concluded that, in Rio de Janeiro, crime may impact the choice of areas for the installation of operational bases of an e-Carsharing service. As a consequence, this could reduce the economic viability of the enterprise or even make it unfeasible.

Key-words: e-Carsharing; Urban Crime; Rio de Janeiro

1. Introdução

A pauta climática redirecionou o debate acadêmico acerca do uso dos recursos energéticos em todo mundo. Dentre os temas deste campo, destaca-se a mobilidade urbana e o atual paradigma de substituição dos veículos a combustão por veículos elétricos (VEs) na esfera local. Neste sentido, governos locais vêm

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oferecendo incentivos como a diminuição de impostos e isentando os proprietários de VEs das tarifas de estacionamentos em locais públicos, assim como permitindo a utilização das faixas de rodagem preferenciais.

Se por um lado os VEs são importantes agentes na redução das emissões de gases de efeito estufa do setor de transporte, por outro, o seu preço de aquisição e a dificuldade em se desenvolver uma rede de infraestrutura pública de recarga ainda são importantes barreiras para a sua massificação. Em decorrência disso, modelos de negócios de economia compartilhada, como o *e-Carsharing*, vem observando um importante crescimento em grandes centros urbanos. Segundo Luo *et al*. (2022), o *carsharing* é um modelo de serviço de aluguel de veículos no qual os usuários podem utilizar este bem sem a necessidade de adquiri-lo. Além disso, os usuários não precisam ser responsáveis por sua manutenção e/ou estacionamento.

Assim, o compartilhamento de veículos é um recurso que busca dispor sobre a decisão de desistência da aquisição de carros particulares em detrimento da utilização de veículos compartilhados, que entregam menor custo de viagem, menores taxas de acidentes e menores índices de congestionamentos (WEBB *et al*., 2019). Shaheen e Cohen (2012) identificaram uma série de influências para a escolha deste tipo de serviço que incluem as incertezas econômicas, os custos crescentes com manutenções, os esforços para aumentar a eficiência dos veículos e a redução das emissões dos gases de efeito estufa (GEE).

No entanto, ainda que o *carsharing* possa resultar em soluções adequadas sob a ótica financeira e ambiental, alguns desafios devem ser endereçados para sua implantação efetiva nas cidades brasileiras. Dentre estas questões, destaca-se a necessidade de uma alta taxa de utilização, assim como a identificação e seleção de suas infraestruturas de recarga (GALATOULAS *et al*., 2018). Uma vez que tanto os veículos quanto seus pontos de recarga representam um grande investimento de capital, fatores como a redução do risco de depredação e roubo devem ser prioritários quando de sua concepção.

Neste sentido, o presente estudo tem como objetivo analisar a interferência da criminalidade urbana no processo de seleção das áreas mais indicadas para a prestação do serviço de e-*Carsharing*. Com esta finalidade, este trabalho utiliza a metodologia SMARTER para classificar os bairros da cidade do Rio de Janeiro quanto a implementação de um serviço de e-*Carsharing*.

Este trabalho está dividido em seis seções, onde a primeira corresponde a esta introdução e a segunda faz uma conceituação sobre o serviço de *Carsharing*. Na terceira e quarta seções são examinados os impactos da criminalidade no carsharing e apresentação da metodologia SMARTER, respectivamente. Na quinta seção são apresentados os resultados e, finalmente, na sexta seção é feita uma conclusão do estudo.

2. Conceituação de Carsharing

Apresentando uma tendência de utilização crescente em território brasileiro, o desenvolvimento dos serviços de *carsharing* têm sido objeto de revisões sistemáticas de literatura (NANSUBUGA e KOWALKOWSKI, 2021). Tendo sua primeira experiência registrada ocorrido em 1948 em Zurique, Suíca (HARMS e TRUFFER, 1998) a partir de um grupo privado de indivíduos.

Entre as variações dos modelos de *carsharing*, destacam-se duas categorias principais: os modelos ne negócio e os modelos logísticos. Os modelos de negócio são caracterizados por uma série de arranjos realizados entre os ofertantes e os consumidores que por sua vez qualificam o serviço, como sua estruturação em formato de cooperativas ou intermediada pela tecnologia da informação (SHAHEEN *et al*. 1999). Os modelos logísticos por sua vez ocupam-se dos meios pelos quais a oferta de veículos será espacialmente disponibilizada. Dentre as opções adotadas por este modelo encontram-se o *one-way* ou *round-trip* (WU et al, 2020.; BOYACI *et al*., 2015), nos quais o veículo é retirado em uma estação de distribuição e entregue em outra e no qual é retirado e devolvido na mesma estação, respectivamente.

Com a finalidade de aprofundar a conceituação e caracterização do serviço de *carsharing*, as duas subseções abaixo tratarão de forma pormenorizada os aspectos relacionados aos modelos de negócio e logísticos aplicados ao *carsharing*, descrevendo suas particularidades e contrastando suas diferenças.

2.1. Modelos de negócio aplicados ao carsharing

O modelo de negócios é a forma com a qual uma organização articula seus valores, serviços/produtos e organização entre receitas e despesas (TEECE, 2010). Neste sentido, a pluralidade de serviços de *carsharing* que se desenvolveu após os primeiros experimentos do setor foi capaz de adequar suas características em diferentes modelos de negócio. Com fins de sintetizá-los, é possível aglutinar estes modelos em quatro categorias principais descritas no quadro 1, sendo elas a Negócio para Consumidor (B2C), Negócio para Negócio (B2B), Cooperativas e Pessoa para Pessoa (P2P).

Quadro 1: Modelos de Negócio aplicados ao serviço de carsharing

Modelo de negócio	**B2C**	**B2B**	**Cooperativa**	**P2P**
Exemplos	Zipcar (Estados Unidos), ShareNow (Alemanha)	ShareNow (Alemanha), Volvo car mobility (Suécia)	Modo (Canadá)	Getaround (Estados Unidos), Turo (Estados Unidos)
Serviços	Fornece aos indivíduos o acesso a veículos sem os custos de propriedade	Fornece às organizações o acesso a veículos para fins profissionais sem os custos	Fornece às comunidades o acesso à veículos sem os custos de propriedade	Fornece o acesso aos indivíduos com custos inferiores aos B2C. Proprietários de

		de propriedade		veículos podem utilizar este modelo para abater seu custo de propriedade.
Recursos Chave	Frota de carros, gestão da frota, redes de atendimento	Frota de carros, frota gestão, rede de serviços, gestão da contratação	Frota de carros, rede de membros	Plataforma de tecnologia da informação, cobertura de seguro e assistência, ampla variedade de serviços
Mecanismo de receita	Assinatura mensal ou pay-per-use	Contrato	Assinatura anual ou taxa mensal	Pay-per-use
Investimento requerido para retirada e devolução dos veículos pelo operador	Alto	Alto	Moderado	Baixo
Manutenção e Limpeza dos veículos	Ofertante	Ofertante	Obrigações contratuais	Proprietário do veículo

Fonte: Adaptado de Nansubuga e Kowalkowski (2021), Wilhelms et al. (2017) e Hahn et al. (2020)

O modelo B2C é o mais simples entre os abordados, sendo composto por uma empresa proprietária e ofertante dos veículos e seu público consumidor, que os aluga por um curto período (MUNZEL et al., 2018). Os serviços ofertados por esta modalidade costumam ser remunerados a partir de seu uso, sendo cada consumidor individual responsável por arcar com os custos do período de locação utilizado.

O modelo B2B é caracterizado por uma associação entre a empresa proprietária/ofertante dos veículos e uma empresa de setor distinto interessada na locação de veículos para desenvolver suas atividades (CLARK *et al.*, 2015; FLEURY *et al.*, 2017). O sistema de remuneração deste modelo difere do anterior, sendo pautado por um contrato firmado entre as partes que remunera a disponibilidade de toda a frota locada.

O modelo de Cooperativa é o que mais se distingue dos demais na medida em que não é voltado para a obtenção de lucro. Neste modelo, membros de uma determinada comunidade se unem em uma rede de indivíduos proprietários de veículos e indivíduos com necessidade de deslocamento (NITSCHKE, 2020; COHEN e KIETZMANN, 2014;). Esta rede pode ser formada por associações de moradores, grupos de estudantes, grupos de vizinhos e associações religiosas. Normalmente os membros destas redes pagam uma taxa anual pela utilização deste serviço, que também pode receber financiamento governamental dado seu caráter social e sem fins lucrativos.

Finalmente, o modelo Pessoa para Pessoa (P2P) é composto por indivíduos proprietários de veículos e indivíduos com interesse em alugá-los. Neste modelo, o proprietário do veículo não é uma empresa, mas sim um indivíduo que utiliza plataformas de tecnologia da informação para encontrar consumidores que desejem alugar seus veículos por um período pré-determinado (BARNES e MATTSSON, 2016; HAMARI *et al.*, 2016). que, em geral, também pode atuar como motorista durante o percurso da viagem solicitada. Apesar da redução dos custos contratuais presentes nos modelos B2C e B2B, o custo deste serviço sofre um aumento devido ao repasse obrigatório à empresa responsável pela provisão de tecnologia da informação que direciona às solicitações do passageiro ao proprietário do veículo.

2.2. Aspectos logísticos dos modelos de negócio

Assim como os modelos de negócio podem ser descritos a partir de quatro categorias fundamentais, os modelos logísticos do *carsharing* também se desdobram em quatro categorias distintas. De acordo com Nansubuga e Kowalkowski (2021) os modelos logísticos podem ser compreendidos a partir de suas categorias de localização e relocalização, ou seja: de onde se retira e onde se devolve os veículos utilizados.

A flexibilidade dos modelos de *carsharing* permite ao ofertante a seleção do modelo mais adequado às suas estratégias (MOEIN e AWASTHI, 2020; MULLER *et al.*, 2017). Neste sentido, é realizada abaixo (Quadro 2) uma descrição pormenorizada das quatro categorias de modelos logísticos vigentes:

Quadro 2: Modelos Logísticos aplicados ao serviço de *carsharing*

Modelos logísticos de carsharing			
ONE-WAY	**ROUND TRIP**	**FREE FLOATING**	**FREE FLOATING ZONE**

Um trecho	Ida e volta	Um trecho	Um trecho
Várias estações para retirada do veículo	Várias estações para retirada do veículo	Retirada do veículo em qualquer lugar	Retirada do veículo em qualquer lugar pré-determinado
Devolução em qualquer estação	Devolução na mesma estação de retirada do veículo	Devolução em qualquer lugar	Devolução em qualquer lugar em uma área pré-determinada
Aluguel por app	Aluguel por app / internet ou em lojas	Aluguel por app	Aluguel por app
Picos de demanda durante os dias de semana e horários de almoço	Picos de demanda durante os dias de semana e horários de almoço	Picos de demanda durante os dias de semana e horários de almoço	Picos de demanda durante os dias de semana e horários de almoço
Frota própria de veículos	Frota própria de veículos	Não necessita de frota própria de veículos	Não necessita de frota própria de veículos

Fonte: França *et al*. (2021)

O modelo logístico *one-way* é caracterizado pelo início do percurso em uma estação de retirada de veículos e sua finalização em outra (SHAHEEN *et al*. 2015). Apesar de oferecer praticidade ao usuário ao não requerer sua devolução na mesma estação, este modelo restringe as possibilidades de viagens do consumidor ao exigir que seu destino final seja a estação de devolução (BOYACI *et al*., 2015).

O modelo *round trip* é mais restritivo que o anterior, exigindo que o usuário realize uma viagem ida e volta e entregue o veículo na mesma estação em que o retirou (ALENCAR *et al*., 2019). Neste sentido, o perfil de consumidores desta modalidade acaba sendo o de clientes com necessidade de realizar viagens com tempo e distâncias maiores (GIORGIANI *et al*., 2020), como por exemplo ida e volta a uma cidade vizinha, devolvendo o veículo na cidade em que a viagem se originou.

O modelo logístico *free-floating* é o que permite maior flexibilidade ao usuário dentre os demais, posto que este pode devolver o veículo em qualquer ponto (HEILIG *et al*., 2018). Neste sentido, esta modalidade atende preferencialmente aos consumidores de viagens esporádicas e de percurso irregular (BECKER *et al*., 2018). Apesar da flexibilidade oferecida, esta modalidade é a que enfrenta maiores obstáculos logísticos para provisão e manutenção da frota, dado que a imprevisibilidade de sua localização dificulta sua gestão eficiente (KYPRIADIS *et al*. 2020).

Finalmente, o modelo *free-floating zone* busca oferecer a liberdade de escolha do modelo *free-floating* e as vantagens de previsibilidade espacial do modelo *round-trip* ao permitir que o usuário inicie e finalize sua viagem em qualquer estação disponível dentro de uma base situada em um recorte geográfico específico (HEILIG *et al*., 2018). Neste sentido, Alencar *et al* (2019) aponta que este modelo possui maior atração sobre os consumidores com viagens esporádicas dentro de limites fixos e regulares, como entre bairros de uma mesma cidade.

3. Desafios e oportunidades do *e-Carsharing* na cidade do Rio de Janeiro

Seguindo a tendência internacional de desenvolvimento do serviço de *carsharing*, a cidade do Rio de Janeiro tem observado um consumo crescente deste setor (PORTUGAL e GOLDNER, 2013). Este fenômeno tem atendido a demandas ambientais e urbanísticas de redução do tráfego e emissão de poluentes atmosféricos, constando em seu Plano Diretor de Desenvolvimento Urbano Sustentável, estabelecido pela lei complementar nº 111 de 01/02/2011 e pela sua Política Municipal de Mudanças Climáticas, instituída pela lei nº de 5.248 de 27 de novembro de 2011.

No entanto, fatores exógenos à elaboração de políticas públicas atuam como condicionantes da expansão do *carsharing* na cidade do Rio de Janeiro (BATISTA, 2003; AMARAL, 2010). Dentre os principais fatores investigados consta o alto índice de violência urbana, que limita tanto a demanda como a oferta do serviço. Este complicador, no entanto, está heterogeneamente distribuído pela cidade, cujas diferentes regiões apresentam graus maiores ou menores de criminalidade (AMARAL, 2010; EMILIANO *et al*. 2020). Esta dispersão do fenômeno baliza, por sua vez, a propensão dos provedores de *carsharing* em ofertar seus serviços em determinada área, a depender do grau de risco percebido como aceitável.

O fenômeno de seleção espacial do *carsharing* em uma grande cidade, como é o caso do município do Rio de Janeiro, se agrava quando este serviço é caracterizado pela eletromobilidade, posto que esta qualificação exige um alto grau de investimento tanto em sua aquisição e instalação quanto para sua manutenção. Neste sentido, tornam-se necessárias análises sofisticadas de geolocalização da oferta dos veículos e de suas bases com as infraestruturas de recarga (eletropostos) para reduzir as incertezas do investidor e ao mesmo tempo atrair consumidores potenciais (BECKER *et al*., 2017; HU *et al*. 2018).

3.1. Impacto da violência no serviço de *e-Carsharing*

Dada a flexibilidade dos serviços de *carsharing* ao selecionar os modelos logísticos e de negócios mais atrativos para sua operação, iniciativas com diferentes perfis de *carsharing* passaram a oferecer seus serviços em diversas localidades.

Sob a ótica da revisão da literatura especializada no desenvolvimento deste setor, Nansubuga e Kowalkowski, 2021 (2021) sintetizam os estudos mais relevantes em quatro eixos de análise: modelos de negócio; comportamento do usuário; balanceamento dos veículos e forças e barreiras.

Conforme descrito na primeira seção deste trabalho, os modelos de negócio são as estratégias utilizadas pelos ofertantes de *carsharing* ao estruturar seu serviço. Nesta dimensão são analisados e comparados os elementos próprios de cada modelo, como modalidades de pagamento; aspectos jurídicos pertinentes à locação do veículo; custos transacionais; variedade da frota e cobertura espacial da rede atendida.

Os estudos que compõem o eixo “comportamento do usuário” ocupam-se de identificar as características dos usuários que demandam este serviço, como idade; renda; propósito de viagem e frequência de uso. De acordo com De Luca e Di Pace (2015); Hjorteset e Bocker (2020) e Tyndall (2017) o perfil predominante de usuário dos serviços de *carsharing* é jovem, masculino, pertencente a classe média, com alto grau de instrução e habitante de residências com tamanho acima da média – o que pode explicar tanto sua propensão ao gasto com deslocamento como o conhecimento necessário para acessar estes serviços, como ferramentas e aplicativos virtuais, acesso à internet móvel e internet banking. Sob o aspecto locacional, a predominância dos usuários deste serviço se encontra em grandes centros urbanos, o que favorece a solicitação de corridas curtas e com propósito sazonal, como lazer e acesso a centros médicos ou religiosos (PRIETO *et al*., 2017).

O eixo de estudos relativos ao “balanceamento de veículos” analisa a dinâmica entre demanda e oferta de veículos de *carsharing* em uma determinada região. Neste sentido, o foco principal deste campo de estudos identifica e pondera a participação de diferentes fatores na busca do equilíbrio entre oferta e demanda, como os processos de localização das estações de retirada e devolução dos veículos, eixos atrativos de viagem e proporção ideal entre os consumidores potenciais e número de veículos ofertados. Integrando um eixo de investigações voltado principalmente para o aspecto logístico dos serviços de *carsharing*, estas investigações avaliam os efeitos do aumento e flexibilização dos pontos de retirada e devolução dos veículos (NAIR e MILLER-HOOKS, 2011), bem como o desenvolvimento e otimização de modelos matemáticos preditivos de demanda, pois permitem ao ofertante disponibilizar seus veículos em locais com o maior fluxo de consumidores (MOEIN e AWASTHI, 2020; MULLER *et al*., 2017).

Finalmente, o campo de análise correspondente às forças e barreiras se ocupa em identificar as principais vantagens oferecidas pelo *carsharing* atratoras de usuários, bem como os fatores que afastam e/ou reduzem a inclinação de uso do *carsharing* por seus consumidores potenciais. Neste sentido, esta área de estudos concentra as investigações a respeito de como reforçar os estímulos positivos ao consumidor e minorar os aspectos redutores de consumo. Para tanto, é avaliada a qualidade do serviço prestado (FLEURY *et al*, 2017), percepção e sensibilidade do usuário aos benefícios ambientais (KIM *et al*. 2017, MUNZEL *et al*., 2020; JULSRUD e FARSTAD, 2020). De acordo com os resultados obtidos, os usuários do *carsharing* se mostram altamente sensíveis à qualidade do serviço prestado, que engloba aspectos como o comportamento do motorista e características do veículo, relatando os benefícios ambientais associados apenas em segundo plano.

Além dos eixos de análise descritos acima, a literatura tem se ocupado recentemente dos efeitos trazidos pela adoção de veículos elétricos em suas frotas. Constituindo uma modalidade de transportes em expansão, os veículos elétricos apresentam uma série de vantagens, como a redução de emissão de gases de efeito estufa.

Dado que os custos de aquisição dos veículos elétricos ainda se situam em patamares significativamente superiores à sua alternativa movida por combustão interna, o *carsharing* se mostra uma solução viável para o usuário que deseje utilizar este serviço sem incorrer em sua compra. No entanto, esta vantagem também implica em uma fragilidade para o operador, dado que eventuais danos incorridos pelos veículos ou infraestrutura de recarga oriundos da violência urbana representam um risco financeiro superior em comparação aos veículos tradicionais.

Neste sentido, Barros (2017) discute o aspecto de segurança aplicado ao *e-Carsharing* brasileiro, avaliando que o conhecimento insuficiente dos riscos associados ao serviço impede que as operadoras de seguro ofertem produtos pertinentes a este setor. Ainda neste aspecto, a autora aponta a indefinição das distribuições de competências entre as instituições envolvidas no processo de securitização do *e-Carsharing*, ocasionando dúvidas sobre o escopo de atuação e distribuição de responsabilidades entre atores como guarda civil municipal, polícia militar, usuário, companhias de seguros e empresários de *e-Carsharing*.

Ainda que este campo de investigação não esteja plenamente amadurecido, estudos desenvolvidos por Galhadardi (2021); Auer *et al*. (2020) e Associação das Empresas de Transportes Urbanos (NTU, 2021) demonstram que as depredações sofridas pelos ônibus brasileiros de transporte coletivo no período 2004-2022 implicaram em perdas econômicas de aproximadamente R$ 1,1 bilhão, conforme demonstra o Gráfico 1:

Figura 1 - Gráfico do Custo associado aos ônibus brasileiros incendiados no período 2004-2022

Fonte: NTU (2021)

Nota [1] : O custo total é a somatória do custo dos passageiros não transportados, do custo para reposição dos veículos e do custo das horas não trabalhadas pelos passageiros que deixaram de ser transportados nos dias das ocorrências dos incêndios. (Assumiu-se o custo de R$ 10,20 da hora trabalhada (IBGE,2021)).

De acordo com Galhadardi (2021) o fator segurança pública é especialmente relevante na matriz de transporte brasileira posto que seus operadores frequentemente ficam expostos a depredações orquestradas por grupos criminosos em represália a ações policiais conduzidas pelo Estado. Neste sentido tem-se que os sistemas de e-*Carsharing* que busquem operar na cidade do Rio de Janeiro compreendam em seus modelos de negócio estratégias para evitar e/ou mitigar os custos potenciais relativos à violência urbana, dado que os consumidores deste serviço se mostram altamente sensíveis a este aspecto no momento de decisão pelo consumo (BONALDO, 2021). Para tanto, na seção seguinte é descrita e modelada uma simulação de localização preferencial para o *carsharing* na cidade do Rio de Janeiro utilizando o fator de segurança pública como um dos critérios considerados, descrevendo os resultados encontrados e gerando conclusões sobre a análise empreendida.

4. Metodologia:

Basicamente, a ideia do estudo é construir dois cenários de ranqueamento – com e sem a dimensão da criminalidade – dos bairros mais indicados do Rio de Janeiro para receber um serviço de *e-Carsharing* e comparar a sua composição. A cidade do Rio de Janeiro possui 136 bairros, onde residem 6,748 milhões de pessoas.

Tendo em vista a subjetividade e complexidade do tema abordado, escolheu-se a metodologia de estatística multicritério para tratar o problema. Mais especificamente, utilizou-se o método SMARTER (Simple Multi-Attribute Rating Technique using Exploiting Rankings) multicritério de apoio à decisão, proposto por Edwards e Barron (1994). A escolha do método em questão se justifica por sua simplicidade e a característica de produzir *outputs* em forma de ranking, o que permite realizar a classificação dos bairros da cidade. Adicionalmente, o método não necessita de entrevistas na fase de definição de preferências (como o método AHP – Analytic Hierarchical Process) e facilita a definição de preferências diminuindo a subjetividade do problema.

Esta metodologia ordena os critérios são ordenados em ordem de preferência, onde o peso do k-ésimo (w_k) é calculado conforme equação 1:

$$w_k = \left(\frac{1}{k}\right)\sum_{i=1}^{k}\frac{1}{i}\ sendo\ w_1 \geq w_2 \geq \cdots \geq w_k \qquad (1)$$

Sendo k o número de critérios. Depois da atribuição dos pesos, o ranqueamento terá como base os valores calculados pela utilidade multiatributo, cujo cálculo é demonstrado pela equação 2:

$$U(a) = \sum_{j} w_j u_{,}(a) \qquad (2)$$

O grande diferencial desta metodologia em relação à programação matemática, metodologia alternativa, é a sua capacidade de lidar com questões subjetivas e que trazem imprecisões para a avaliação. Neste sentido, observa-se uma consistente aplicação da metodologia SMATER na avaliação de unidades de negócio, tais como restaurantes (ZUHEROS *et al*., 2021) e unidades de serviço (LOPES e ALMEIDA, 2008).

Em relação aos dados utilizados neste estudo, eles correspondem a microdados extraídos de bases públicas contabilizados para o ano de 2020, organizados pelos bairros da cidade do Rio de Janeiro.

A base de dados utilizada foi extraída de França *et al*., (2022). Entretanto, o ordenamento foi modificado, pois os autores deste trabalho preferiram adotar uma postura mais conservadora ao inserir a criminalidade no modelo. Esta foi inserida como o último critério, possuindo assim menor peso dentre todos os critérios utilizados. As variáveis utilizadas neste trabalho são apresentadas na tabela 1, onde é demonstrada a ordem de importância definida para o estudo.

Tabela 1 – Ordenamento dos critérios utilizados

Ordenamento	Critérios	Descrição da variável	Fonte
1	IDH	IDH calculado para a localidade.	IPP, 2010
2	População	Quantidade de pessoas residentes.	Data Rio, 2020
3	Shoppings Centers	Quantidade de Shoppings Centers.	TripAdvisor, 2020
4	Supermercados	Somatório da quantidade de mercados, supermercados e hortifrutis.	Google Maps, 2020
5	Turismo	Quantidade de pontos turísticos ponderados pelo seu grau de importância (Quantidade de "check in").	Rio 20, 2020
6	Criminalidade	Total de registros de ocorrências contabilizadas.	ISP, 2020

Cabe ressaltar que a tabela 1 reflete o ordenamento do cenário 2, o qual leva em conta a criminalidade como um critério. Para o cenário 1, suprimiu-se o critério criminalidade e manteve-se a ordem dos demais critérios. Sobre a definição da criminalidade como o critério mais importante, isto é fundamentado pelo grande impacto da violência na depredação dos meios de transporte público, como indicado pelos estudos de Amaral (2010), Batista (2003) e Galhadardi (2021), presentes na seção 3 deste trabalho.

Por fim, cumpre informar que a análise foi executada utilizando o software Microsoft Excel.

5. Resultados:

Tendo em vista a equação 1, os primeiros resultados apresentados nesta seção se referem aos pesos atribuídos a cada uma das dimensões de análises utilizadas na simulação multicritério deste estudo. Portanto, na tabela 2 são apresentados os resultados obtidos para o Cenário 1 (sem a dimensão de criminalidade) e para o cenário 2 (com a dimensão criminalidade):

Tabela 2 - Pesos

Dimensão	Pesos Cenário 1 (Sem Crime)	Pesos Cenário 2 (Com Crime)
IDH	0,46	0,41
POPULAÇÃO	0,26	0,24
SHOPPINGS	0,16	0,158
MERCADO	0,09	0,103
TURISMO	0,04	0,06
CRIME	-	0,03

Fonte: elaboração própria

É importante notar que esses pesos são atribuídos automaticamente pela metodologia, tendo em vista a ordem e quantidade de dimensões de análises que são organizadas. Desta forma, verifica-se que, no cenário 2, com a inclusão de criminalidade, os pesos das cinco primeiras dimensões serão reduzidos em sua magnitude. Isto fará com que se observe uma redução da pontuação final dos bairros obtida a partir delas e um crescimento daquelas com menores índices de criminalidade.

O ranqueamento da unidade multiatributo calculada através da equação 2 é demonstrada nas tabelas 3 e 4. Nelas são dispostos os quinze bairros mais bem ranqueados, com suas informações da área de planejamento da cidade na qual estão inseridas e o valor calculado da utilidade multiatributo.

Tabela 3 - Resultados Cenário 1 (Sem Criminalidade)

Bairro	Área de Planejamento	Utilidade Multiatributo
Barra da Tijuca	AP 4 (Baixada de Jacarepaguá)	0,7047
Campo Grande	AP 5 (Zona Oeste)	0,6935
Centro + Lapa	AP 1 (Centro)	0,6854
Botafogo	AP 2 (Zona Sul e Grande Tijuca)	0,6753
Copacabana	AP 2 (Zona Sul e Grande Tijuca)	0,6323
Urca	AP 2 (Zona Sul e Grande Tijuca)	0,5599
Tijuca	AP 2 (Zona Sul e Grande Tijuca)	0,5585
Ilha do Governador	AP 3 (Zona Norte)	0,5323
Leblon	AP 2 (Zona Sul e Grande Tijuca)	0,5249
Catete	AP 2 (Zona Sul e Grande Tijuca)	0,5234
Bangu	AP 5 (Zona Oeste)	0,5165
Laranjeiras	AP 2 (Zona Sul e Grande Tijuca)	0,5118
Flamengo	AP 2 (Zona Sul e Grande Tijuca)	0,5092
Ipanema	AP 2 (Zona Sul e Grande Tijuca)	0,5053
Recreio dos Bandeirantes	AP 4 (Baixada de Jacarepaguá)	0,5051

Fonte: elaboração própria

A tabela 3 mostra que, no cenário 1, a Barra da Tijuca foi o bairro mais bem avaliado. Isto deve-se ao seu IDH ser um dos nove mais altos e por ser o bairro com o maior número de shoppings do Rio de Janeiro, fatores estes considerados relevantes para a implantação do serviço em análises anteriores (BONALDO, 2021; DE LUCA e DI PACE, 2015). Por outro lado, Campo Grande, segundo colocado, é o bairro com o maior contingente populacional e ocupa a vigésima primeira posição em IDH no município. Fechando as três primeiras posições, tem-se a área que compreende os bairros do Centro e Lapa. Juntos, eles detêm o maior número de pontos turísticos, assim como possuem boa pontuação nos demais critérios.

A partir das informações obtidas, torna-se necessária uma análise comparativa entre as regiões urbanas presentes no município do Rio de Janeiro com fins de melhor compreender sua lógica de socioespacialização de fenômenos como a criminalidade, identificando, portanto, como as oportunidades de negócios (oferta de veículos elétricos) se distribui a partir deste indicador. Neste sentido, os bairros identificados podem ser analisados a partir das Áreas de Planejamento presentes no Plano Diretor do município do Rio de Janeiro. Constituindo um instrumento fundamental para a condução das políticas de urbanização e expansão viária, o Plano Diretor é nacionalmente instituído pela Lei nº 10.257 de 10 de julho de 2001, sendo obrigatório para as cidades brasileiras com mais de vinte mil habitantes. Neste sentido, o Plano Diretor do município do Rio de Janeiro divide a cidade em cinco Áreas de Planejamento (APs), sobre as quais se distribuem seus 136 bairros, conforme demonstra a figura 1:

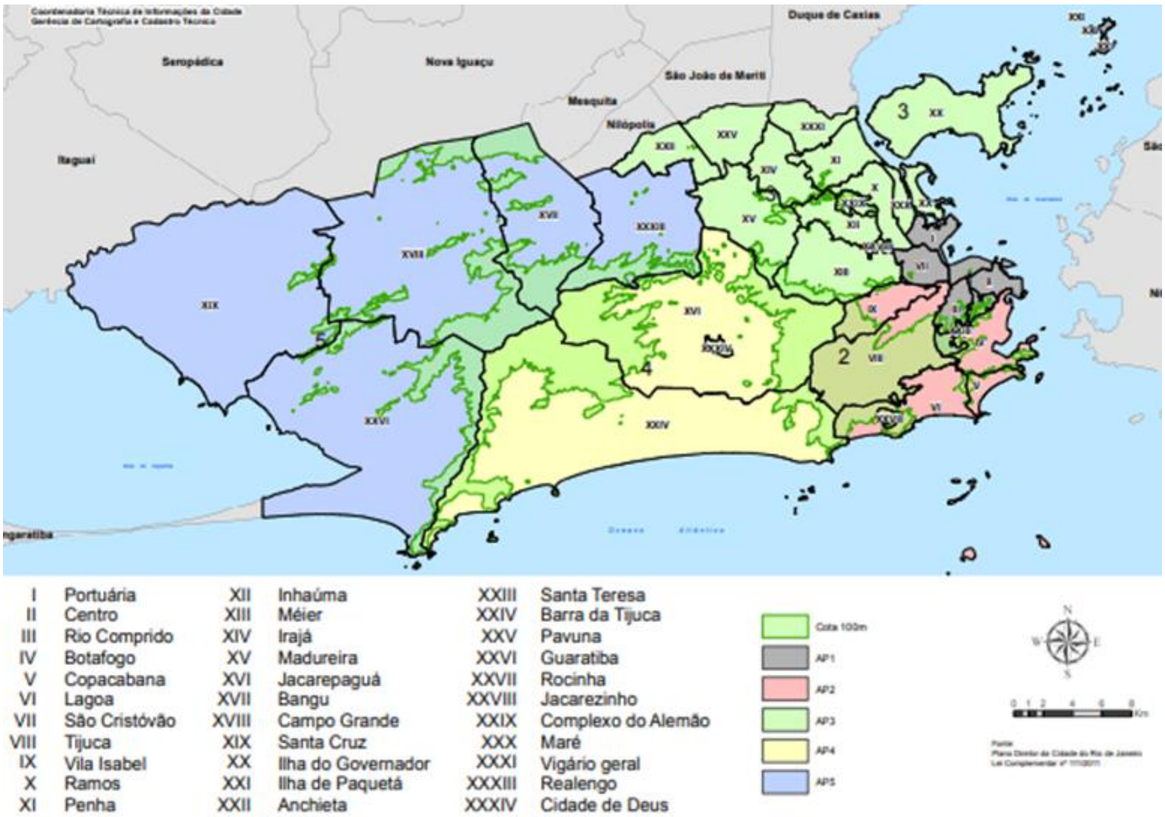

Figura 1 – Mapa das Áreas de Planejamento da cidade do Rio de Janeiro

Fonte: Instituto Pereira Passos, 2022

De modo geral, observa-se uma predominância da Área de Planejamento 2 dentre os quinze bairros mais indicados, indicando nestas localidades a concentração dos indicadores considerados. Entretanto, destaca-se que o bairro mais bem colocado da AP2 é Botafogo, que está na quarta posição, onde os bairros das três primeiras colocações são respectivamente das AP4, AP5 e AP1. Ou seja, apesar da concentração no grupo examinado, observa-se uma pluralidade de regiões ocupantes das posições de maior destaque.

Tendo em vista o impacto que a criminalidade possui no custo das iniciativas de mobilidade na cidade do Rio de Janeiro, a tabela 4 demonstra um novo ranqueamento produzido no cenário 2, onde os pesos dos critérios e a Utilidade Multiatributo são recalculados. Em relação a tabela 3 foi acrescentada a coluna "diferença de posição" que corresponde a quantidade de posições que cada bairro se movimentou no ranqueamento.

Tabela 4 - Resultados Cenário 2 (Com Criminalidade)

Bairro	Área de Planejamento	Utilidade Multiatributo	Diferença De Posição
Botafogo	AP 2 (Zona Sul e Grande Tijuca)	0,6723	3
Barra da Tijuca	AP 4 (Baixada de Jacarepaguá)	0,6702	-1
Centro + Lapa	AP 1 (Centro)	0,6645	0
Campo Grande	AP 5 (Zona Oeste)	0,6500	-2
Copacabana	AP 2 (Zona Sul e Grande Tijuca)	0,6205	0
Urca	AP 2 (Zona Sul e Grande Tijuca)	0,5557	0
Tijuca	AP 2 (Zona Sul e Grande Tijuca)	0,5259	0
Leblon	AP 2 (Zona Sul e Grande Tijuca)	0,5220	1
Catete	AP 2 (Zona Sul e Grande Tijuca)	0,5119	1
Ilha do Governador	AP 3 (Zona Norte)	0,5071	-2
Ipanema	AP 2 (Zona Sul e Grande Tijuca)	0,5025	3
Flamengo	AP 2 (Zona Sul e Grande Tijuca)	0,4977	1
Laranjeiras	AP 2 (Zona Sul e Grande Tijuca)	0,4966	-1
Lagoa	AP 2 (Zona Sul e Grande Tijuca)	0,4950	4
Leme	AP 2 (Zona Sul e Grande Tijuca)	0,4899	1

Fonte: elaboração própria

Nesta análise destaca-se a movimentação de onze dos quinze bairros pertencentes às quinze primeiras colocações da nova simulação, indicando a relevância do fator criminalidade no estabelecimento de um ranking comparativo (AUER *et al.*, 2020; SILVA, 2019; BARROS, 2017). Dentre este grupo quatro bairros caíram, sete aumentaram e quatro permaneceram na mesma posição. O bairro com maior destaque positivo foi Botafogo, que ascendeu três posições, chegando à liderança. Isto deve-se à disparidade entre o número de ocorrências policiais entre este bairro e Barra da Tijuca, Campo Grande e Centro + Lapa. Em 2020, Botafogo teve menos da metade de ocorrências registradas frente às observadas nos outros três bairros.

Ainda examinado o desempenho dos bairros, destaca-se que a maior queda ocorreu em Bangu, que inclusive deixou de figurar entre as quinze melhores localidades. Bangu caiu seis posições, saindo de décimo primeiro para décimo sétimo, pois a quantidade de registros policiais ultrapassa duas vezes e meia a quantidade observada em Botafogo. Outras importantes quedas foram observadas em Campo Grande e Ilha do Governador. Ambos os bairros perderam duas posições, visto que são representantes do grupo dos 20 bairros com maiores registros de ocorrência policial. Este resultado elimina a participação da AP5 e reduz a participação da AP4 no grupo, assim como aprofunda o domínio da AP2 com a entrada do Leme e Lagoa em lugar de Bangu e Recreio dos Bandeirantes.

Em contraste ao resultado observado Bangu, Campo Grande e Ilha do Governador, todos os outros bairros da AP2, com a exceção do bairro de Laranjeiras, melhoraram suas colocações. Em comum, estes bairros são considerados os mais nobres da cidade do Rio de Janeiro, e que, de alguma forma, no geral possuem menos registros criminais. Desta forma, incorporar a criminalidade no espectro de análise, reforça-se a preferência pelos bairros mais nobres da cidade, que não necessariamente possuem a maior demanda pelo modal, fenômeno este apontado por Amaral (2010) e Batista (2003).

A análise da movimentação dos bairros no ranqueamento também é demonstrada espacialmente no mapa da cidade (figura 2). Os bairros na cor azul não estiveram entre os quinze em nenhum dos dois cenários, enquanto os demais foram classificados em um dos cenários ou mesmo nos dois. Os bairros em vermelho obtiveram um desempenho pior no cenário 2 (com criminalidade), perdendo posições no ranqueamento; enquanto, os bairros em preto deixaram de fazer parte do ranqueamento no cenário 2. Os bairros em verde observaram uma melhora no seu ranqueamento e, os em amarelo, permaneceram na mesma colocação em ambos os cenários.

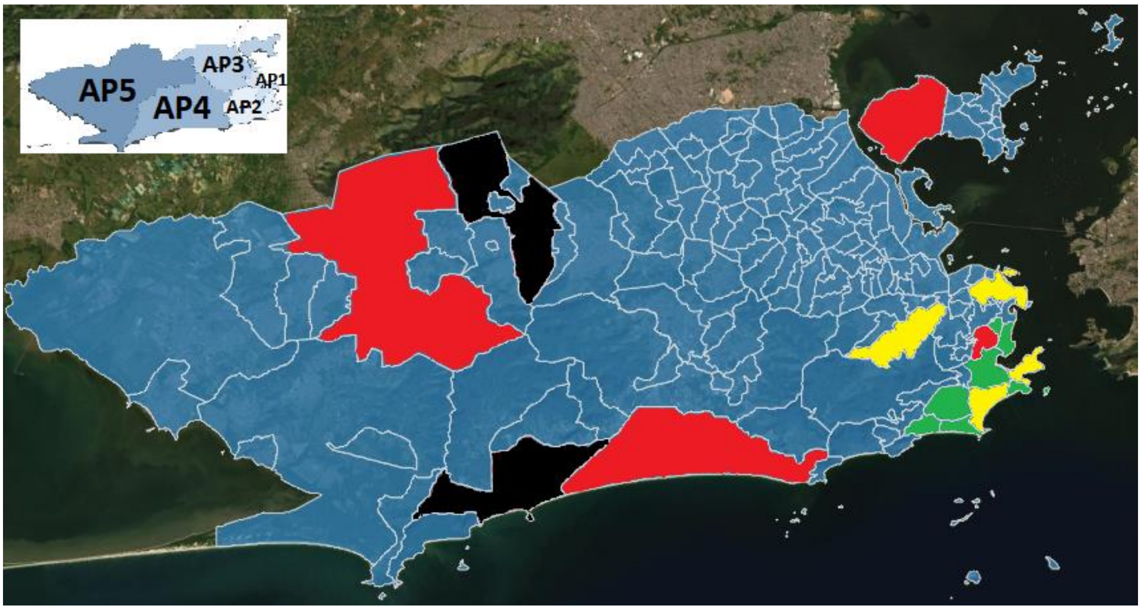

Figura 2 – Mapa da cidade do Rio de Janeiro com a movimentação no ranqueamento

Fonte: Adaptado de IPP (2022)

Na figura observa-se uma flagrante predisposição para a seleção de áreas localizadas próximas à região costeira, seja ela na AP2 - onde há maior concentração - ou na AP4, ambas áreas consideradas nobres e com altos índices de especulação imobiliária (AMARAL, 2010). Destaca-se também a localização mais a oeste dos bairros Bangu e Recreio dos Bandeirantes, ambas em preto, que deixaram de figurar entre os quinze bairros mais indicados para receber uma base operacional de *e-Carsharing*. Por último, chama a atenção a concentração espacial dos bairros com melhora no cenário 2, o que acaba por consolidar a região da cidade conhecida como Zona Sul (AP2) como a mais indicada para receber o serviço. Sob a ótica da distribuição espacial, no entanto, constata-se que a região representa uma parcela muito pequena do espaço urbano da cidade.

Por último, buscando observar o comportamento consolidado de todos os bairros segregados por Área de Planejamento têm-se a tabela 5. Nesta é analisada a mudança média de posições para cada AP.

Tabela 5 – Média das Diferenças por Área de Planejamento

Área de Planejamento	Média de Diferença
AP 1 (Centro)	4,9
AP 2 (Zona Sul e Grande Tijuca)	2,5
AP 3 (Zona Norte)	-0,3
AP 4 (Baixada de Jacarepaguá)	-0,7
AP 5 (Zona Oeste)	-5,3

Fonte: Elaboração Própria

A tabela confirma a tendência consolidada de subida de posição dos bairros da AP2. Apesar de expressiva, o crescimento da AP1 deve ser observado com cuidado, pois a maior parte de seus representantes não tiveram boa performance na avaliação. Com exceção de Santa Teresa, que figurou na trigésima segunda posição, os demais bairros ficaram abaixo da septuagésima posição, com utilidade multiatributo média 45% inferior à primeira colocada. Em síntese, verificou-se que a fator violência pública se mostrou determinante no rankeamento das APs, pois sua influência na média de diferença observada tornou-se responsável por uma redistribuição expressiva dos bairros analisados, rebaixando as localidades periféricas e privilegiando bairros com alta concentração de renda e IDH, corroborando análises prévias a respeito da socioespacialização urbana (AMARAL, 2010; BATISTA, 2003; FRANÇA *et al.*, 2021)

6. Conclusão:

Este trabalho teve como objetivo analisar a interferência da criminalidade urbana no processo de seleção das áreas mais indicadas para a prestação do serviço de e-*Carsharing* na cidade do Rio de Janeiro. Para tanto, inicialmente buscou-se na literatura a conceituação do serviço de *carsharing* e as particularidades de seus modelos e operacionais (NANSUBUGA e KOWALKOWSKI, 2021; BECKER *et al.*, 2017) e logísticos (HEILIG *et al.*, 2018; KYPRIADIS *et al.*, 2020; MULLET *et al.*, 2017).

Compreendidas as especificidades e potencialidades do *carsharing*, passou-se à identificação dos principais fatores de sucesso do serviço, tendo estudos como De Luca e Di Pace (2015) e Hahn *et al.* (2020) apontado aspectos como limpeza e conforto do usuário como decisivos, enquanto estudos como Hu *et al.*

(2018) e Nair e Miller-Hooks (2011) focaram principalmente na previsibilidade e disponibilidade dos veículos. Ainda sob o aspecto das preferências dos consumidores, é importante destacar estudos como os realizados por TURON, CZECH e TOTH (2019), que apontaram a prioridade de itens de segurança, boa interface de segurança de dados e acompanhamento da viagem e adaptabilidade no veículo para crianças, idosos e portadores de necessidades especiais para uma parcela da população.

Identificados os fatores determinantes na literatura para o sucesso dos empreendimentos de *carsharing*, passou-se então à exploração do impacto da violência urbana sobre este modelo de negócio (BARROS, 2017; SILVA, 2019; BONALDO, 2021; FRANÇA *et al*. 2021). Para tanto, aplicou-se uma metodologia multicritério para determinação as localidades preferenciais para o recebimento deste investimento, resultando na concentração dos melhores bairros em uma região específica da cidade, concentração esta amplificada quando se considerou o critério de criminalidade. Estes resultados corroboram os achados de Batista (2003), Amaral (2010) e Auer *et al*. (2020), que apontam a violência urbana na cidade do Rio de Janeiro como fator limitante das ofertas de bens e serviços principalmente nos eixos menos valorizados da cidade.

O impacto desta dinâmica é perverso para as questões de mobilidade e, sobretudo, para iniciativas de eletrificação de frota por meio de um serviço de *e-Carsharing* (BARROS, 2017). Localidades com grande potencial para oferecer capilaridade ao serviço mostraram-se desaconselháveis devido ao impacto dos índices de criminalidade. Tais questões sociais intrínsecas às grandes cidades latinas (HALHARDI, 2018; NTU, 2022) impacta na cobertura importantes áreas de interesse, como o caso do bairro Recreio dos Bandeirantes, o que tenderá a impactar as taxas de utilização dos veículos nesta região. Neste sentido, concluiu-se no presente estudo a redução da viabilidade econômica do modelo de negócio de *e-Carsharing* em determinadas localidades em função dos fatores criminalidade e violência pública, o que pode se desdobrar em uma dificuldade adicional para os países latinos na missão de reduzir suas emissões via utilização da mobilidade elétrica.

Finalmente, destaca-se que este estudo possui alguma limitação em razão da disponibilidade de dados, sobretudo os que melhor retratam a renda das famílias residentes nos bairros analisados, bem como o contingente populacional que circula nestas localidades. Portanto, os autores sugerem que estudos futuros sejam executados utilizando novas variáveis, assim como sejam testadas novas metodologias de análise.

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Referências:

ALENCAR, V.A., ROOKE, F., COCCA, M., VASSIO, L., ALMEIDA, J. e VIEIRA, A.B., **Characterizing client usage patterns and service demand for car-sharing systems**, Information Systems, Article in press, 101448, 2019.

AMARAL, Layne. **O imaginário do medo: violência urbana e segregação espacial na cidade do Rio de Janeiro**. Contemporânea (Título não-corrente), v. 8, n. 1, p. 34-45, 2010.

ASSOCIAÇÃO NACIONAL DAS EMPRESAS DE TRANSPORTES URBANOS (NTU). **Impacto dos ônibus incendiados (1987-2022) - Cenário Nacional**. Edição de Abril/2022. Disponível em: < https://www.ntu.org.br/novo/upload/Publicacao/Pub637855542236993652.pdf>. Acesso em 05 out. 2022. Brasilia, 2022.

AUER, Emilian; THEDIN, Marcelo; DINIZ, Nivea; AZEVEDO, Vanessa; COLONESE, Vinicius F. e Sousa, Wellington. **Um modelo de gerenciamento de risco no transporte urbano de passageiros no Rio de Janeiro**. 2020. Trabalho de Conclusão de Curso (Especialização em Gestão do Negócio) - Fundação Dom Cabral; Instituto de Transporte e Logística, Rio de Janeiro, 2020.

BARROS, Lidyane S.S.. **Compartilhamento de carros elétricos: análise de incertezas em iniciativas públicas de mobilidade urbana**. 2017. Dissertação de Mestrado. Universidade de São Paulo.

BARNES, S.J. e MATTSON, J., **Understanding current and future issues in collaborative consumption: a four-stage Delphi study**, Technological Forecasting and Social Change, Vol. 104, pp. 200-211, 2016.

BATISTA, Vera Malaguti SW. **O medo na cidade do Rio de Janeiro: dois tempos de uma história**. Rio de Janeiro: Revan, 2003, 270p.

BECKER, H., Ciari, F. e AXHAUSEN, K.W., **Measuring the car ownership impact of free-floating car-sharing–A case study in Basel, Switzerland**, Transportation Research Part D: Transport and Environment, Vol. 65, pp. 51-62, 2018.

BECKER, H.; LODER, A.; SCHMID, B.; AXHAUSEN, K. W. **Modeling car-sharing membership as a mobility tool: A multivariate Probit approach with latent variables**. Travel Behav. Soc., 8 (2017), pp. 26-36, 10.1016/j.tbs.2017.04.006.

BONALDO, Manuela Gortz. **Fatores críticos de sucesso na operação de serviço de mobilidade compartilhada: estudo de caso do serviço de car-sharing**. 2021. Tese (Doutorado em Tecnologia e Sociedade) - Universidade Tecnológica Federal do Paraná, Curitiba, 2021.

BOYACI, B., ZOGRAFOS, K.G. and GEROLIMINIS, N. (2015), **An optimization framework for the development of efficient one-way car-sharing systems**, European Journal of Operational Research, 2015, Vol. 240 No. 3, pp. 718-733.

BRENDEL, A.B., LICHTEMBERG, S., PRINZ, C. e HERRENKING, B., **Increasing the value of shared vehicles: insights from an implementation of user-based relocation in station-based one-way carsharing**, Sustainability, 2020, Vol. 12 No. 21, p. 8800.

DE LUCA, S. e DI PACE, R., **Modelling users' behavior in inter-urban carsharing program: a stated preference approach**, Transportation Research Part A: Policy and Practice, Vol. 71, pp. 59-76. 2015.

CLARK, M., GIFFORD, K., ANABLE, J. e LE VINE, S., **Business-to-business carsharing: evidence from Britain of factors associated with employer-based carsharing membership and its impacts**, Transportation, 2015, Vol. 42 No. 3, pp. 471-495.

COHEN, B. e KIETZMANN, J., **Ride on! Mobility business models for the sharing economy**, Organization and Environment, 2014, Vol. 27 No. 3, pp. 279-296.

EDWARDS, W.; BARRON, F. H.**. SMARTS and SMARTER: Improved simple methods for multiattribute utility measurement**. Organizational behavior and human decision processes, 1994, v. 60, n. 3, p. 306-325.

FLEURY, S., TOM, A., JAMET, E. e COLAS-MAHEUX, E., **What drives corporate carsharing acceptance? A French case study**, Transportation Research Part F: Traffic Psychology and Behaviour, 2017, Vol. 45, pp. 218-227.

FRANÇA, Tamara; BRUM, Tarcisio; MANGIA, Leonardo; MARUJO, Lino; LIMA, Roberto Ivo. **Compartilhamento de veículos elétricos: um estudo sobre a localização de eletropostos na cidade do Rio de Janeiro**. Texto de Discussão do Setor Elétrico nº110. Grupo de Economia do Setor Elétrico. Universidade Federal do Rio de Janeiro. Rio de Janeiro, setembro 2021.

GALATOULAS, Nikolaos-Fivos; GENIKOMSAKIS, Konstantinos N.; IOAKIMIDIS, Christos S. **Analysis of potential demand and costs for the business development of an electric vehicle sharing service**. Sustainable Cities and Society, v. 42, p. 148-161, 2018.

GALHARDI, Eurico Divon. **Fogueiras da insensatez: porque queimam os ônibus no Brasil**. Brasília: NTU, 2018.

HAHN, R., OSTERTAG, F., LEHR, A., BUTTGEN, M. e BENOIT, S.. **I like it, but I don't use it': impact of carsharing business models on usage intentions in the sharing economy**, Business Strategy and the Environment, 2020, Vol. 29 No. 3, pp. 1404-1418.

HAMARI, J., SJOKLINT, M. e UKKONEN, A., **The sharing economy: why people participate in collaborative consumption**, Journal of the Association for Information Science and Technology, 2016, Vol. 67 No. 9, pp. 2047-2059.

HARMS, Sylvia; TRUFFER, Bernard. **The Emergence of a Nationwide Carsharing Co-operative in Switzerland**. Anstalt fur Wasserversorgung und Gewasserschutz, Switzerland, 1998.

HEILIG, M., MALLIG, N.,SCHRODER, O., KAGERBAUER, M. e VORTISCH, P. **Implementation of freefloating and station-based carsharing in an agent-based travel demand model**, Travel Behaviour and Society, Hong Kong Society for Transportation Studies, 2018, Vol. 12, pp. 151-158.

HJORTESET, M.A. e BOCKER, L., **Car sharing in Norwegian urban areas: examining interest, intention and the decision to enrol**, Transportation Research Part D: Transport and Environment, Vol. 84, p. 102322. 2020.

HU, S.; CHEN, P.; LIN, H.; XIE, C.; CHEN, X. **Promoting carsharing attractiveness and efficiency: An exploratory analysis**. Transport. Res. Transport Environ., 2018 nº 65, pp. 229- 243, 10.1016/j.trd.2018.08.015.

Instituto Pereira Passos. **Mapa das Áreas de Planejamento do Município do Rio de Janeiro**. Disponível em: < https://www.data.rio/documents/PCRJ::%C3%A1reas-de-planejamento-ap-regi%C3%B5es-administrativas-ra-e-%C3%A1reas-acima-da-cota-100m-no-munic%C3%ADpio-do-rio-de-janeiro/explore > Acesso em 13 ago. 2022.

KIM, D., Park, Y. e KO, J., **Factors underlying vehicle ownership reduction among carsharing users: a repeated cross-sectional analysis**, Transportation Research Part D: Transport and Environment, Vol. 76, pp. 123-137. 2019.

KYPRIADIS, D., PANTZIOU, G., KONSTANTOPOULOS, C. e GAVALAS, D., **Optimizing relocation cost in free-floating car-sharing systems**, IEEE Transactions on Intelligent Transportation Systems, 2020, Vol. 21 No. 9, pp. 4017-4030.

LOPES, Yuri Gama; DE ALMEIDA, Adiel Teixeira. **Enfoque multicritério para a localização de instalações de serviço: aplicação do método SMARTER**. Sistemas & Gestão, v. 3, n. 2, p. 114-128, 2008.

LUO, W., WANG, Y., JIAO, P., WANG, Z., ZHAO, P. **What Kind of Travellers Are Using Carsharing in Beijing? A Study Based on Selective Ensemble Learning**. Sustainability 2022, 14(1), 540; https://doi.org/10.3390/su14010540

MOEIN, E. e AWASTHI, A., **Carsharing customer demand forecasting using causal, time series and neural network methods: a case study**, International Journal of Services and Operations Management, 2020, Vol. 35 No. 1, pp. 36-57.

MULLER, J., CORREIA, G.H.D.A. e BOGENBERGER, K., **An explanatory model approach for the spatial distribution of free-floating carsharing bookings: a case-study of German cities**, Sustainability, 2017, Vol. 9 No. 7, p. 1290.

MUNZEL, K., BOON, W., FRENKEN, K. e VASKELAINEN, T. **Carsharing business models in Germany: characteristics, success and future prospects**, Information Systems and E-Business Management, 2018, Vol. 16 No. 2, pp. 271-291.

MUNZEL, K., BOON, W., FRENKEN, K., BLOMME, J. e VAN DER LINDEN, D., **Explaining carsharing supply across Western European cities**, International Journal of Sustainable Transportation, Vol. 14 No. 4, pp. 243-254. 2020.

NAIR, R. e MILLER-HOOKS, E., **Fleet management for vehicle sharing operations**, Transportation Science, Vol. 45 No. 4, pp. 524-540. 2011.

NANSUBUGA, Brenda; KOWALKOWSKI, Christian. **Carsharing: A systematic literature review and research agenda**. Journal of Service Management, 2021.

NITSCHKE, L., **Reconstituting automobility: the influence of non-commercial carsharing on the meanings of automobility and the car**, Sustainability, 2020, Vol. 12 No. 17, p. 7062.

PRIETO, M., BALTAS, G. e STAN, V., **Car sharing adoption intention in urban areas: what are the key sociodemographic drivers?**, Transportation Research Part A: Policy and Practice, Vol. 101, pp. 218-227. 2017.

RIO DE JANEIRO. **Lei Complementar nº 111 de 01/02/2011**. Disponível em: < https://www.legisweb.com.br/legislacao/?id=178079>. Acesso em 8 jul. 2022.

____________. **Lei nº 5.248 de 27/01/2011**. Disponível em: < https://www.legisweb.com.br/legislacao/?id=178109#:~:text=Institui%20a%20Pol%C3%ADtica%20Municipal%20sobre,Janeiro%20e%20d%C3%A1%20outras%20provid%C3%AAncias.&text=Art.>. Acesso em 8 jul. 2022.

SILVA, André Koide da. **Modelos de negócio adotados por empresas de compartilhamento de carros no contexto da mobilidade inteligente: estudos de caso múltiplos em empresas que atuam no Brasil**. 2019. Tese de Doutorado. Universidade de São Paulo.

SHAHEEN, S. A.; COHEN, A. P. **Carsharing and Personal Vehicle Services: Worldwide Market Developments and Emerging Trends. International Journal of Sustainable Transportation**, 2012, v. 7, n. 1, p. 5–34, 2012.

SHAHEEN, S. A.; COHEN, A. P. **Carsharing and Personal Vehicle Services: Worldwide Market Developments and Emerging Trends**. International Journal of Sustainable Transportation, , 2012, v. 7, n. 1, p. 5–34, 2012.

SHAHEEN, S., Sperling, D. and Wagner, C., **Carsharing and partnership management: an international perspective**, Transportation Research Record, 1999, Vol. 1666 No. 1, pp. 118-124.

SHAHEEN, S.A., Chan, N.D. and Micheaux, H., **One-way carsharing's evolution and operator perspectives from the Americas**, Transportation, 2015, Vol. 42 No. 3, pp. 519-536.

TEECE, D.J. , **Business models, business strategy and innovation**, Long Range Planning, 2010, Vol. 43 Nos 2-3, pp. 172-194.

TUROŃ, Katarzyna; CZECH, Piotr; TÓTH, János. **Safety and security aspects in shared mobility systems**. Zeszyty Naukowe. Transport/Politechnika Śląska, 2019.

TYNDALL, J., **Where no cars go: free-floating carshare and inequality of access**, International Journal of Sustainable Transportation, Vol. 11 No. 6, pp. 433-442. 2017.

WEBB. J., WLSON, C., KULARANTE, T.,. **Will people accept shared autonomous electric vehicles? A survey before and after receipt of the costs and benefits**. 2019, Economic Analysis and Policy, 61

WILHELMS, M.P., MERFELD, K. e HENKEL, S., **Yours, mine, and ours: a user-centric analysis of opportunities and challenges in peer-to-peer asset sharing**, Business Horizons, 2017, Vol. 60 No. 6, pp. 771-781.

WU, Chenyang, LE VINE, S., CLARK, M., GIFFORD, K., e POLAK. **Factors associated with round-trip carsharing frequency and driving-mileage impacts in London**. International journal of sustainable transportation, v. 14, n. 3, p. 177-186, 2020.

ZUHEROS, Cristina; MARTINEZ-CAMARA, Eugenio; HERRERA-VIEDMA, Enrique; HERRERA, Francisco. **Sentiment analysis based multi-person multi-criteria decision making methodology using natural language processing and deep learning for smarter decision aid**. Case study of restaurant choice using TripAdvisor reviews. **Information Fusion**, v. 68, p. 22-36, 2021.

Determinantes de la demanda de automóviles en Bogotá y sus implicaciones en la movilidad

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1. Resumen

En esta investigación se examinaron los principales determinantes socio demográficos de demandar automóvil, a partir de la Encuesta Multipropósito para Bogotá (EMB) que ofrece el DANE para los años 2014 y 2017. El análisis se basó en los conceptos de utilidad aleatoria desarrollada por Daniel McFadden (1974). Los principales resultados obtenidos mediante un modelo Probit muestran que variables proxies del ingreso incentivan la adquisición de vehículos en Bogotá; adicionalmente, las facilidades económicas como un mayor nivel educativo, estar casado o en unión libre y tener vivienda propia son factores que llevan a las personas y los hogares a tener automóvil.

2. Palabras Clave

Demanda de automóviles, Utilidad aleatoria, Encuesta Multipropósito, Sociodemográfica.

3. Abstract

In this research, the main socio-demographic determinants of car demand were examined, based on the Multipurpose Survey for Bogotá (EMB) offered by DANE for the years 2014 and 2017. The analysis was based on the concepts of random utility developed by Daniel McFadden (1974). The main results obtained through a Probit model show that proxy variables of income encourage the acquisition of vehicles in Bogotá; additionally, economic facilities such as a higher level of education, being married or in a free union and having their own home are factors that lead people and households to own a car.

4. Keyword

Automobile demand, Random utility, Multipurpose Survey, Sociodemographic.

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5. Introducción

El transporte particular ocupa el primer puesto del parque automotor en la ciudad de Bogotá con 1.901.395 vehículos (observatorio de movilidad de Bogotá, 2021) siendo el principal agente de caos en movilidad de la ciudad, es por ello que, esta investigación tiene como objetivo identificar los factores que determinan la decisión de los hogares y personas demandar automóviles de uso particular en Bogotá. Esa decisión es uno de los aspectos de mayor relevancia en términos de movilidad ya que determina el desarrollo y el bienestar de una comunidad, gracias a que brinda la posibilidad y facilidad de desplazarse de un lugar a otro para realizar diferentes actividades (como trabajar, estudiar, entre otras), mejorando la calidad de vida de las personas.

La intención de este trabajo es dar una mirada a la demanda de automóviles desde características socio demográficas de la población en Bogotá, esto lleva a observar diferentes factores que afectan la demanda de automóviles. Según Erdem (2013), cada una de las regiones presenta comportamientos independientes que afectan directamente la demanda de automóviles. Para el caso de la región europea se demostró por medio de un estudio métodos de panel de cointegración que involucra variables en el que las nuevas matriculaciones dependen del precio de los vehículos, del índice de confianza del consumidor, de la renta disponible, de los tipos de interés, del precio de los combustibles, del índice de producción industrial, así como también del saldo neto externo. Adicionalmente, se evidenció que en los países analizados los factores macroeconómicos influyen más en las ventas de automóviles que aquellos asociados a la teoría de la demanda destacando la importancia de las expectativas de los consumidores siendo esta variable más significativa que los tipos de interés o la renta. No ocurre lo mismo con el precio de los combustibles, ya que en su investigación parecen no influir en las matriculaciones de nuevos vehículos.

Por otro lado, Agostini (2010) en su estudio estimó el efecto del diferencial de impuestos a los combustibles en la demanda de automóviles en Chile, tomando los datos mensuales de importaciones de automóviles registrados por el Servicio Nacional de Aduanas para el periodo 2002-2008. Con la ayuda de un modelo de demanda por automóviles encontró qué, uno de los efectos más importantes que tiene la diferencia de tasas de impuesto existente en Chile, entre la gasolina y el diésel, es que incentiva la compra de automóviles con motor apto para este combustible, por lo que la demanda de este tipo de automóviles es bastante sensible al precio del automóvil y al diferencial de impuestos entre la gasolina y el diésel.

Sin embargo, en España la demanda de automóviles se ha visto afectada por factores exógenos como la crisis económica de 2008 que perjudicó a la economía española ya que el sector automotriz aporta cerca del 10 % al PIB y emplea al 8,1 % de la PEA esto para 2013. Lo anterior debido a la disminución de la renta disponible de las personas en España y el mundo además de mayores dificultades para acceder a financiación. Si bien a largo de la historia, desde 1904 el sector automotriz español ha atravesado situaciones difíciles, por lo que el gobierno ha adoptado medidas como el Plan Renove I y Plan Renove II, Plan Prever y el Plan Integral de Automoción, Programa de Incentivos al Vehículo Eficiente. Teniendo en cuenta lo anterior Baldomir (2015), buscó analizar qué factores inciden en la decisión de los consumidores a la hora de comprar un nuevo vehículo mediante un modelo de demanda de matriculaciones de los automóviles en España entre 1987 y el 2014, por medio de un modelo de regresión múltiple al que se le aplica el método de estimación por mínimos cuadrados ordinarios que evalúa variables como: el índice de precios de los automóviles, tipos de interés, el índice de confianza del consumidor y el PIB per cápita variable. A partir de los resultados del modelo se ha comprobado que variables como el precio de los vehículos, el índice de confianza de los consumidores y el PIB per cápita tienen un gran poder explicativo sobre las matriculaciones de automóviles en España.

Pero no solo fue España quien se vio afectado por la crisis del 2008, los países miembros del grupo denominado G7, formado por Alemania, Canadá, Estados Unidos, Francia, Italia, Japón y Reino Unido también sufrieron una disminución en la venta de automóviles en el último trimestre de ese año. Para explicar esta situación Haugh (2010), utiliza un modelo simple en el que las ventas de automóviles dependen del PIB per cápita, del precio real del petróleo y, por último, de las condiciones del mercado financiero.

Para esto se desarrolló una ecuación para cada país del grupo como un modelo de corrección de errores y se estimó a través de un procedimiento de dos etapas, llegando a la conclusión que las condiciones del mercado financiero tienen un gran poder explicativo en todos los países del grupo, excepto Francia. Así, los resultados indican que un aumento de las restricciones para acceder al crédito puede explicar más del 80 % de la caída de las ventas de automóviles en Estados Unidos y Canadá durante el período analizado, ya que, ante esta situación, muchos consumidores se vieron obligados a aplazar la compra de un nuevo vehículo.

Sin embargo, otros países presentaron un aumento de la comercialización de vehículos, tal es el caso de Colombia que recibe grandes importaciones de vehículos provenientes de México gracias a las medidas de apertura del mercado a nivel global se creó en 1994 el G-3, uno de los principales acuerdos que se realizaron fue para el sector automotriz mediante un proceso de desgravación paulatino que finalizaría en el año 2007. Como consecuencia a esta medida, el volumen de automóviles comercializados en Colombia pasó de 50.000 en el año 2000 a 220.000 aproximadamente en el año 2008.

Mediante el modelo de equilibrio parcial Restrepo (2010) pudo determinar que a partir de las medidas de desgravación el precio de los vehículos provenientes de México disminuiría en un 23 % para el año 2008, en comparación con el precio si existiese aún alguna medida impositiva, esto facilita el acceso a los consumidores a vehículos de mejor calidad e incluso tener más de un vehículo por núcleo familiar.

A nivel regional de acuerdo con Gómez (1995), en la ciudad de Bogotá la demanda de automóviles se incrementó principalmente por las preferencias de los consumidores al hecho de poseer un vehículo, es decir, que pese a la alta congestión vehicular de la ciudad dentro de las principales vías, además de los altos costos e incremento en el tiempo comparado con otros medios de transporte los conductores valoran ciertas características a la hora de desplazarse en automóvil como lo son la seguridad, la comodidad, la conveniencia, entre otros.

Tabla 1. Elasticidades de costo y tiempo de viajes al trabajo según medio de transporte en la ciudad de Bogotá en 1976.

Medio de transporte	**Elasticidad del costo**	**Elasticidad del tiempo**
Automóvil	-0.2733	-0.0072
Bus	-0.0853	-1.0726
Buseta	-0.2315	-1.4111
Caminar	-	-5.3185

Fuente: Elaboración propia a partir de Gómez 1982

Como se puede observar en la tabla 1, a pesar de que haya un incremento significativo en el tiempo de viaje al trabajo, las personas de la ciudad de Bogotá prefieren usar sus vehículos particulares sobre medios de transporte públicos u otras opciones de desplazamiento como caminar, esto quiere decir que la variable de posesión de un automóvil es más inelástica frente a otras alternativas de transporte. No obstante, si se presenta un aumento en el costo el uso de vehículos particulares resulta más afectado, siendo la variable más elástica y la que resulta menos afectada es el uso de bus de servicio público. A nivel global la demanda de automóviles incrementó de forma significativa durante los últimos años. Esto se debe principalmente al crecimiento de las ciudades y su efecto sobre las distancias en los desplazamientos, así como el auge económico en las grandes ciudades, la mayor participación del mercado laboral especializado, y los cambios en los patrones familiares entre otros aspectos. (Rodríguez, 2018).

6. Metodología

Esta metodología está basada en los conceptos de utilidad aleatoria, es por ello que para comprender los determinantes de la demanda de vehículos en la ciudad de Bogotá es necesario tener en cuenta la teoría de la utilidad aleatoria desarrollada por Daniel McFadden (1974), la cual establece que una función de utilidad puede ser descrita como la suma de una variable observable y de una variable no observable de naturaleza aleatoria dada por preferencias de cada individuo. Esta característica permite evidenciar la razón por la que ciertos individuos que presentan características similares escogen alternativas diferentes.

Para comprender los determinantes de la demanda de vehículos en la ciudad de Bogotá es necesario tener en cuenta la teoría de la utilidad aleatoria desarrollada por Daniel McFadden (1974), la cual establece que una función de utilidad puede ser descrita como la suma de una variable observable y de una variable no observable de naturaleza aleatoria dada por preferencias de cada individuo. Esta característica permite evidenciar la razón por la que ciertos individuos que presentan características similares escogen alternativas diferentes.

La demanda de automóviles de acuerdo con Nolan (2001), se encuentra asociada con las variables como sexo del jefe del hogar, la edad, nivel de ingresos, la ocupación, el número de personas que componen el hogar, entre otras sobre la propiedad de automóviles en la ciudad de Dublín. Esto fue determinado a partir de un modelo probit de tipo binario realizado a partir de la maximización de utilidades aleatorias, en el cual se determinó que la posesión de un automóvil en esta ciudad irlandesa viene dada principalmente por el sexo del jefe de hogar pues se evidencia que cuando los hogares son encabezados por mujeres existe una preferencia por el uso de autobuses y taxis.

En contraste, en la ciudad de Popayan, Colombia, se realizó un análisis de la elección modal entre el transporte público y privado a partir de una función de utilidad indirecta y aleatoria, la cual considera qué aspectos, tanto sociales como económicos de los demandantes, influyen de manera directa en dicho proceso. Así, con base en dos modelos econométricos del tipo Logit Multinomial se logró identificar, por un lado qué, el factor tiempo es clave en la elección modal, y por otro lado, variables como el género y el ser o no jefe de hogar no influye en la elección (Fajardo Gómez, 2015).

Por otra parte, la teoría de la utilidad aleatoria también puede ser usada para la elección del transporte aéreo. Según Muñoz (2014), el modelo de selección discreta permite calcular la probabilidad de que un individuo con determinadas características haga una elección dada, en este caso la elección de transporte aéreo para el caso de Medellín que cuenta con dos terminales aéreas, el Aeropuerto Enrique Olaya Herrera y el Aeropuerto José María Córdoba. A partir de la teoría de la utilidad aleatoria y las encuestas realizadas en los dos aeropuertos, se determinó que las variables para elegir determinada terminal son los costos de los tiquetes, los costos de desplazamientos al aeropuerto así como el tiempo. Asi mismo, Muñoz et. all., (2022) analizó la importancia de las variables latentes (seguridad y comodidad) en la elección del modo de transporte, aéreo o terrestre, en viajes domésticos Medellín-Barranquilla, para lo que se llevó a cabo un modelo de elección discreta con ayuda de la implementación de encuestas de preferencias declaradas realizadas cara a cara en el 2018, con el fin de obtener los mejores resultados ofrecidos por este modelo de muestreo. Estas variables resultaron significativas, lo que demuestra la importancia de incluir atributos de percepción para mejorar la capacidad predictiva de los modelos de elección.

Por otro lado, la teoría de la utilidad aleatoria puede ser aplicada incluso para determinar recomendaciones en rutas de transporte diferentes a las preestablecidas por sistemas de navegación en la que se valora el tiempo de viaje a su destino y la espera en paradero, tiempo de caminata y número de transbordos. Este modelo fue planteado por Vera (2020), quién a partir de datos pasivos obtenidos por medio de tarjetas de transporte y GPS de buses para generar un panel de información de las preferencia de los usuarios, para determinar la elección de rutas se desarrollo un modelo con un componente determinístico, observable y medible y un componente aleatoria no observable, como se muestra en la siguiente expresión:

$$U_{i,n} = V_{i,n} + \epsilon_{i,n} = \beta X_i + \epsilon_{i,n} \tag{1}$$

Donde:
$U_{i,n}$ es la utilidad que genera la alternativa i a un individuo n.
$V_{i,n}$ y $\epsilon_{i,n}$ corresponden a la componente sistemática y aleatoria de la utilidad respectivamente. Además de ser una combinación lineal sobre los parámetros de gustos β y los atributos medibles de las alternativas X_i.

Basados en Galán (2004), para la modelación demandar un carro se estimó un modelo de elección discreta tipo Probit, el cual se caracteriza por emplear una función de distribución normal con media cero y varianza uno, tomando como variable dependiente una dicotómica por naturaleza que toma el valor de 1 si cumple con las características de estudio y 0 cuando no, el modelo tiene la siguiente expresión:

$$F(Z) = \phi(Z) = \int_{-\infty}^{z} \theta(V)\, dv \tag{2}$$

- Donde θ es la función de densidad normal.
- Donde la variable z es una variable dicotómica que sigue una distribución normal con media cero y varianza uno.

De tal modo que el modelo Probit puede ser expresado como:

$$Y_i = F(Z) = (\beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n) = \int_{-\infty}^{\beta_0+\beta_1 X_1+\beta_2 X_2+...+\beta_n X_n} \frac{1}{\sqrt{2\pi}} e^{\frac{-z^2}{2}}\, dv \tag{3}$$

De tal forma se tiene que:

$$P\left(Y_i = \frac{1}{\beta^T X_i^T}\right) = \phi(\beta^T X_i^T) \tag{4}$$

$$i = 1, 2, 3, ..., n$$

A partir de este modelo se realizaron diferentes estimaciones a partir de modelos de maximización de la utilidad aleatoria, multinomial logit, mixed logit y parámetros individuales de los cuales se pudo concluir que la distribución del gusto es un factor relevante en la estimación del modelo además que existen variables como si es un día laboral y las horas pico en las que la urgencia de llegar al destino de viaje puede primar por sobre la comodidad del viaje.

Los análisis y la estimación se realizan a través de la encuesta multipropósito para Bogotá (EMB) 2017 que tienen como objetivo general “obtener información estadística, por localidades y estratos, sobre aspectos demográficos, sociales, económicos y del hábitat de los hogares y de los habitantes de Bogotá, que permita formular, hacer seguimiento y evaluación a las políticas públicas necesarias para el desarrollo de la ciudad” (DANE, 2011, 1).

Inicialmente se realizó un análisis descriptivo donde se contrasta la variable exógena como se muestra en la tabla 2, con respecto a cada una de las variables endógenas que se muestran en la tabla 3, para luego realizar un ejercicio de estimación a través de un modelo de tipo Probit.

Tabla 2. Variables de Estudio Endógenas

Descripción de las variables 2017	**Códigos**
Compra vehículos en el último año	NHCMP11E

Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

De esta manera, la presente investigación utiliza variables socioeconómicas de los hogares a través de la EMB. Las variables exógenas estarán divididas en tres grupos, las primeras son categóricas: nivel educativo (primaria, secundaria, técnico, tecnólogo, pregrado y posgrado), estado civil (unión libre, casado, viudo, separado y soltero), categoría ocupacional (asalariados, domésticos, cuenta propia , patrono empleador y empleado sin remuneración). Las segundas son dicotómicas como género, si la persona trabaja o no, y si posee vivienda propia como proxi del ingreso.

Por último, se tuvieron en cuenta las variables continuas como edad y número de personas que conforman el hogar como se evidencia en la tabla 3.

Tabla 3. Variables de Estudio Exógenas

Descripción de las variables 2017	**Códigos**
Tipo de vivienda	NHCCP1
Número de personas en el hogar	NHCCPCTRL2
Garaje	NHCCP22C
Poseen Carro	NHCCP41A
¿Cuántos?	NHCCP41B
Modelo Carro	NHCCP41C
Herramienta de trabajo?	NHCCP41D
Localidad	LOCALIDAD
Género	NPCEP5
Edad	NPCEP4
Estado Civil	NPCEP7
Nivel educativo	NPCHP4
Medio de transporte utilizado	NPCHP18D
Trabaja	NPCKP1
Categoría Ocupacional	NPCKP17
Medios de transporte	NPCKP45A
Percepción Vías	NHCLP7A
Percepción Transmilenio	NHCLP7G

Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

Así, Y_i representa la situación de que una persona tenga más de un carro o no; X_i son las variables exógenas que determinan que una persona tenga o no tenga más de un carro, por ejemplo, la edad, género, vivienda, entre otras, y los son los coeficientes estadísticos a estimar. Las especificaciones Probit se aplicarán en la construcción de las variables categóricas y el interés se centra en evaluar en qué medida explica el comportamiento de una variable de respuesta en un conjunto de factores o variables explicativas que clasifican cada unidad de observación en función de una descripción de la subpoblación de unidades a las que pertenece (Arnau, 1996). Este ejercicio permitió inferir cuáles son los factores socioeconómicos que inciden con mayor fuerza sobre demandar automóvil.

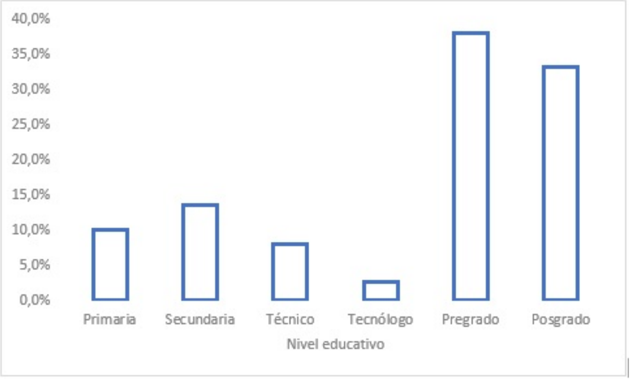
Para determinar el grado de ajuste del modelo, se utilizan dos estadísticos: el primero pretende comparar el valor original de los datos con el valor estimado por grupo de observación, en esta prueba si se rechaza la hipótesis nula, no puede hacerse inferencia acerca de la relación entre las variables explicativas y la probabilidad de tener dos o más autos, esta prueba es conocida como Hosmer-Lemeshow (H-L) Galán (2000); la segunda se distribuye como un chi-cuadrado con grados de libertad el número de patrones de covariables menos el número de parámetros, con el fin de que el modelo presente un buen ajuste.

Teniendo en cuenta el posible sesgo por selección en la muestra, existe la posibilidad de implementar el procedimiento en dos etapas propuesto por Heckman (1979). El procedimiento consiste en estimar en primer lugar un modelo de tipo Probit, en el que se calcula la probabilidad de tener uno o más automóviles, dadas unas variables de interés. A partir del modelo se obtiene un estadístico llamado razón inversa de Mills, que captura la magnitud de dicho sesgo. Después de realizar el cálculo del modelo Probit, la razón de Mills estimada se añade al modelo original, para que se convierta en un regresor más. Así la significatividad de este coeficiente muestra la magnitud de sesgo en que se incurriría si no se hubiese incorporado éste al modelo inicial (Sanchez Figueroa, Cortinas Vásquez , Iñigo Tejera, 2012)

7. Resultados

A partir de los microdatos de las Encuestas Multipropósito, realizadas para Bogotá en el año 2017, se realizó inicialmente un análisis descriptivo de las variables seleccionadas y especificadas en la metodología de la presente investigación. De la población de estudio, se recuerda que las variables observadas representan a los jefes de hogar que demandan automóvil.

Gráfica 1. Personas que compraron auto vs nivel educativo

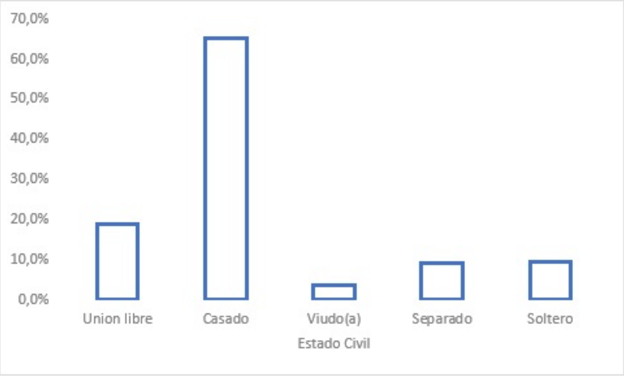


Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

Por otro lado, teniendo en cuenta que la variable endógena de estudio es la demanda de automóvil, se realizó un análisis de ésta frente a las principales variables exógenas, que se consideran tienen una estrecha relación con la misma, según los resultados de las investigaciones por Galán (2000, 2005), en las que se relaciona las variables socioeconómicas con el hecho de demandar automóvil. En la gráfica 1, se observa el comportamiento de la demanda dado el nivel educativo.

La gráfica 1, deja ver que las personas con educación técnica y tecnológica tienen el menor porcentaje en la demanda de carro. Este resultado puede ser causa de la cantidad de personas que conforman este nivel educativo. De igual forma, la gráfica muestra un comportamiento controversial en los niveles educativos más bajos, ya que según se observan las personas con primaria y secundaria tienen un porcentaje mayor de demandar automóvil frente a los descritos anteriormente.

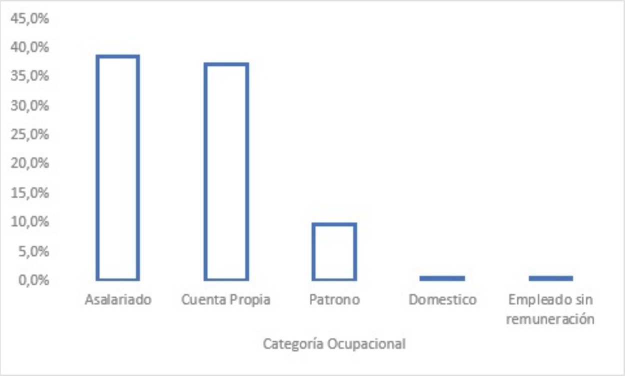
Gráfica 2. Personas que compraron auto vs Estado Civil



Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

En la gráfica 2 se observa que las personas casadas representan la mayor cantidad, alrededor del 60 % para los años analizados, la estadística de la gráfica 3 revela que las personas casadas son las que poseen la mayor demanda de automóviles.

Gráfica 3. Personas que compraron auto vs categoría ocupacional

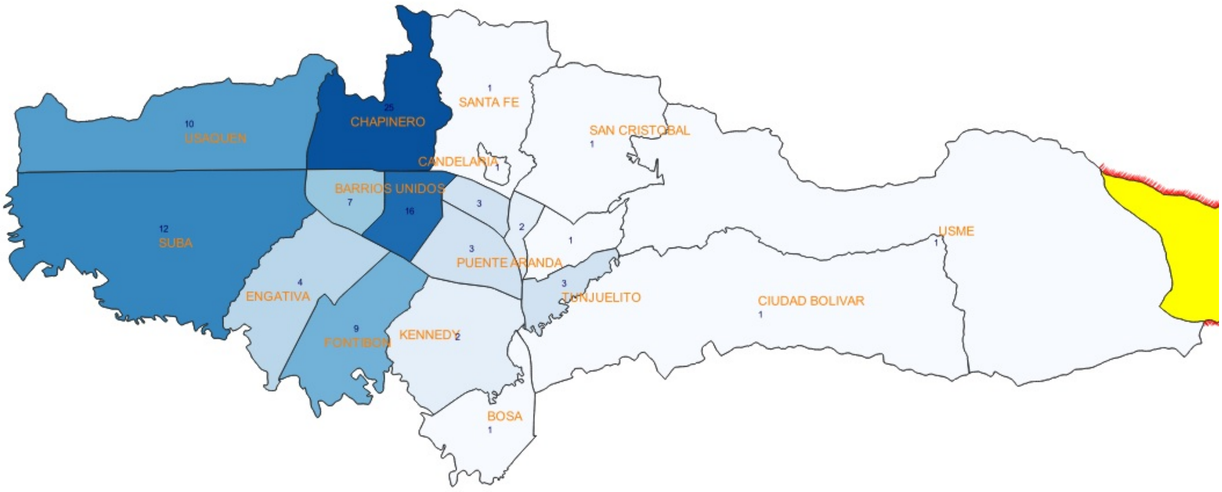


Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

En la gráfica 3 las personas pertenecientes a cuenta propia y asalariados son las que tienen el porcentaje más alto en la adquisición de automóviles. De tal manera que aquellas personas que tienen un trabajo fijo y estable tienen posibilidades o facilidades frente a la variable endógena de estudio. De igual forma, se observó que de las personas que tienen más de un carro, el 67,33 % (2014) tienen vivienda propia, por lo que variables como ésta, el tipo de trabajo, el nivel educativo y enfrentar gastos en pareja, muestran la importancia del factor ingreso ante la compra de un automóvil.

Finalmente, en esta primera parte vale la pena observar las localidades de la ciudad en las que están concentradas la mayor parte de personas que demandan autos. Esta información la brinda la gráfica 4, en donde se observa que la localidad de Chapinero alberga el mayor porcentaje con un 25 %, seguida de Teusaquillo y Usaquén. Lo que corrobora la observación anterior sobre la importancia del estatus económico sobre la variable endógena analizada en la presente investigación.

Gráfica 4. Personas que compraron auto vs Localidades



Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

El procedimiento de la estimación se hizo en dos etapas siguiendo la metodología de Heckman, en aras de descartar un posible sesgo de selección en la muestra. Los resultados mostraron que para ninguno de los modelos existe evidencia por sesgo de selección, razón por la cual se corre un modelo Probit de forma tradicional.

En este trabajo se estimó el modelo, en el que se tomó como variable dependiente la compra de carros por hogar (dicotómica: 1 si compro carro y 0 si no compro carro), explicada por las variables socioeconómicas de la EMB, tal como se especificó en la metodología. Los efectos marginales se encuentran en la Tabla 4.

Del modelo se esperaba inicialmente que los hombres tuvieran una mayor probabilidad de tener más de un carro con respecto a las mujeres, ya que inicialmente en las estadísticas descriptivas se observó que más del 70 % de la muestra poblacional eran hombres. Pero en los resultados econométricos ésta variable no fue significativa, por lo que se podría decir que el género, no tiene un impacto sobre el hecho de tener más de un carro.

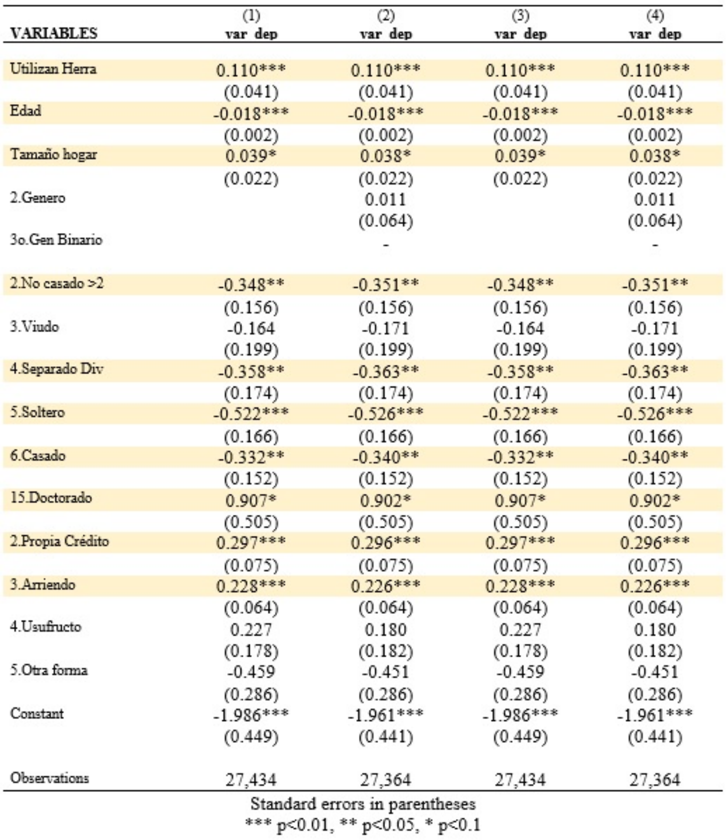
El modelo 1 es con todos los integrantes del hogar. El modelo 2 es sin missing values (no hay diferencia en realidad) con el primero. Y el Modelo 3 y 4 son solo para cabeza de hogar. Observamos que los oddratios mayores a 1 en la medida que varia la variable de referencia esta impacta de forma considerable en la compra o adquisición del vehículo. Las estimaciones se han realizado con la encuesta del año 2017.

Notamos que las personas jóvenes, incluso aquellos que tienen estudios de posgrado de alto nivel como los doctores es muy probable que adquieran o que decidan movilizarse y adquirir vehículo.

Las decisiones del jefe de hogar son recogidas por las informaciones que brindan los integrantes de esa unidad.

Población de estado civil soltero son mas propensos también adquirir vehículos. Entre géneros no se presenta suficiente significancia estadística para decir que alguno de los grupos se decida mas o tenga una mayor probabilidad de comprar autos.

Tabla 4. Efectos marginales del modelo para 2017 en Colombia



VARIABLES	(1) var dep	(2) var dep	(3) var dep	(4) var dep
Utilizan Herra	0.110***	0.110***	0.110***	0.110***
	(0.041)	(0.041)	(0.041)	(0.041)
Edad	-0.018***	-0.018***	-0.018***	-0.018***
	(0.002)	(0.002)	(0.002)	(0.002)
Tamaño hogar	0.039*	0.038*	0.039*	0.038*
	(0.022)	(0.022)	(0.022)	(0.022)
2.Genero		0.011		0.011
		(0.064)		(0.064)
3o.Gen Binario		-		-
2.No casado >2	-0.348**	-0.351**	-0.348**	-0.351**
	(0.156)	(0.156)	(0.156)	(0.156)
3.Viudo	-0.164	-0.171	-0.164	-0.171
	(0.199)	(0.199)	(0.199)	(0.199)
4.Separado Div	-0.358**	-0.363**	-0.358**	-0.363**
	(0.174)	(0.174)	(0.174)	(0.174)
5.Soltero	-0.522***	-0.526***	-0.522***	-0.526***
	(0.166)	(0.166)	(0.166)	(0.166)
6.Casado	-0.332**	-0.340**	-0.332**	-0.340**
	(0.152)	(0.152)	(0.152)	(0.152)
15.Doctorado	0.907*	0.902*	0.907*	0.902*
	(0.505)	(0.505)	(0.505)	(0.505)
2.Propia Crédito	0.297***	0.296***	0.297***	0.296***
	(0.075)	(0.075)	(0.075)	(0.075)
3.Arriendo	0.228***	0.226***	0.228***	0.226***
	(0.064)	(0.064)	(0.064)	(0.064)
4.Usufructo	0.227	0.180	0.227	0.180
	(0.178)	(0.182)	(0.178)	(0.182)
5.Otra forma	-0.459	-0.451	-0.459	-0.451
	(0.286)	(0.286)	(0.286)	(0.286)
Constant	-1.986***	-1.961***	-1.986***	-1.961***
	(0.449)	(0.441)	(0.449)	(0.441)
Observations	27,434	27,364	27,434	27,364

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Fuente: Elaboración propia a partir de las encuestas multipropósito para Bogotá 2017

8. Conclusiones

Uno de los aspectos que caracteriza el desarrollo y el bienestar de una comunidad es la movilidad, entendida como la posibilidad y facilidad de desplazarse de un lugar a otro para realizar diferentes actividades (como trabajar, estudiar, entre otras), mejorando la calidad de vida de las personas. En Bogotá, la movilidad ocupa el tercer puesto de los mayores problemas que enfrenta la ciudad (Redacción Bogotá, 2015). Entre el 2007 y 2015, el número de vehículos registrados aumentó en un 86 %, mientras que la malla vial solo se incrementó 7 % para el mismo periodo (Instituto de Desarrollo Urbano, 2016) y (Secretaría Distrital de Ambiente, 2016).

El incremento de vehículos en la ciudad ha generado congestión vehicular, y ante esta problemática una de las medidas establecidas para contrarestar la misma ha sido el Pico y Placa. No obstante, según lo argumentado por Medina y Vélez (2011), estas medidas drásticas en las que se restringe el uso del automóvil son poco efectivas. Este tipo de medidas, han dado lugar al aumento de la demanda por vehículos por parte de los hogares y negocios, debido a la necesidad de realizar sus actividades económicas.

Además, no han sido acompañadas de una mejora en la estructura vial (Medina Vélez, 2011).

Desde la teoría de la tragedia de los comunes, se entiende a las vías de la ciudad como recursos comunes limitados y ante el evidente incremento de automóviles (que parece ser ilimitado) como un agravante más de la tortuosa situación de movilidad que enfrenta hoy Bogotá. Es por esto que la presente investigación se fundamentó en estudiar los determinantes de la demanda de automóvil y sus implicaciones en la movilidad por hogares haciendo uso de EMB. La economía del transporte cuenta con modelos que permiten estimar estos determinantes, los cuales se basan en la teoría económica de la utilidad aleatoria, desarrollada por Daniel McFadden.

Los principales resultados estadísticos mostraron que el 50 % de la población observada es casada y alrededor del 30 % tienen pregrado y el 20 % postgrado, además el 70 % son asalariados, cuenta propia y vivienda propia. Por las características de las variables observadas, estos resultados apuntan en primera medida a personas que poseen altos ingresos; resultados similares a los encontrados por Galán (2004).

Los resultados econométricos obtenidos en el modelo muestran que el género no es una variable que determine el hecho demandar un carro, también se encuentra que las personas casadas y en unión libre tienen una probabilidad mayor de demandar carro; esto muestra que, por intuición económica, la suma de los ingresos en el hogar es un determinante para la adquisición de un carro. De la misma forma, el nivel educativo de pregrado y posgrado; así como las personas que poseen vivienda propia, son determinantes en la compra de un carro, ya que brinda a las personas un mejor estatus económico que les permite mayores ingresos. Sintetizando estos resultados, se observa que las variables referentes al ingreso, son variables que incentivan la adquisición de más de un carro en Bogotá, hallazgos similares a los encontrados por McFadden (1974) y Galán (2000, 2004, 2005).

Ante esto, una de las alternativas plausibles que generarían descongestión y eficiencia en el uso de los automóviles son los acuerdos de cooperación en el sentido planteado por Ostrom (2009, 2010, 2011). Así, posiblemente, acuerdos de movilidad entre vecinos del sector en el que se habita podría traer una solución al problema de congestión vehicular.

En cualquier caso, se evidencia que existe mucho por elaborar tanto en materia teórica como práctica, en las que se desarrollen y se aborden nuevos análisis que permitan dar soluciones a la problemática sobre movilidad.

9. Bibliografía

Acción de tutela contra Bancos, Sentencia T-170 (Corte Constitucional 25 de Febrero de 2005).

Alcaldía Mayor de Bogotá D.C. (15 de Abril de 2016). Secretaría Distrital de Movilidad. Obtenido de www.movilidadbogota.gov.co/?sec=539

Agostini (2010). Efectos del diferencial de impuestos a las gasolinas en la demanda de automóviles.

Berenson, M. L., Levine, D. M., Krehbiel, T. C. (2006). Estadistica para administración. Mexico D.F.: Pearson.

Borra Marcos, C., Palma Martos, L. (2005). El análisis de la demanda de transporte de mercancías: Revisión metodológica del estado de la cuestión y resultados metodológicos. Cuadernos de CC.EE. y EE.(48), 61-82.

Cabrera Parrado, M. L., Guerrero Maldonado, J. M. (2005). Evaluación de la efectividad de la medida del pico y placa en Bogotá D.C. Bogotá: Pontificia Universidad Javeriana.

Concejo Privado de Competitividad Colombia. (2011 2012). Informe Nacional de Competitividad. Bogotá: Nomos. Coord.: Jaume Arnau . (1996). Métodos y técnicas avanzadas de análisis de datos en ciencias del comportamiento. Barcelona: Universitat de Barcelona.

DANE. (2011). Ficha metodológica encuesta multiproposito para Bogotá. Bogotá: DANE.

Fischer, M. (1993). Travel Demand. European Transport Economics.

Galán González , J. R. (Mayo de 2004). Posesión de coches y elección modal: el caso del Área Metropolitana de Monterrey. Ensayos, XXIII(1), 77-138.

Galán González, J. R. (2000). Determinantes de uso de medios de transporte urbano para el Área Metropolitana de Monterrey: Estimaciones y políticas de transporte. Universidad Autónoma de Nuevo León, 1-53.

Galán González, J. R. (2005). Determinantes de la demanda por transporte público y privado en el Área Metropolitana de Monterrey. Ciencia UANL, VIII(4), 495-501.

Garrett, H. (1968). The Tragedy of Commons. Science, 162, 1243-1248.

Heckman, J. (1979). Sample Selection as a Specification Error. Econometrica, 47, 131-161.

Heilbroner, R. L. (1968). Vida y doctrina de los grandes economistas. Barcelona: Orbis.

Lassibille, G., Navarro, L. (1983). Estimación de modelos de elección cualitativa. 77-102.

Lerma, H. (2009). Metodología de la investigación: propuesta, anteproyectos y proyectos (Cuarta ed.). Bogotá: Ecoe Ediciones.

Libertad contractual/autonomía privada/autonomía de la voluntad, Sentencia T-240/93 (Corte Constitucional 23 de Junio de 1993).

López P., P. (2006). La autonomía privada y los derechos fundamentales. Los intereses generales, Mandato Constitucional. Biblioteca Jurídica Virtual del Instituto de Investigaciones de la UNAM, 146-173.

McFadden, D. (1974). The measurement of urban travel demand. Journal of Public Economics, 3: 303-328.

Mantilla E., F. (2011). El solidarismo contractual en Francia y la constitucionalización de los contratos en Colombia. Revista Chilena de Derecho Privado(16), 187-241.

Medina, C. A., Vélez, C. (2011). Aglomeración económica y congestión vial: los perjuicios por racionamiento del tráfico vehicular. Borradores de Economía(678).

Merryman, J. H. (2012). La tradición jurídica romano-canónica (Vol. XIV). México D.F.: Fondo de cultura económica.

Moré Jaramillo, R., Giret, M. (2013). Movilidad sostenible en Bogotá: Caso metro Bogotá. Universidad del Bosque.

Nolan, A. (2003). The determinants of urban households' transport decisions: A microeconometric study using Irish data. International Journal of Transport Economics, 30(1), 103-132.

Noriega, F. (2006). Energìa Solar. Lima: Norma.

Ortúzar, J., Willumsen, L. G. (1994). Modelling Transport. New Jersey: Wiley.

Ostrom, E. (24 de July de 2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. Science, 325, 419-421.

Ostrom, E. (4 de May de 2010). The intitutional analsys and development framework and the commons. Cornell Law Review, 95, 807-815.

Ostrom, E. (2011). Background on the institutional analysis and development framework. The Policy Studies Journal, 39(1), 7-27.

Páez, J., González, F. (2013). Implementación del modelo LWR en MATLAB para la movilidad en Bogotá. Universidad Nacional de Colombia.

Pedrajas, M. (2006). La transformación ética de la racionalidad ecónomica en Amartya Sen. Una recuperación de Adam Smith. Quaderns de filosofia i ciència, 105-117.

Redacción Bogotá. (22 de Agosto de 2015). Propuestas para mejorar la movilidad de Bogotá. El Espectador.

Rodríguez, I. (2018). Determinantes socioeconómicos de la posesión de automóviles. Universidad Autónoma Metropolitana, 84 (191-212).

Robles, D., Ñañez , P., Quijano, N. (2009). Control y simulación del tráfico urbano en Colombia: Estado del arte. Universidad de los Andes.

Roll, E. (1994). Historias de las doctrinas económicas. México: Fondo de cultura económica.

Ruiz Olabuénaga, J. I. (2012). Metodología de la investigación cualitativa (Quinta ed.). Bilbao, España: Universidad de Deusto.

Sallenave, J. P. (1990). Gerencia y planeación estratégica. Bogotá: Norma.

Sanchez Figueroa, C., Cortinas Vásquez , P., Iñigo Tejera, M. (2012). James Heckman, El sesgo de Selección Multiple. En J. M. Arribas Macho, A. Almazán Llorente , B. Mañas Ramírez , A. Vallejos Izquiero, Historia de la probabilidad y de la estadística VI (págs. 233-241). Madrid: UNED.

Secretaría Distrital de Ambiente. (Junio de 2016). Observatorio Ambiental de Bogotá. Obtenido de http://oab.ambientebogota.gov.co/es/indicadores?id=272

Small, K. A., Verhoef, E. T. (2007). The economics of urban transportation. Routledge.

Smith, A. (1776). Una investigación sobre la naturaleza y causas de la riqueza de las naciones. Londres, Reino Unido: W. Strahan T. Cadell.

Thomson, I., Bull, A. (2002). La congestión del transito urbano: causas y consecuencias económicas y sociales. Revista de la CEPAL(76), 109-121.

Toury, G. (2004). Los estudios descriptivos de traducción y más allá: metodología de la investigación en estudios de traducción. Madrid: Cátedra.

Valderrama Real , J. (2010). Del transporte a la movilidad, algunas reflexiones sobre la evolución de la planeación urbana en Bogotá 1995-2010. Pontifica Universidad Javeriana.

Variable renewable energies to strengthen hydro-dominated power systems against climate change: The Colombian case

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ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) has warned about the potential effects of climate change on different human activity systems. Electric power systems will not be immune to its effects, especially if hydro-dominated. Variable renewable energies (VRE) have been advocated to reduce the CO2 emitted by the energy sector. However, little has been said about their potential to strengthen power systems in the face of climate change. This paper analyzes VRE's role in supporting a hydro-dominated power system in the face of five climate-change scenarios. The Colombian case will be used to this end. It has a hydro-thermal power system, which has proved very vulnerable to extreme weather fluctuations, particularly those brought by El Niño-Southern Oscillation (ENSO). A stochastic optimization model for capacity expansion planning is developed to do so. The model minimizes energy costs and blackout events, subject to various supply and demand constraints. The IPCC's five main climate change scenarios and prospective changes in electricity demand are considered. Model results indicate that VRE are the best way forward to strengthen the Colombian power system, even in the worst-case scenario. Besides being environmentally friendly, the results suggest that VRE are also the fastest and most economical way to expand power capacity in Colombia. Thus, the paper contributes to the literature by proposing a methodology to envisage the effects of climate change in hydro-dominated power systems and potential solutions forward. Also, it reports the particular results for the Colombian case, which has not been analyzed yet in the literature.

Keywords*:* Climate change, power capacity expansion, variable renewable energies, stochastic optimization, Colombia.

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Modelling the delays in power grid expansion for a system based on 100% renewables

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Keywords: renewables; power grid; electricity markets; system dynamics

1. Introduction

Solar and wind power have become attractive alternatives to reduce dependence on hydroelectricity generation and to guarantee system reliability (Carvajal-Romo et al., 2019; Rueda-Bayona et al., 2019). This raises questions regarding the extent of the spreading of renewables, their effect on security of supply and their economic impact (Zapata et al., 2019). However, these questions have been explored without including electricity transmission capacity. Recently, Colombia has been unsuccessful in promoting renewables through Law 1715, 2014, due to implementation deficiencies and a lack of transmission infrastructure.

In Colombia, the best region for wind power production is in the north and several dams are in the centre of the country. New renewable capacity requires more transmission infrastructure to ensure electricity transport to demand centres (Herrera et al., 2019; Velasco et al., 2011), that is, the deployment of this renewable energy must overcome an important barrier, the transmission connections that link the projects to the grid. Thus, despite the existence of Law 1715, Colombia has not yet developed its transmission infrastructure sufficiently to support solar and wind technologies. Thus, this paper might contribute to the planning of 100% renewable energy systems and limited power grid facilities.

Colombia has large potential for new renewable energy, mainly wind and solar (López et al., 2020). The north of Colombia is the best region for wind power production, with average speed values between 8 and 12 m/s at 80 meters high, this wind regime is rated among the best in South America (Carvajal-Romo et al., 2019; Mejía et al., 2006). The greatest potential of solar resources is found in the department of La Guajira with radiation of 6 kWh/m2/day (UPME, 2002). Currently, it is expected that solar and wind power capacity will grow by 8,863 MW before 2030 (UPME, 2021). In this context, it may be worth emphasising that high-quality renewable resources are located far from existing demand centres. In addition, as the rest of Colombia is mainly hydrothermal, it is important to consider the energy exchanges required between northern Colombia (La Guajira) and the rest of the country, and how these may contribute to achieving the country's energy needs through 100% renewable energy.

There is much uncertainty concerning the implementation of Law 1715 due to multiple delays to the licencing of new projects. Multiple policy barriers, as well as lack of infrastructure, are preventing the major addition of renewables into the power grid (Henao et al., 2019). This is like the situation in Brazil, where there are delays in grid constructions of well over three years (Bayer, 2018; Herrera et al., 2020; Ochoa et al., 2013).

2. Methodology

In this context, the main objective is to assess the intraday electricity dispatch between regions in Colombia until 2030 to analyse the impact of delays in the construction of both transmission and renewable energy infrastructure. Colombia has been selected because of its favourable conditions to generate electricity from RES. In this way, the paper shows the intraday electricity dispatch between regions incorporating delays to transmission construction in the system. To do this, our research adopts the system dynamics (SD) modelling approach, which has been used successfully for assessing the difussion of renewables in the Colombian electricity market. Many of these studies consider the effects of the insertion of renewables, but none incorporates transmission infrastructure. The modelling approach used here proposes a dynamic behaviour hypothesis, builds a simulation model, conducts its validation, and assesses four scenarios.

This paper uses scenario analysis to explore future pathways for the Colombian electricity system. These scenarios consider possible delays in transmission line projects, renewable power plant projects and the hourly electricity dispatch between regions. For the latter, an electricity dispatch is carried out during the day and another at night. A day starts at 6:00 am and finishes at 6:00pm, while night starts at 6:00pm and finishes at 6:00am. The simulation time horizon is 9 years, between 2021 and 2030.

3. Results

The results show that the excess energy produced from renewable power plants in the northern region will be exported to the central region of Colombia. However, most of the projects awarded at the renewable auction may not go into operation as planned due to transmission problems between the northern and the central region of the country. Under this scenario the insufficient transmission infrastructure slows down the energy exchange between regions.

4. Conclusion

This paper shows that the hydropower capacity in place in Colombia along with its solar and wind energy potentials may be used to balance the energy needs of both regions in the country. During the day, the energy surplus produced by the renewable resources of the northern region is exported to the central region to supply electricity demand. At night, the energy surplus produced in the central region from run of river power plants and hydropower plants is exported to the northern region. These energy exchanges may be affected by delays in renewable energy projects and transmission lines, which has environmental consequences.

Expansión de la transmisión bajo la transformación de la industria eléctrica

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Introducción

La entrada de las energías renovables no convencionales (ERNC) como la solar y eólica a gran escala, la generación distribuida y el almacenamiento están creando un nuevo rumbo en la planeación de la generación y transmisión del sistema eléctrico a largo plazo [Zhang et al. 2020]. La transición energética está provocando grandes cambios en la planeación del sistema, debido a la ubicación de las nuevas plantas de generación solar y eólica, el cambio en los patrones de generación y consumo de energía y la incertidumbre que existe por la disponibilidad de los recursos energéticos en el corto y largo plazo[Lu et al. 2020]. Es de suma importancia comprender que la expansión de la transmisión depende de tres pilares importantes; los cuales son: el crecimiento de la demanda de energía, la ubicación de las nuevas plantas de generación y la disponibilidad de los recursos naturales [Liu et al. 2017; Nie et al. 2018]. Además, la planeación de la transmisión es mandatoria, puesto que depende de los proyectos de generación que la UPME y el CAPTD definan para su adjudicación a los agentes transmisores; lo cual exige que ante la entrada de estas nuevas tecnologías se realice una buena coordinación entre los generadores y transmisores para que puedan brindar el suministro de energía cuando el sistema lo requiera [Gbadamosi & Nwulu, 2020]. La transmisión siempre se ha definido como un monopolio regulado, ya que podría ejercer alguna dominancia sobre las redes eléctricas e imponer precios costosos. Teniendo en cuenta lo anterior la descentralización del sistema y la disminución del uso de las redes en las horas de sol, podría presentarse una modificación en la regulación provocando un cambio en el comportamiento del agente transmisor; ya que podría pasar de ser un agente pasivo a uno activo [Iria & Soares, 2019].

Metodología

En la literatura se identificaron algunos estudios de la expansión de la transmisión con la transición energética. Las principales metodologías que se encontraron fueron: optimización, simulación y estadística, entre otros. Las comentadas anteriormente presentaron algunas limitaciones para predecir el comportamiento de la transmisión a largo plazo teniendo en cuenta la transición energética. La optimización, por ejemplo, asume racionalidad perfecta. La estadística no permite representar el cambio estructural que está presentando el sistema con la entrada de las nuevas tecnologías. Adicionalmente, los modelos de simulación y optimización existentes son muy detallados y pesados computacionalmente. La mayoría de dichos modelos fueron desarrollados para resolver problemas de corto plazo, en los que es importante modelar todos los detalles técnicos de la red, sin embargo, son poco útiles para predecir el largo plazo, ya que requieren demasiados datos de entrada que dificultan el análisis de escenarios. Se propone entonces desarrollar un modelo de dinámica de sistemas para representar las necesidades de transmisión, puesto que es una herramienta que se basa de la causalidad, permite tener en cuenta las retroalimentaciones entre las diferentes variables para representar el comportamiento del sistema a largo plazo, y es sencillo analizar diferentes escenarios. En la creación del modelo se tuvo en cuenta las zonas eléctricas de cada país con el propósito de simular las diferentes interconexiones entre las zonas. El modelo de dinámica de sistemas se basa de tres variables principales para construir nuevos kilómetros de transmisión; las cuales son: el crecimiento de la demanda de energía eléctrica, la entrada de nueva potencia de generación y la congestión de la red (desbalances entre la oferta y demanda de cada zona eléctrica).

Resultados

El modelo representa el efecto de la transición energética en las necesidades de transmisión de Colombia, Perú, Brasil y Chile. Se obtuvieron las necesidades de transmisión a nivel interno de cada zona eléctrica, de interconexión entre las zonas y las necesidades de generación a 2040 en cada país. Los resultados de las simulaciones muestran que el impacto de la introducción de la generación distribuida (DER) en las necesidades de transmisión depende de dos variables principales las cuales son: la capacidad instalada de hidroeléctricas con embalse que permitan desplazar la disponibilidad de energía y la cantidad de generación de energía solar que producen los módulos solares para disminuir la importación de energía de las zonas eléctrica. El modelo tiene un mayor impacto en Colombia y Brasil, puesto que son países con una matriz hidráulica considerable; lo cual produce que la disminución de la demanda de energía en las horas de sol provoque almacenamientos de agua mayores en los embalses que resultan en una mayor disponibilidad de la generación hidroeléctrica; esto genera un retraso en las necesidades de inversión en generación y, por tanto, de transmisión. Como se comentó anteriormente la congestión de la red entre las zonas eléctricas de los países disminuye, puesto que las zonas pueden autoabastecer una porción de su energía en diferentes horas, provocando una reducción en la importación de energía de las zonas importadoras. Por otro lado, Perú y Chile tienen un impacto mucho menor en las necesidades de transmisión que los otros países, ya que la matriz hidráulica de estos es muy pequeña. Teniendo una disminución de la demanda de energía de la red en las horas de sol considerable, no se produce una disminución significativa en el despacho de energía hidráulica, ya que la capacidad de hidro es escasa y no alcanza a ser desplazada. Sin embargo, se aprecia una pequeña disminución en los kilómetros de estos países por la disminución en la congestión de la red.

Conclusiones

A través de dinámica de sistemas se representaron los efectos que podría tener la transición energética en las necesidades de transmisión. En resumen, la entrada de generación distribuida y de las ERNC a gran escala pueden llegar a disminuir las necesidades de transmisión; sin embargo, depende el comportamiento de otras variables como la generación hidráulica de cada país, el crecimiento de la demanda y la ubicación de las nuevas tecnologías de generación en las diferentes zonas eléctricas. Adicionalmente, poder comparar diferentes países nos demuestra que depende de las condiciones y características de cada país.

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Referencias

Gbadamosi, S. L., & Nwulu, N. I. (2020). A multi-period composite generation and transmission expansion planning model incorporating renewable energy sources and demand response. *Sustainable Energy Technologies and Assessments*, *39*(October 2019), 100726. https://doi.org/10.1016/j.seta.2020.100726

Iria, J., & Soares, F. (2019). Real-time provision of multiple electricity market products by an aggregator of prosumers. *Applied Energy*, *255*(May), 113792. https://doi.org/10.1016/j.apenergy.2019.113792

Liu, Z., Huang, G., Wu, C., Ji, L., & Niu, D. (2017). Factorial Based Stochastic Optimization Approach for Energy and Environmental Systems Management Under Uncertainty. *Environmental Engineering Science*, *34*(7), 469–480. https://doi.org/10.1089/ees.2016.0180

Lu, X., Li, K., Xu, H., Wang, F., Zhou, Z., & Zhang, Y. (2020). Fundamentals and business model for resource aggregator of demand response in electricity markets. *Energy*, *204*, 117885. https://doi.org/10.1016/j.energy.2020.117885

Nie, S., Huang, Z. C., Huang, G. H., Yu, L., & Liu, J. (2018). Optimization of electric power systems with cost minimization and environmental-impact mitigation under multiple uncertainties. *Applied Energy*, *221*(March), 249–267. https://doi.org/10.1016/j.apenergy.2018.03.194

Zhang, C., Cheng, H., Liu, L., Zhang, H., Zhang, X., & Li, G. (2020). Coordination planning of wind farm, energy storage and transmission network with high-penetration renewable energy. *International Journal of Electrical Power and Energy Systems*, *120*(March), 105944. https://doi.org/10.1016/j.ijepes.2020.105944

Desarrollo de un modelo de pronóstico meteorológico de radiación solar y temperatura ambiente empleando series temporales en el municipio del Inírida – Colombia.

Development of a meteorological forecast model of solar radiation and ambient temperature using a time series in the municipality of Inírida - Colombia.

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Resumen

En este trabajo se presenta el desarrollo de un modelo de pronóstico meteorológico como una herramienta importante para la toma de decisiones en el campo de la generación de energía, a base de recursos renovables en el municipio del Inírida, departamento del Guainía, Colombia.

Estos modelos atmosféricos permiten el pronóstico de variables como, temperatura, velocidad del viento y radiación solar, haciendo uso de modelos matemáticos como el Autorregresivos Integrados de Medias Móviles (ARIMA) que permiten estimar su comportamiento futuro. Este tipo de modelos de series de tiempo basado en el uso de la metodología Box-Jenkins permite identificar la fiabilidad para generar pronósticos de carácter aleatorio como las variables atmosféricas.

La base de datos de las variables de temperatura y radiación solar, fueron obtenidas de la plataforma Prediction Of Worldwide Energy Resources (POWER - power.larc.nasa.gov), cuya información está relacionada a la investigación de recursos energéticos y meteorológicos a nivel mundial realizados por la NASA, con el objetivo de apoyar la energía renovable y la creación de conjuntos de datos a partir de nuevos sistemas satelitales. La disponibilidad e información de datos es de acceso abierto.

La base de datos está compuesta por variables meteorológicas, que se consolidan mensualmente desde el año 2000 hasta el año 2022, recolectando 7811 datos para cada variable meteorológica como la temperatura ambiente y la radiación solar, cuyo análisis y caracterización fueron desarrollados bajo el software RStudio.

Este modelo contribuye al desarrollo de una herramienta para la predicción y estimación del potencial solar como proceso de planeamiento energético en el dimensionamiento de generación distribuida solar fotovoltaica, favoreciendo la diversificación de la matriz energética de la región.

Palabras claves: ARIMA, pronóstico, radiación solar, series de tiempo, modelo, aleatorio.

1. Introducción

El aumento de la población mundial está directamente relacionado con la demanda energética que es cada vez mayor, las fuentes energéticas convencionales escasean y se busca nuevas formas de energía que entren a suplir el déficit [1]. Es por esto que la energía juega un papel fundamental en el desarrollo económico y social de las comunidades, está presente en cualquier actividad económica en el mundo desarrollado ya que cualquier actividad industrial, comercial o de transportes está íntimamente ligada al consumo de energía. Su necesidad está también relacionada con el estado de bienestar y comodidades presentes en los hogares [2].

Como alternativas de solución a esta crisis energética, la contaminación ambiental y el calentamiento global [3], se resalta la importancia de buscar mayor promoción e implementación de fuentes de energía ambientalmente sostenibles, es decir fuentes de energía limpias, es así que la mayoría de los países está tomando conciencia acerca de la importancia de utilizar tecnologías innovadoras para la generación de energía amigable con el ambiente.

Es por esto, que en los últimos años, el sector eléctrico ha mostrado un interés por la Generación Distribuida (GD) debido a diversos factores como: avances en las tecnologías de generación a pequeña escala, la liberación del sector eléctrico y una renovada conciencia ecológica [4]. Otra causa que genera mayor interés en la Generación Distribuida es la contribución al desarrollo sostenible; ya que ésta se asocia comúnmente con la producción de energías limpias y la contribución a la seguridad energética mejorando los niveles de confiabilidad del sistema eléctrico de potencia [5].

Para el caso específico de Colombia se promueve la Generación Distribuida (GD) en su plan nacional de desarrollo, ya que por su ubicación privilegiada cuenta con diversos recursos para implementar tecnologías limpias (biomasa, solar, eólica, geotérmica) y asegurar una provisión energética eficiente en Zonas No Interconectadas (ZNI) que corresponden al 52% del territorio nacional, caso que ya se viene presentando a baja escala [6]. Sin embargo, las Zonas No Interconectadas (ZNI), que no tienen acceso a un servicio de energía eléctrica constante y de calidad a través de un sistema interconectado debido a los costos y a los impactos ambientales que tendría la instalación de la infraestructura necesaria, pero que cuentan con soluciones locales, generalmente a partir de combustibles líquidos [7]. Esto afecta directamente la calidad de vida de las personas, ya que se restringen las horas con acceso a energía con la consecuente disminución de las oportunidades de educación, la productividad y el acceso a las tecnologías de la información y la comunicación (TIC), lo que perpetúa, a su vez, la desigualdad regional en el país [8].

Entre estas tecnologías, los sistemas fotovoltaicos se constituyen como una alternativa que se ha fortalecido recientemente, gracias a que los costos se han reducido gradualmente en los últimos años y el desarrollo tecnológico ha mejorado la eficiencia de sus componentes [9]. Por otro lado, la energía solar como fuente primaria de energía (energía solar foto-voltaica o térmica) se caracteriza por ser una fuente inagotable y limpia, ya que su proceso de captación, transformación y conversión a energía eléctrica depende de factores climáticos, geográficos y técnicos.

En los sistemas de generación fotovoltaico, la capacidad de generación de electricidad solar está estrechamente ligada a condiciones climáticas en la región donde se quiera implementar el sistema [10],[11], es así que para el diseño de sistemas de generación fotovoltaica, los parámetros ambientales más importantes son la irradiancia solar y la temperatura, que se caracterizan por tener un comportamiento intermitente, debido a fenómenos atmosféricos como las precipitaciones, las nubes, las altas y bajas temperaturas, los vientos, etc. Estas fluctuaciones e intermitencias presentes en la base de datos climáticos tienen una consecuencia en la producción de energía y en el índice de desempeño de sistemas de generación fotovoltaicos [12]. Por lo que se busca y se hace necesario el desarrollo de herramientas que permitan obtener información del comportamiento de los parámetros ambientales como la irradiancia solar y la temperatura ambiente de cualquier parte del mundo, ya que un pronóstico confiable y eficiente pueden conducir a la toma de decisiones y un aprovechamiento más eficiente de la energía producida en las centrales solares.

En este trabajo se desarrolló una metodología usando técnicas de series temporales con modelos ARIMA (autoregressive integrated moving average, por sus siglas en inglés) [13],[14],[15],[16], con el objetivo de caracterizar la predicción y estimación del comportamiento real de la irradiancia solar y la temperatura ambiente, utilizando la base de datos de la plataforma Prediction Of Worldwide Energy Resources (POWER - power.larc.nasa.gov) [17], como proceso de planeamiento energético para el dimensionamiento conceptual de generación distribuida solar fotovoltaica.

2. Metodología

En el presente trabajo se describe la metodología de caracterización de variables ambientales usando técnicas de series temporales, cuyo objetivo fue la predicción y estimación del comportamiento de la irradiancia solar y la temperatura ambiente como condición inicial para el dimensionamiento conceptual de generación solar fotovoltaica del municipio del Inírida, departamento del Guainía, Colombia, georefenciado con las siguientes coordenadas 95 metros de altitud · Latitud: 3.867. Longitud: -67.917.

En principio, se puede definir que las series de tiempo son un conjunto de información o datos que se observan durante un periodo de tiempo, como también un proceso estocástico, cuyo objetivo principal es describir y predecir algún proceso de variables aleatorias según un determinado parámetro. Estas variables pueden ser discretas o continuas ordenadas respecto al tiempo [18], [19], [20].

Específicamente se empleó la metodología Box-Jenkins [21], estimando modelos ARIMA (AutoRegresive Integrated Moving Average), para las variables ambientales que se abordaron en esta investigación. La metodología consta de 4 etapas que incluyen: la identificación del modelo, ajuste del modelo, validación de modelo y pronóstico.

Este modelo busca describir de la manera más óptima los pronósticos de la serie estocástica; es decir, en función de datos históricos determinar el modelo probabilístico que rige el comportamiento de la serie temporal.

El modelo general ARIMA (p,d,q) toma la expresión general de la siguiente ecuación:

$$\left(1 - a_1 L_1 - a_2\, L_2 - \cdots \ldots . -a_p L_P\right)(1 - L) dY_t$$

$$= \left(1 - b_1 L_1 - b_2\, L_2 - \cdots \ldots . b_q L_q\right)\varepsilon_t \qquad (1)$$

Siendo:
Y_t: Valor de la variable en el momento t.
L: Operador de retardos (Yt-1=Yt*L).
a_p: Coeficientes del operador de retardos para el componente autorregresivo.
b_q: Coeficientes del operador de retardos para el componente de medias móviles.
ε_t: Componente aleatoria.

3. Filtrado de Datos

Inicialmente se han recopilado de la base de datos Prediction Of Worldwide Energy Resources (POWER), las variables meteorológicas de la irradiancia solar, y la temperatura ambiente para el tratamiento estadístico y econométrico. Los programas informáticos usados fueron Microsoft Excel y RStudio.
Para la irradiancia solar y la temperatura ambiente se tomaron los datos como base inicial desde enero del año 2000 hasta julio del año 2022, lo que representa un total de 7811 datos diarios por cada variable agrupado por meses y años.
Una vez se consolida la cantidad de datos para cada variable, estos son procesados empleando modelos ARIMA, con el fin de obtener el mejor modelo que se ajuste a los datos reales.

4. Resultados y discusión

En este análisis y procesamiento de datos (variables de temperatura ambiente e irradiancia solar) se utilizó la metodología Box-Jenkins, compuesta por 4 etapas del modelo que incluyen: la identificación, el ajuste, la validación y el pronóstico, como se observa en la Tabla 1.

Metodologia Box-Jenkins			
Etapas metodología		Descripción de las etapas del Modelo	
1	*Identificación del Modelo*	Gráfico de la serie	*Generar la gráfica de la serie de tiempo. * Se observa si la serie es estacionaria, es decir, si la serie de tiempo parece variar alrededor de un nivel fijo.
		Análisis de la Función de Autocorrelación y Autocorrelación Parcial (ACF) (PACF)	*Análisis de los Correlogramas muestral. *Proporciona la autocorrelación en todos los retrasos posibles. *Ayuda a identificar el número de coeficientes.
		Prueba de Dickey – Fuller	Hipótesis: H0:H0: La serie es no estacionaria: Tiene raíz unitaria H1:H1: La serie es estacionaria: No tiene raíz unitaria
		Primera Diferencia ó Segunda Diferencia	* Se toma la primera diferencia a la serie. * Se observa que la serie se estabiliza en torno a un valor medio.
		Gráfico de la serie Diferenciada	*Generar la gráfica de la serie Diferenciada. * Análisis de los Correlogramas Diferenciados. * Prueba de Dickey – Fuller.
2	*Ajuste del Modelo*	Selección de Modelos	* Selección y prueba de modelos tentativos.
		Criterio de informacion (AIC) de Akaike y error estandar σ2	* Comparar los modelos con los valores mas bajos de AIC y σ2
3	*Validación del Modelo*	Estacionariedad de los residuos.	* Estacionariedad entre los residuales del modelo. * Esto lo confirmaremos con un correlograma.
		Autocorrelacion de los residuos	* Los correlogramas muestran que no existe autocorrelación significativa en los residuos.
		Normalidad de los residuos	* Los gráficos Q-Q son una herramienta eficaz para evaluar la normalidad. * Los puntos tienden a seguir la línea recta bastante de cerca.
4	*Pronóstico del Modelo*	Modelo ARIMA	* Los parámetros del modelo ARIMA se pueden usar como modelo predictivo para hacer pronósticos de valores futuros

Tabla 1. Etapas de la Metodología Box-Jenkins.
Fuente: elaboración propia.

Caso A. Temperatura Ambiente

Los datos analizados y monitoreados son los valores promedio diario y mensual de temperatura ambiente registrado en la capital de Inírida, departamento del Guainía, Colombia, reportados por la base de datos POWER.

1) Identificación del modelo

- Graficas: Se grafican las curvas del patrón de tendencia y la serie de tiempo de la temperatura promedio diario mensual para observar si la serie es estacionaria, es decir, si la serie de tiempo parece variar alrededor de un nivel fijo.

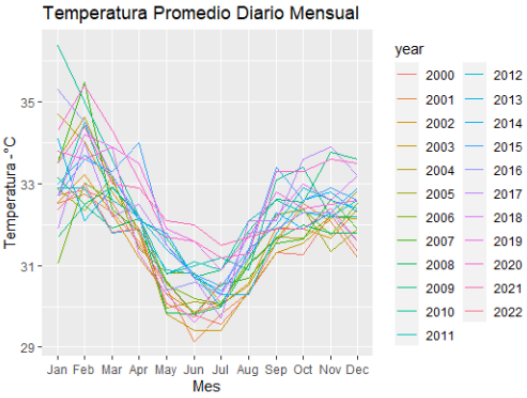


Figura 1. Patrón de tendencia - Temperatura Diaria Mensual - año 2000 hasta 2022.
Fuente: elaboración propia.

En la Figura 1, se observa el patrón de tendencia de la temperatura promedio diario mensual por año, donde se registran los máximos datos de temperatura en los meses de febrero y marzo con valores entre 34 °C y 35,5 °C y los mínimo datos de temperatura con registros que oscilan entre los 29,3 °C y 30 °C entre los meses de mayo hasta agosto. Este patrón de tendencia cuenta con registros de la temperatura promedio mensual desde los años 2000 hasta el año 2022.

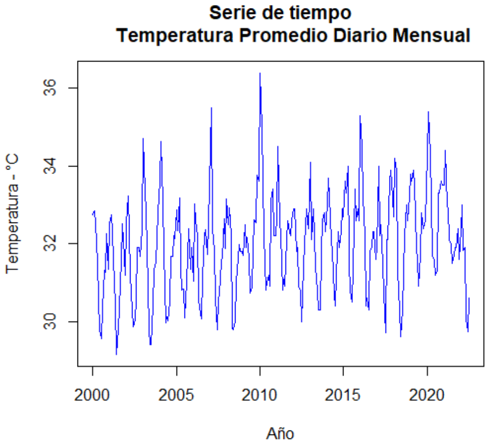


Figura 2. Serie de tiempo – Temperatura Diaria Mensual – Año 2000 hasta 2022.
Fuente: elaboración propia.

En la Figura 2, aparece el gráfico de la serie de tiempo donde se proyectan los promedios diarios mensuales, el grafico nos indica un leve cambio en el nivel promedio de la serie como una leve tendencia, por lo tanto, se considera que esta serie es no estacionaria, se deduce que los datos no tienen una media ni varianza constante.

- Correlograma de la serie original (ACF y PACF).

La función de auto correlación (ACF y PACF) proporciona la auto correlación en todos los retrasos posibles.

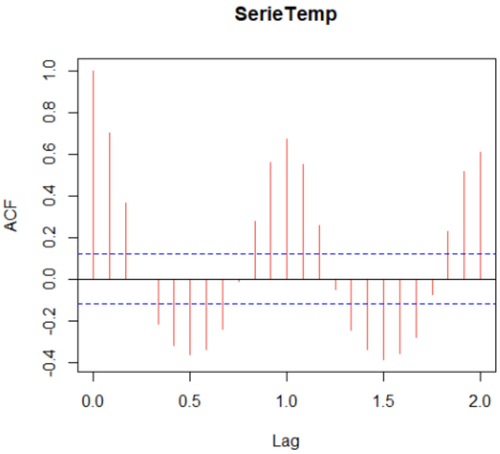


Figura 3. Función de Autocorrelación.
Fuente: elaboración propia.

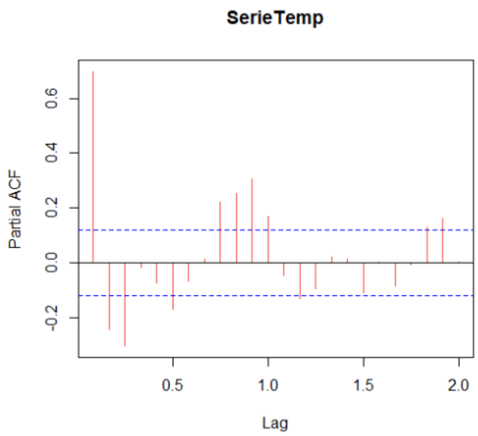


Figura 4. Función de Autocorrelación Parcial.
Fuente: elaboración propia.

Adicionalmente, al observar la gráfica de la Figura 3 y Figura 4, se ve que los valores del correlograma ACF tienden a decrecer muy lentamente por lo que se considera que no es estacionaria. Ya que se debe cumplir que los datos sean estacionarios

- Primera Diferencia: Se toma la primera diferencia ordinaria a la serie de tiempo original.

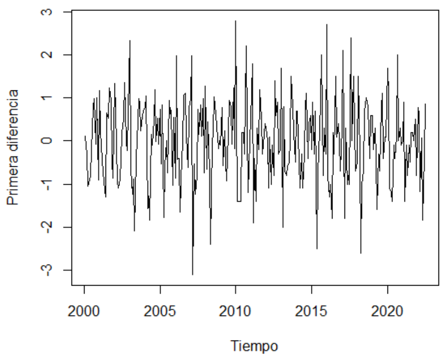


Figura 5. Serie de tiempo con la primera diferencia.
Fuente: elaboración propia.

Como se nota en la Figura 5, al tomar las primeras diferencias observamos que la serie se estabiliza en torno a un valor medio, se deduce que los datos tienen una media y varianza constante.

- Correlograma de la serie diferenciada (ACF y PACF).

Si se hace una diferencia a la serie de tiempo original se observa que el correlograma ACF y PACF 1era Diferencia de la Figura 6 y 7, presentan un declinamiento rápido en función del tiempo. Se considera que la serie con la primera diferenciada es estacionaria. Ya que se debe cumplir que los datos sean estacionarios. Para corroborar la estacionariedad se aplica la prueba de Dickey – Fuller.

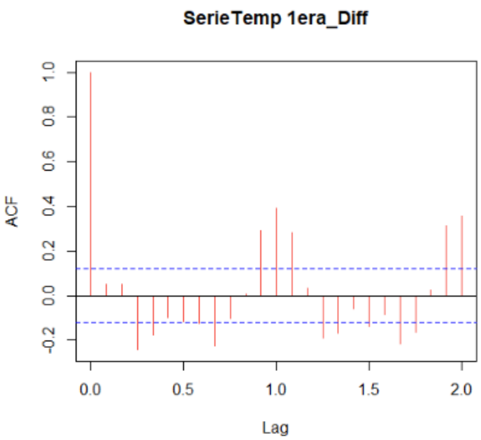


Figura 6. ACF 1era Diferencia.
Fuente: elaboración propia.

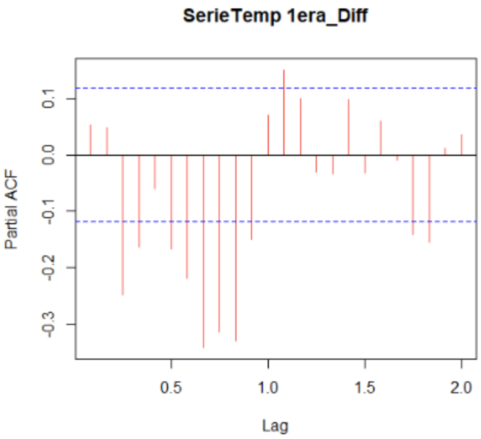


Figura 7. PACF 1era Diferencia.
Fuente: elaboración propia.

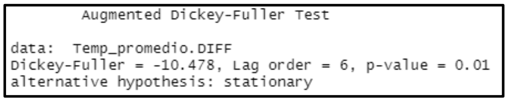
- Prueba de Dickey – Fuller:

Estos valores del estadístico de prueba de Dickey – Fuller, comprueban la estacionariedad de las series temporales si el p-valor se encuentra < 0.05.

Esta prueba se aplica a la serie de primera diferencia.

Hipótesis:

H0:H0: La serie es no estacionaria: Tiene raíz unitaria
H1:H1: La serie es estacionaria: No tiene raíz unitaria



```
        Augmented Dickey-Fuller Test

data:  Temp_promedio.DIFF
Dickey-Fuller = -10.478, Lag order = 6, p-value = 0.01
alternative hypothesis: stationary
```

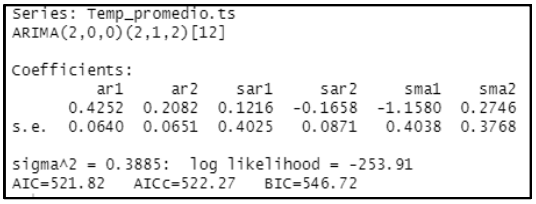
Tabla 2. Prueba de Dickey–Fuller.
Fuente: elaboración propia.

Esta prueba ejecutada como lo muestra la Tabla 2, indica que el valor obtenido del estadístico Dickey-Fuller fue de (-10,478), con un p-valor menor a 0,05 por lo que la hipótesis nula cae en la región de rechazo, ósea que la serie con una primera diferencia ordinaria indica que es estacionaria.

Una vez que se ha obtenido la serie de tiempo estacionaria, se pasa a identificar la forma del modelo que se utilizará.

2) Ajuste del modelo

- Modelos: Selección y prueba del modelo tentativo.



```
Series: Temp_promedio.ts
ARIMA(2,0,0)(2,1,2)[12]

Coefficients:
         ar1     ar2    sar1     sar2     sma1    sma2
      0.4252  0.2082  0.1216  -0.1658  -1.1580  0.2746
s.e.  0.0640  0.0651  0.4025   0.0871   0.4038  0.3768

sigma^2 = 0.3885:  log likelihood = -253.91
AIC=521.82   AICc=522.27   BIC=546.72
```

Tabla 3. Ajuste automático de los coeficientes ARIMA
Fuente: elaboración propia.

La Tabla 3, nos muestra el resultado del modelo ARIMA (p,d,q)(P,D,Q) - (2,0,0) (2,1,2)[12], usando la función automática del comando RStudio "auto.arima". También muestra los coeficientes ajustados y el error estándar (s.e.) para cada coeficiente. Los vectores (p,d,q) corresponde a la parte regular o tendencia y la parte estacional (P,D,Q).

- Encontrar el Criterio de Información (AIC) de Akaike y error estándar σ2.

Para escoger el mejor modelo se debe encontrar el Criterio de información (AIC) de Akaike para un conjunto de modelos y comparar los modelos con los valores de AIC más bajos, este proceso se hace cuando se comparan varios modelos ARIMA. Los resultados del valor de AIC = 521,82 y σ2=0,3885 son los entregados y calculados por la función automática "auto.arima".

3) Validación del modelo

- Estacionariedad residual.
- Función de Autocorrelación Residual.
- Estadístico de Ljung-Box Test – Hipótesis Validez de ruido Blanco.
- Normalidad de los residuos – Grafica Q-Q.

En este paso se comprueba la eficiencia del modelo y se decide si es estadísticamente adecuado, ya que los residuales deben ser independientes entre sí o completamente aleatorios.
Las perturbaciones aleatorias o ruido blanco no se pueden identificar directamente en una serie de tiempo. Sin embargo los residuales del modelo ARIMA ecuación (2), proporcionan un cálculo aproximado de las perturbaciones reales a_t [22].
Por lo tanto, si los residuales están correlacionados de alguna manera, significa que estos no son ruido blanco y se debe buscar otro modelo cuyos residuales sean completamente aleatorios.

$$\hat{a}_t = y_t - \hat{y}_t \qquad (2)$$

Donde
$\hat{a}_t$: Residual en el tiempo t.
y_t: Serie Original.
$\hat{y}_t$: Serie calculada con los parámetros estimados.

La función de autocorrelación de los residuales, se utiliza para determinar si el modelo es estadísticamente adecuado. El cálculo de los coeficientes de autocorrelación de residuales se realiza por la siguiente formula (3). Mediante esta función se busca que los coeficientes de autocorrelación sean cero o cercanos a él [22].

$$r_k(\hat{a}) = \frac{\sum_{t=1}^{n-k}(\hat{a}_t-\bar{a})(\hat{a}_{t+k}-\bar{a})}{\sum_{t=1}^{n}(\hat{a}_t-\bar{a})^2} \qquad (3)$$

Donde:
$r_k(\hat{a})$: Coeficiente de autocorrelación residual para un retraso de k periodos.
$\hat{a}_t$: Residual en el periodo t.
$\bar{a}$: Media de los residuales.
$\hat{a}_{t+k}$: Residual en el periodo con k retrasos.
n: Número total de residuos

El estadísticos de Ljung-Box Test – Hipótesis Validez de ruido Blanco, se enfoca al análisis de los coeficientes de autocorrelación de los residuales, pero de manera grupal. Esta prueba considera un conjunto de K coeficientes de autocorrelación. La ecuación (4) es la que define el estadístico de Ljung-Box [23].

$$Q^* = n(n+2)\sum_{k=1}^{k}(n-k)^{-1}r_k(\hat{a}_t)^2 \qquad (4)$$

Donde:
$n = n - d$
n: Es el número de observaciones de la serie.
d: Es el grafico de la diferenciación.
$r_k(\hat{a}_t)^2$: es el cuadrado de $r_k(\hat{a}_t)$.
k: Numero de autocorrelaciones, puede ser (6,12,18,24).

La validez del ruido blanco, se comprueba si:

- El valor del estadístico es mayor que 0.01 pero menor que 0.05, el modelo se rechaza.

- Si el valor del estadístico es mayor a 0.05, el modelo es aceptado. Esto significa que el error es igual a cero y la varianza constante.

Para ejemplificar la validación del modelo, analizamos las Figura 8, de acuerdo a la selección del modelo ARIMA propuesto automáticamente, donde se observa que:

- La gráfica de Estacionaridad Residual, cumple con el criterio de presentar media cero y varianza constante.

- La grafica de la Función de Autocorrelación Residual, cumple, por lo tanto el modelo se acepta estadísticamente. Esto debido a que se establece que los coeficientes de los valores de autocorrelación No son significativos, ya que no sobrepasan las bandas de puntos según la gráfica, y los residuales son independientes entre sí.

- La grafica del Estadístico de Ljung-Box Test, y los resultados de la Tabla 4, demuestran y comprueba la validez del modelo, ya que el valor del estadístico es mayor a 0.05, por lo tanto el modelo es aceptado estadísticamente. Esto significa que se puede dar paso al cálculo del pronóstico.

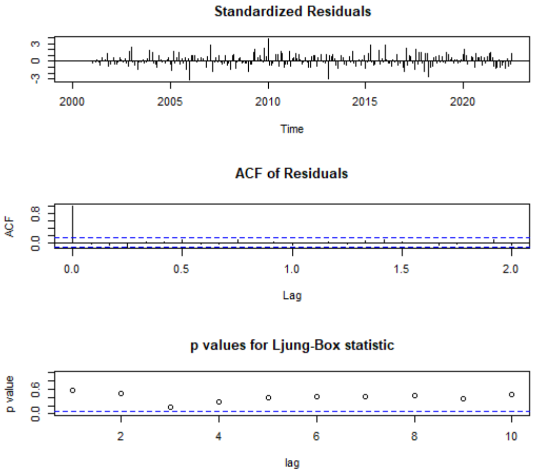
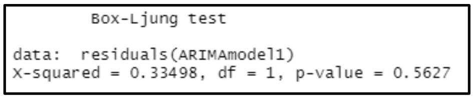


Figura 8. Estacionariedad residual, ACF residual, p _values Ljung - Box
Fuente: elaboración propia.



```
        Box-Ljung test

data:  residuals(ARIMAmodel1)
X-squared = 0.33498, df = 1, p-value = 0.5627
```

Tabla 4. Prueba del estadístico Ljung-Box
Fuente: elaboración propia.

Normalidad de los residuos – Grafica Q-Q. Los gráficos Q-Q (quantile-quantile) son una herramienta eficaz para evaluar la normalidad, en la Figura 9, se puede observar que los puntos tienden a seguir la línea recta bastante cerca; esto indica que se acepta la normalidad de los residuos en este modelo.

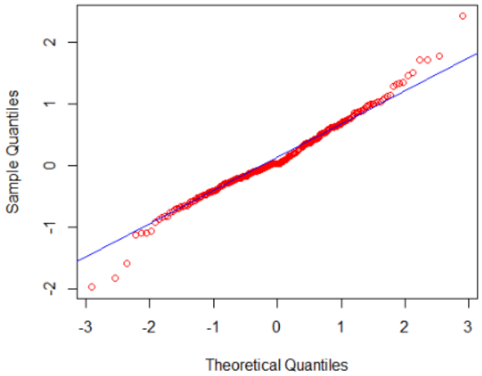


Figura 9. Grafico Q-Q para evaluar
Fuente: elaboración propia

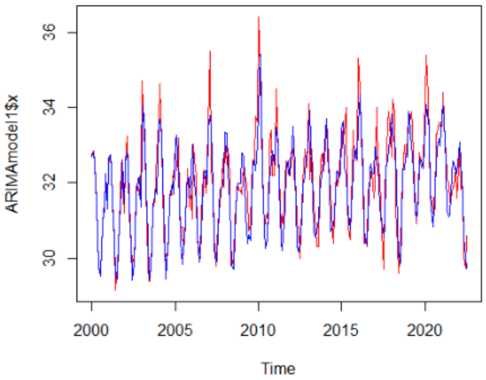


Figura 10. Grafico de datos observados Vs datos esperados.
Fuente: elaboración propia

En la Figura 10, se puede observar que la curva de color rojo hace parte del modelo diferenciado (observado), y la curva de color azul hace parte del modelo ajustado o esperado, indicando que estas se sobreponen o se corresponden casi en sincronismo, cumpliendo con las características de un patrón de ruido blanco. Indicando que el modelo es adecuado para el pronóstico.

4) Pronostico

Es importante restablecer o hacer la integración de la serie temporal para el pronóstico adecuado del modelo.

Para el pronóstico de nuestro modelo, proyectamos la serie a 48 meses, como se observa en la Figura 11, con tendencia a presentar picos máximos de temperatura cercanos a los 36°C y temperaturas promedio mínimo de 29,5 °C durante los cuatro periodos anuales de muestreo, iniciando el análisis de pronostico en julio de año 2022 y finalizando en julio del año 2026, como se refleja en la Tabla 5.

Es importante destacar que el pronóstico modelado posee intervalos de confianza asociado a la probabilidad de que el dato de la variable de temperatura se encuentre dentro de dicho intervalo de confianza.

El intervalo de confianza del modelo se establece con el 80% y 95% de probabilidad.

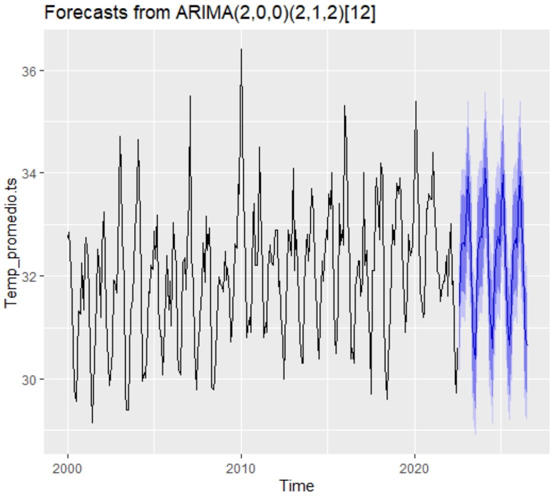
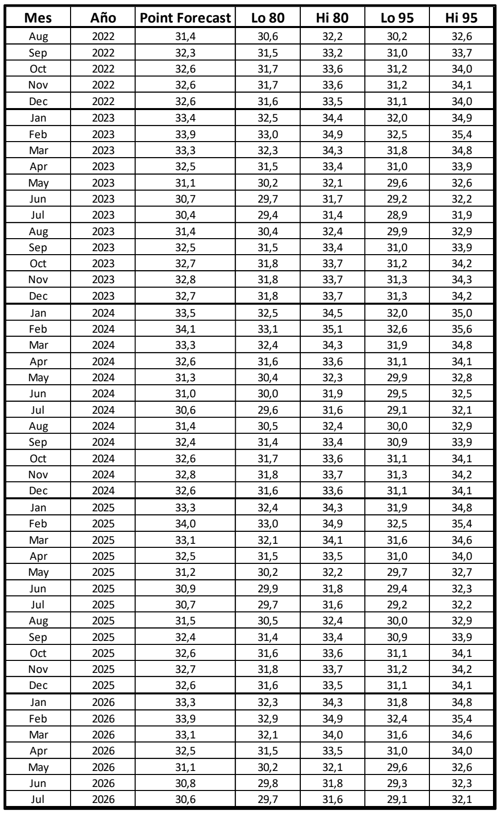


Figura 11. Pronostico de la temperatura promedio.
Fuente: elaboración propia.



Mes	Año	Point Forecast	Lo 80	Hi 80	Lo 95	Hi 95
Aug	2022	31,4	30,6	32,2	30,2	32,6
Sep	2022	32,3	31,5	33,2	31,0	33,7
Oct	2022	32,6	31,7	33,6	31,2	34,0
Nov	2022	32,6	31,7	33,6	31,2	34,1
Dec	2022	32,6	31,6	33,5	31,1	34,0
Jan	2023	33,4	32,5	34,4	32,0	34,9
Feb	2023	33,9	33,0	34,9	32,5	35,4
Mar	2023	33,3	32,3	34,3	31,8	34,8
Apr	2023	32,5	31,5	33,4	31,0	33,9
May	2023	31,1	30,2	32,1	29,6	32,6
Jun	2023	30,7	29,7	31,7	29,2	32,2
Jul	2023	30,4	29,4	31,4	28,9	31,9
Aug	2023	31,4	30,4	32,4	29,9	32,9
Sep	2023	32,5	31,5	33,4	31,0	33,9
Oct	2023	32,7	31,8	33,7	31,2	34,2
Nov	2023	32,8	31,8	33,7	31,3	34,3
Dec	2023	32,7	31,8	33,7	31,3	34,2
Jan	2024	33,5	32,5	34,5	32,0	35,0
Feb	2024	34,1	33,1	35,1	32,6	35,6
Mar	2024	33,3	32,4	34,3	31,9	34,8
Apr	2024	32,6	31,6	33,6	31,1	34,1
May	2024	31,3	30,4	32,3	29,9	32,8
Jun	2024	31,0	30,0	31,9	29,5	32,5
Jul	2024	30,6	29,6	31,6	29,1	32,1
Aug	2024	31,4	30,5	32,4	30,0	32,9
Sep	2024	32,4	31,4	33,4	30,9	33,9
Oct	2024	32,6	31,7	33,6	31,1	34,1
Nov	2024	32,8	31,8	33,7	31,3	34,2
Dec	2024	32,6	31,6	33,6	31,1	34,1
Jan	2025	33,3	32,4	34,3	31,9	34,8
Feb	2025	34,0	33,0	34,9	32,5	35,4
Mar	2025	33,1	32,1	34,1	31,6	34,6
Apr	2025	32,5	31,5	33,5	31,0	34,0
May	2025	31,2	30,2	32,2	29,7	32,7
Jun	2025	30,9	29,9	31,8	29,4	32,3
Jul	2025	30,7	29,7	31,6	29,2	32,2
Aug	2025	31,5	30,5	32,4	30,0	32,9
Sep	2025	32,4	31,4	33,4	30,9	33,9
Oct	2025	32,6	31,6	33,6	31,1	34,1
Nov	2025	32,7	31,8	33,7	31,2	34,2
Dec	2025	32,6	31,6	33,5	31,1	34,1
Jan	2026	33,3	32,3	34,3	31,8	34,8
Feb	2026	33,9	32,9	34,9	32,4	35,4
Mar	2026	33,1	32,1	34,0	31,6	34,6
Apr	2026	32,5	31,5	33,5	31,0	34,0
May	2026	31,1	30,2	32,1	29,6	32,6
Jun	2026	30,8	29,8	31,8	29,3	32,3
Jul	2026	30,6	29,7	31,6	29,1	32,1

Tabla 5. Pronostico con intervalos de confianza de la temperatura.
Fuente: elaboración propia.

Caso B. Radiación

Igual que el Caso A, se analizan los datos de radiación solar promedio diario y mensual de la ciudad del Inírida, reportados por la base de datos POWER.

1) Identificación del modelo

- Graficas: Se grafican las curvas del patrón de tendencia y la serie de tiempo de la radiación para observar si la serie es estacionaria.

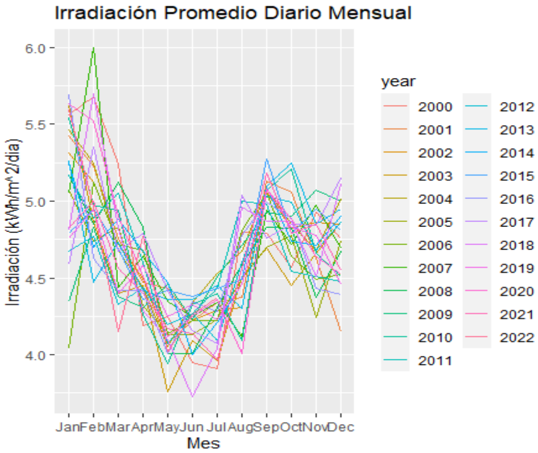


Figura 12. Patrón de tendencia - Radiación Diaria Mensual - año 2000 hasta 2022.
Fuente: elaboración propia.

En la Figura 12, se observa el patrón de tendencia de la irradiación promedio diario mensual por año, donde se registran los máximos datos de radiación en los meses de febrero y marzo con valores entre 5,5 kWh/m²/dia y 6 kWh/m²/dia y los mínimo datos registrados que oscilan entre los 3,7 kWh/m²/dia y 4 kWh/m²/dia entre los meses de mayo hasta agosto.

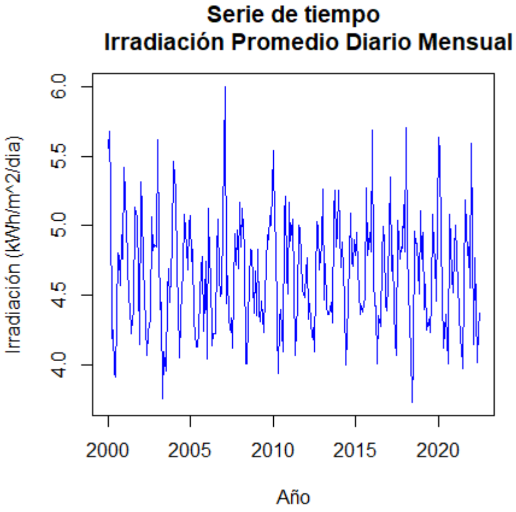


Figura 13. Serie de tiempo – Radiación Diaria Mensual – Año 2000 hasta 2022.
Fuente: elaboración propia

Para poder generar un buen pronóstico, es necesario que la serie de tiempo de la Figura 13, se le realice una primera diferencia como criterio metodológico para confirmar que la serie es estacionaria.

- Primera Diferencia: Se toma la primera diferencia ordinaria a la serie de tiempo original.

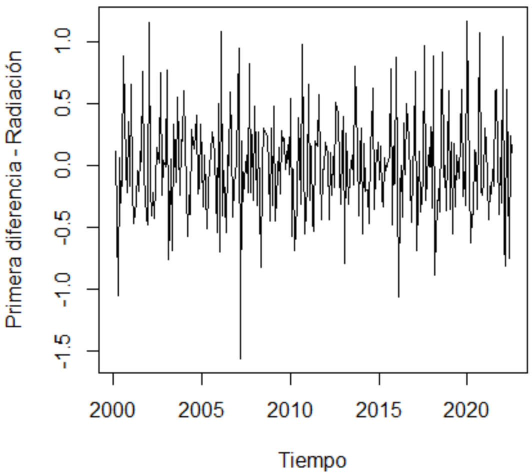


Figura 14. Serie de tiempo con la primera diferencia.
Fuente: elaboración propia

Como se nota en la Figura 14, al tomar las primeras diferencias observamos que la serie se estabiliza en torno a un valor medio, se deduce que los datos tienen una media y varianza constante.

- Correlograma de la serie diferenciada (ACF y PACF).

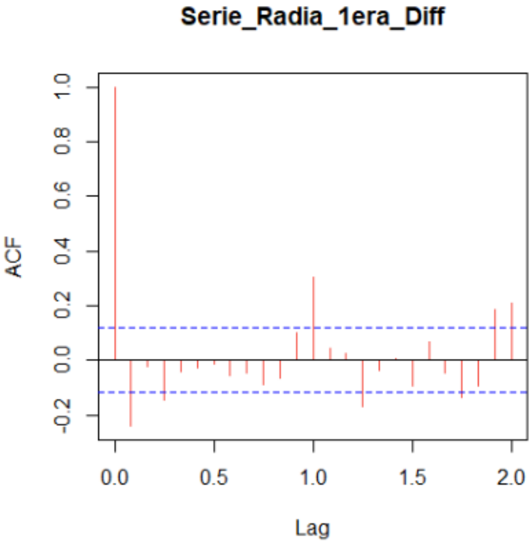


Figura 15. ACF 1era Diferencia.
Fuente: elaboración propia.

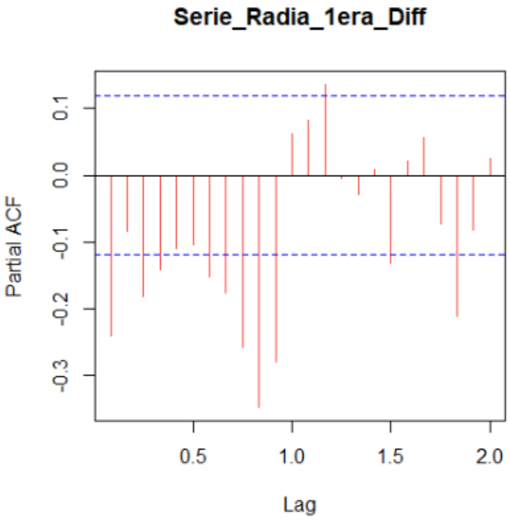


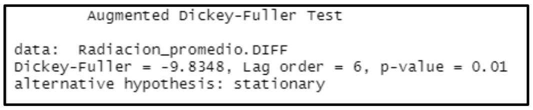
Figura 16. PACF 1era Diferencia.
Fuente: elaboración propia.

Se considera que la serie con la primera diferenciada es estacionaria, Figura 15 y 16. Ya que se debe cumplir que los datos sean estacionarios. Para corroborar la estacionariedad se aplica la prueba de Dickey – Fuller.

- Prueba de Dickey – Fuller:

Prueba de Dickey – Fuller, comprueban la estacionariedad de las series temporales si el p-valor se encuentra < 0.05. Esta prueba se aplica a la serie de primera diferencia.
Hipótesis:

H0:H0: La serie es no estacionaria: Tiene raíz unitaria
H1:H1: La serie es estacionaria: No tiene raíz unitaria



```
	Augmented Dickey-Fuller Test

data:  Radiacion_promedio.DIFF
Dickey-Fuller = -9.8348, Lag order = 6, p-value = 0.01
alternative hypothesis: stationary
```

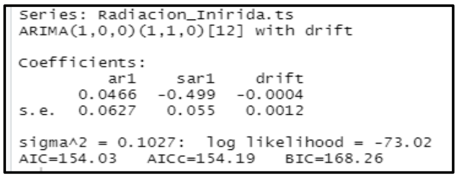
Tabla 6. Prueba de Dickey–Fuller.
Fuente: elaboración propia.

Esta prueba ejecutada como lo muestra la Tabla 6, indica que el valor obtenido del estadístico Dickey-Fuller fue de (-9,8348), con un p-valor menor a 0,05 por lo que la hipótesis nula cae en la región de rechazo, ósea que la serie con una primera diferencia ordinaria indica que es estacionaria.

Una vez que se ha obtenido la serie de tiempo estacionaria, se pasa a identificar la forma del modelo que se utilizará.

2) Ajuste del modelo

- Modelos: Selección y prueba de los modelos tentativos.



```
Series: Radiacion_Inirida.ts
ARIMA(1,0,0)(1,1,0)[12] with drift

Coefficients:
         ar1     sar1     drift
      0.0466  -0.499  -0.0004
s.e.  0.0627   0.055   0.0012

sigma^2 = 0.1027:  log likelihood = -73.02
AIC=154.03   AICc=154.19   BIC=168.26
```

Tabla 7. Ajuste automático de los coeficientes ARIMA
Fuente: elaboración propia.

La Tabla 7, nos muestra el resultado del modelo ARIMA (p,d,q) (P,D,Q) - (1,0,0) (1,1,0)[12], usando la función automática del comando RStudio "auto.arima". También muestra los coeficientes ajustados y el error estándar (s.e.) para cada coeficiente. Los vectores (p,d,q) corresponde a la parte regular o tendencia y la parte estacional (P,D,Q).

- Encontrar el Criterio de Información (AIC) de Akaike y error estándar σ2.

Los resultados del valor de AIC = 154,03 y σ2=0,1027 son los entregados y calculados por la función automática "auto.arima".

3) Validación del modelo

- Estacionariedad residual.
- Función de Autocorrelación Residual.
- Estadístico de Ljung-Box Test – Hipótesis Validez de ruido Blanco.
- Normalidad de los residuos – Grafica Q-Q.

En este paso se comprueba la eficiencia del modelo y se decide si es estadísticamente adecuado.

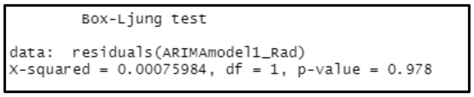
.

La validez del ruido blanco, se comprueba si:

- El valor del estadístico es mayor que 0.01 pero menor que 0.05, el modelo se rechaza.
- Si el valor del estadístico es mayor a 0.05, el modelo es aceptado. Esto significa que el error es igual a cero y la varianza constante.

Para ejemplificar la validación del modelo, analizamos las Figura 17 de acuerdo a la selección del modelo ARIMA propuesto automáticamente, donde se observa que:

- La gráfica de Estacionaridad Residual, cumple con el criterio de presentar media cero y varianza constante.
- La grafica de la Función de Autocorrelación Residual, cumple, por lo tanto el modelo se acepta estadísticamente. Esto debido a que se establece que los coeficientes de los valores de autocorrelación No son significativos, ya que no sobrepasan las bandas de puntos según la gráfica, y los residuales son independientes entre sí.
- La grafica del Estadístico de Ljung-Box Test, y los resultados de la Tabla 8, demuestran y comprueba la validez del modelo, ya que el valor del estadístico es mayor a 0.05, por lo tanto el modelo es aceptado estadísticamente. Esto significa que se puede dar paso al cálculo del pronóstico.



```
        Box-Ljung test

data:  residuals(ARIMAmodel1_Rad)
X-squared = 0.00075984, df = 1, p-value = 0.978
```

Tabla 8. Prueba del estadístico Ljung-Box
Fuente: elaboración propia.

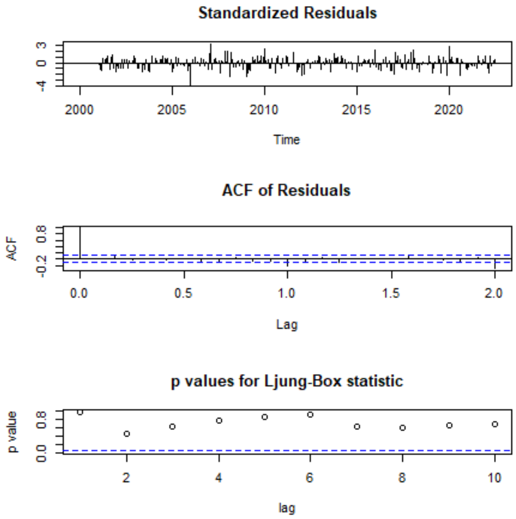


Figura 17. Estacionariedad residual, ACF residual, p _values Ljung - Box
Fuente: elaboración propia.

Normalidad de los residuos – Grafica Q-Q. Los gráficos Q-Q (quantile-quantile) son una herramienta eficaz para evaluar la normalidad, en la Figura 18, se puede observar que los puntos tienden a seguir la línea recta bastante cerca; esto indica que se acepta la normalidad de los residuos en este modelo.

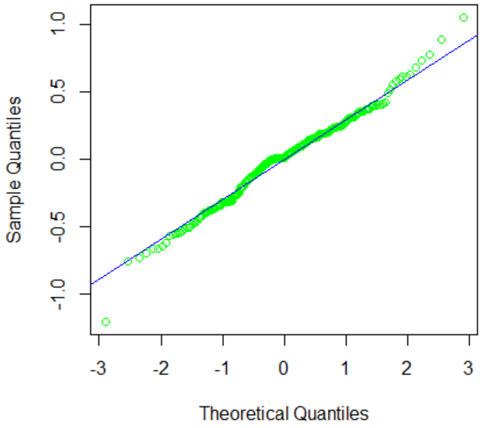


Figura 18. Grafico Q-Q para evaluar normalidad.
Fuente: elaboración propia.

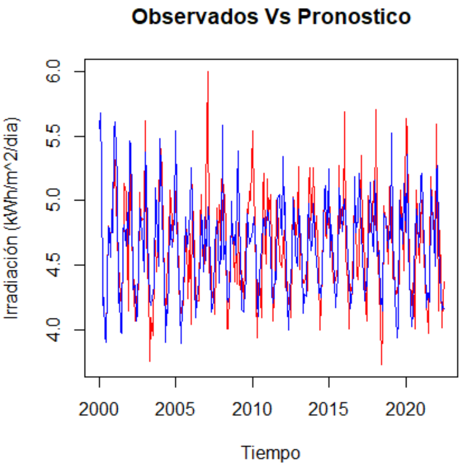


Figura 19. Grafico de datos observados Vs datos esperados. Fuente: elaboración propia.

En la Figura 19, se puede observar que la curva de color rojo hace parte del modelo diferenciado (observado), y la curva de color azul hace parte del modelo ajustado o esperado, indicando que el modelo es adecuado para el pronóstico.

4) Pronostico

Para el pronóstico de nuestro modelo, proyectamos la serie a 48 meses, como se observa en la Figura 20, con tendencia a presentar máximos de radiación solar cercanos a los 5,6 kWh/m²/mes y mínimo de 3,8 kWh/m²/dia durante los cuatro periodos anuales de muestreo, iniciando el análisis de pronostico en julio de año 2022 y finalizando en julio del año 2026, como se refleja en la Tabla 9. Es importante destacar que el pronóstico modelado posee intervalos de confianza asociado a la probabilidad de que el dato de la variable de temperatura se encuentre dentro de dicho intervalo de confianza. El intervalo de confianza del modelo se establece con el 80% y 95% de probabilidad.

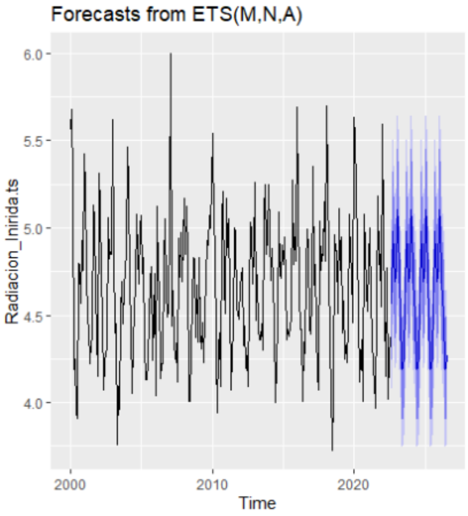


Figura 20. Pronostico de la radiación promedio.
Fuente: elaboración propia.

Mes	Año	Point Forecast	Lo 80	Hi 80	Lo 95	Hi 95
Aug	2022	4,29	3,88	4,70	3,66	4,92
Sep	2022	5,12	4,71	5,54	4,50	5,75
Oct	2022	4,83	4,42	5,24	4,20	5,46
Nov	2022	4,74	4,33	5,15	4,11	5,37
Dec	2022	4,53	4,12	4,94	3,90	5,16
Jan	2023	5,20	4,79	5,61	4,57	5,83
Feb	2023	4,97	4,56	5,38	4,34	5,60
Mar	2023	4,35	3,94	4,76	3,72	4,98
Apr	2023	4,58	4,17	4,99	3,95	5,21
May	2023	4,09	3,68	4,50	3,46	4,72
Jun	2023	4,19	3,78	4,60	3,56	4,82
Jul	2023	4,16	3,75	4,58	3,54	4,79
Aug	2023	4,42	3,96	4,88	3,71	5,12
Sep	2023	5,15	4,69	5,61	4,44	5,85
Oct	2023	4,80	4,34	5,26	4,10	5,51
Nov	2023	4,79	4,33	5,25	4,08	5,49
Dec	2023	4,53	4,07	4,99	3,83	5,24
Jan	2024	5,39	4,93	5,85	4,68	6,09
Feb	2024	4,96	4,50	5,42	4,26	5,66
Mar	2024	4,24	3,78	4,70	3,54	4,95
Apr	2024	4,67	4,21	5,13	3,96	5,37
May	2024	4,05	3,59	4,51	3,34	4,75
Jun	2024	4,22	3,76	4,68	3,52	4,92
Jul	2024	4,26	3,80	4,72	3,56	4,96
Aug	2024	4,35	3,79	4,90	3,50	5,19
Sep	2024	5,13	4,57	5,68	4,28	5,98
Oct	2024	4,81	4,26	5,36	3,96	5,66
Nov	2024	4,76	4,20	5,31	3,91	5,60
Dec	2024	4,52	3,97	5,08	3,68	5,37
Jan	2025	5,29	4,73	5,84	4,44	6,13
Feb	2025	4,96	4,41	5,51	4,11	5,81
Mar	2025	4,29	3,74	4,84	3,44	5,14
Apr	2025	4,62	4,06	5,17	3,77	5,46
May	2025	4,06	3,51	4,62	3,22	4,91
Jun	2025	4,20	3,65	4,75	3,35	5,05
Jul	2025	4,21	3,65	4,76	3,36	5,05
Aug	2025	4,38	3,77	4,99	3,44	5,31
Sep	2025	5,13	4,52	5,74	4,20	6,06
Oct	2025	4,80	4,19	5,41	3,87	5,73
Nov	2025	4,77	4,16	5,38	3,83	5,70
Dec	2025	4,52	3,91	5,13	3,59	5,46
Jan	2026	5,33	4,72	5,94	4,40	6,27
Feb	2026	4,95	4,34	5,56	4,02	5,89
Mar	2026	4,26	3,65	4,87	3,33	5,19
Apr	2026	4,64	4,03	5,25	3,70	5,57
May	2026	4,05	3,44	4,66	3,11	4,98
Jun	2026	4,20	3,59	4,81	3,27	5,14
Jul	2026	4,23	3,62	4,84	3,29	5,16

Tabla 9. Pronostico con intervalos de confianza de la radiación.
Fuente: elaboración propia.

5. Conclusiones

Analizar y caracterizar el comportamiento de los parámetros meteorológicos como la irradiancia solar y la temperatura ambiente en un lugar determinado son fundamentales para el planeamiento, el dimensionamiento, la operación y el despacho de centrales solares, ya que este tipo de parámetros presentan un comportamiento aleatorio difícil de manipular, por lo tanto, se hace vital el estudio de técnicas analíticas y predictivas para el procesamiento de volúmenes de datos capaz de estimar métricas meteorológicas en el futuro próximo.
En esta investigación se desarrolló una metodología para la evaluación y el estudio de series temporales, analizando históricos de variables meteorológicas mediante técnicas y modelos predictivos, permitiendo determinar la predicción y el comportamiento de la irradiancia solar y la temperatura ambiente de forma confiable.

En ese sentido, los resultados del presente estudio indican que los pronósticos ambientales modelados en la ciudad del Inírida, pueden constituir una alternativa para diversificar la matriz energética con fuentes de energía renovable solar fotovoltaica, optimizando el dimensionamiento, la operación y despacho de generación; lo que garantiza una planificación energética eficiente, contribuyendo a la seguridad en el suministro de energía y la confiabilidad del sistema de potencia.

El soporte y uso de programas de simulación generan una herramienta interesante para el estudio y análisis en proyectos de investigación. En nuestro caso el análisis y estudio se enfoca en el uso de modelos ARIMA y técnicas de Box-Jenkins para la caracterización y predicción de las métricas meteorológicas de la zona, logrando obtener un buen desempeño en el pronóstico a partir de la base de datos analizada, con intervalos de confianza del 95% de probabilidad, confirmando así, el óptimo uso del modelo ya que su nivel de estimación es muy cercano a la realidad.

5. Referencias

[1] C. Mondial, D. E. L. É. Gie, Y. D. Kim, L. Birnbaum, G. Ward, and C. Frei, “Recursos energéticos globales,” World Energy Counc., p. 27, 2013.

[2] P. Sarmiento y P. Antonio, «Planificación eficiente de redes inteligentes (smartgrids) incluyendo la gestión activa de la demanda: aplicación a ecuador», 2018.

[3] Vafaeipour M, Hashemkhani S, Morshed M, et al. Assessment of regions priority for implementation of solar projects in Iran: new application of a hybrid multi-criteria decision making approach. Energy Convers Manag. 2014;86:653–663.

[4] Power System Economics: Designing Markets for Electricity | IEEE eBooks | IEEE Xplore.

[5] Agencia Internacional de la Energía, Contribución de las energías renovables a la seguridad energética, IEA, París, 2007.

[6] M. S. J. Joaquín y R. P. Carlos, «Model of application of distributed generation in Colombia rural zones», en PES T&D 2012, may 2012, pp. 1-9.

[7] ZNI Diagnóstico de la prestación delservicio de energía eléctrica 2017. Recuperado de: http://webdav.superservicios.gov.co:8080/Media/Imagenes/Destacados/ZNI-Diagnostico-de-la-prestacion-del-servicio-de-energiaelectrica-2017.

[8] Bustos, J., Sepúlveda, A., Triviño, L. (2014). Zonas no interconectadas eléctricamente en Colombia: problemas y perspectiva (Non Electric Interconnection Zones in Colombia: Problems and Perspectives). SSRN Electronic Journal. https://doi.org/10.2139/SSRN.2603023.

[9] M. R. Gámez, A. V. Pérez, A. M. V. Quiroz, and W. M. S. Arauz, “Mejora de la calidad de la energía con sistemas fotovoltaicos en las zonas rurales,” Revista Científica, vol. 3 (33), pp. 265-274, 2018. https://doi.org/10.14483/23448350.13104.

[10] E. Obando-Paredes and R. Vargas-Cañas, “Desempeño de un sistema fotovoltaico autónomo frente a condiciones medioambientales de una región en particular,” Rev. la Acad. Colomb. Ciencias Exactas, Físicas y Nat., vol. 40, no. 154, pp. 27–33, 2016.

[11] R. J. Davy and A. Troccoli, “Interannual variability of solar energy generation in Australia,” Sol. Energy, vol. 86, no. 12, pp. 3554–3560, 2012.

[12] M.S. Mahmodian, R. Rahmani, E.Taslimi, and S. Mekhilef., “Step By Step Analyzing, Modeling and Simulation of Single and Double Array PV system in Different Environmental Variability,” 2012 Int. Conf. Futur. Environ. Energy IPCBEE, vol. 28, pp. 37–42, 2012.

[13] Harvey,A., (1990). The Econometric Analysis of Time Series.2ªEd. Philip Allan. Great Britain.

[14] Avila Blas O. J. (1997). Análisis Espectral de Series de Temperatura de Superficie. Revista FACENA, Univ. Nac. Nordeste, 13, 79-99.

[15] Avila Blas, O., Abril, J.C. y Lesino, G. (1999). Análisis Estadístico Estructural de Series de Radiación Diaria, Avances en Energías Renovables y Medio Ambiente, Vol. 3, Nº 2, pp. 11.17-11.20.

[16] Aguiar R. y Collares Pereira M. (1992). Tag: A time dependent, autorregressive, gaussian model for generating synthetic hourly radiation, Solar Energy, 49, 3, 167-174.

[17] La base de datos relacionada a la investigación de recursos energéticos y meteorológicos a nivel mundial realizados por la NASA, creación de conjuntos de datos a partir de nuevos sistemas satelitales plataforma: Prediction Of Worldwide Energy Resources (POWER - power.larc.nasa.gov). https://power.larc.nasa.gov/data-access-viewer/.

[18] Reyes Polanco, A. E. (2021). SERIES DE TIEMPO: Conceptos básicos de análisis de series de tiempo en el dominio del tiempo. En A. E. Reyes Polanco, SERIES DE TIEMPO: Conceptos básicos de análisis de series de tiempo en el dominio del tiempo (págs. 21-25). Madrid: Edicion Kindle.

[19] Correa, E, Series de tiempo: conceptos básicos, Universidad Nacional de Colombia, Facultad de Ciencias, Departamento de matemáticas, Medellín (2004).

[20] Yanhua, Y., J. Wang., M. Song., J. Song, Network traffic prediction and result analysis based on seasonal ARIMA and correlation coefficient, International Conference Intelligent System Design and Engineering Application (ISDEA), IEEE, 980-983 (2010).

[21] Hernández, C, Desarrollo de un modelo estadístico que permita estimar pronósticos futuros de tráfico en redes WiMax a través del modelamiento en series de tiempo Universidad Distrital "Francisco José de Caldas", Maestría en Teleinformática, Colombia (2006).

[22] Pankratz, A. (1983) Forecasting with Univariate Box-Jenkins Models. Wiley & Sons, Inc., New York. 16 de agosto de 1983 - ISBN: 9780471090236 | ISBN en

línea: 9780470316566 - Copyright © 1983 John Wiley & Sons, Inc. - http://dx.doi.org/10.1002/9780470316566.

[23] Box, G. E. P., & Jenkins, G. M. (1970). Time series analysis: forecasting and control. In Operational Research Quarterly (537 pp.). New Jersey: John Wiley & Sons.

The future of electricity distribution regulation in Brazil: insights from stakeholders

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Kalyne Brito[4]

Introduction

In the last decade, there has been a growing increase in the share of Distributed Energy Resources (DER), consolidating the decentralization and decarbonization of electricity generation. Meanwhile, smart grid technologies lead the digitalization of the sector, which now has an expanding layer of information and communication technologies, associated with increased control, monitoring and automation. Together, the so-called 3D's of the energy transition result in significant changes in the electricity sector, impacting, especially, distribution utilities. Not only the functions traditionally performed (planning, operation and maintenance of the grid) by these companies will be affected, but also their areas of operation and business model. The utility of the future business model is not yet defined and, in the spectrum of alternatives discussed in the literature, the extremes are represented by theoretical alternatives: on the one hand, the expanded monopoly model, in which the distributors hold all the new assets and services; on the other hand, the platform operator model, characterized by the utility's role as neutral asset integrator and host of competitive activities (Cross-Call et al., 2018). As a natural monopoly activity, the change of utilities' role raises the need for a broad regulatory framework restructuring (Ruester et al., 2014). The historical focus of regulation, translated into support for traditional, prudent, investments, must evolve to an approach focused on optimizing demands and opportunities, considering a broader pool of stakeholders, and compatible with the utility's role in promoting social and environmental goals (Cross-Call et al., 2018b). In this sense, the transition of the distribution network requires: the definition of the market structure, establishing roles, borders and responsibilities of utilities regarding new, and traditional, services, products and assets; and the modernization of distribution utilities economic regulation.

In Brazil, the power sector transition, led by the diffusion of Distributed Generation, tends to consolidate in the coming years. In this scenario, the regulation must advance in order to allow distribution companies to promote the integration of new resources and technologies into the system, based on ensuring flexibility, optimizing resources, and maximizing the value for consumers. Despite the recognition of regulation as a crucial dimension to enable the modernization of the utilities' business model and to ensure the sustainable diffusion of DER, the Brazilian Power Sector Regulatory Agency (ANEEL) actions to prepare the regulation for the evolution of distribution utilities' role are still incipient. In this context, the article aims to contribute to the advancement of this agenda through the following goals: (i) analyze how distribution utilities business model will evolve in the context of the transition of the Brazilian electric sector; (ii) identify the necessary regulatory adaptations in order to make this evolution viable.

Methods

This research is grounded on a literature review of the economic regulation and business model of distribution utilities, aiming to identify the main areas of market structure and economic regulation that must be revisited in order to pave the evolution of utilities business model and distribution network modernization in the context of DERs diffusion. Then, 28 virtual interviews were conducted, between May and June 2022, with stakeholders grouped in 7 categories: (i) distribution companies; (ii) specialists (consultants and academics); (iii) associations and companies from the generation, transmission, and retail segments; (iv) consumer representatives; (v) associations and companies of products and solutions for the electricity sector; (vi) agents focused on renewable sources; and (vii) policymakers.

The interviews had an average duration of 1 hour and the questionnaire were composed of five sessions. In the first one, the aim was to analyze the perception of the interviewees about the target model of the electricity utility of the future in Brazil. In the second session, the interviewees evaluated the utilities' level of actuation in new areas or services, such aggregation and microgrids operation. Next, they were questioned about flexibility procurement mechanisms at the distribution level, considering the services provided by DER and the distribution system's active management. Based on this panorama, Session 4 approached the main challenges related to Brazilian regulatory

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framework, questioning whether the current regulation could become an obstacle to the modernization of the sector. Finally, the interviewees pointed out the main obstacles to the evolution of the role of distribution utilities in Brazil and the regulatory changes that should be prioritized by the Regulatory Agency in the next eight years in order to support this transition.

Results

Regarding the future model of electric energy distributors in Brazil, 60% of interviewees believe that the utilities should evolve to the role of owner and operator of the distribution system, limited to providing the grid service (Model A). The interviewees that advocate for this model believe that the distributors' participation would be harmful to new markets development, since monopoly advantages would persist, imposing disadvantages over new entrants. Limiting the activities of distributors to network services would mitigate the risk of anti-competitive behavior and the transfer of undue costs to consumers. Moreover, maintaining the focus on network services would have a positive impact on the quality of system management.

The second model (Model B), chosen by 40% of the interviewees, presents an evolution to a more verticalized distributor, acting directly in the provision of new products and services, either in a competitive or a monopoly regime. This choice is based on the argument that the distributor could accelerate the insertion of new technologies, due to economies of scale and scope and the expertise of these companies. In addition, given that the utility represents a consolidated brand, its participation would encourage the competitiveness of new agents. As a result, consumers would have an expanded range of services and providers.

When it comes to flexibility procurement, regardless of the distributor model chosen, the need to advance coordination between distributors and the National Electric System Operator (ONS) was highlighted, as well as the development of mechanisms for the contracting of flexibility services by distributors. The analysis suggests that the topic is still incipient and, therefore, there is a need to expand the discussion about flexibility contracting mechanisms in the Brazilian electricity sector.

A topic with relative consensus was economic regulation, with 80% of the interviewees suggesting that it could be an obstacle to the modernization of distribution utilities. Two major groups of regulatory challenges were identified and summarized in the following sentences: (i) how to enable the redefinition of the distributors' business model while guaranteeing the economic balance of the distribution service; and (ii) how to enable the active management of the distribution system, supporting the use of DERs as operational resources.

In the first group, twelve actions were suggested, related to four major goals: promoting the neutrality of distribution utilities and isonomic access to metering data; modernizing tariff structure; supporting financial and economic sustainability of the grid service, mitigating market risk; and redefining the current revenue sharing rules, applied to complementary activities, since they inhibit the development of new services and products by the utilities. Regarding the second challenge, sixteen actions were proposed, associated to seven objectives: enabling the roll-out of smart meters, minimizing the short-term impact on tariffs; developing mechanisms to the flexibility procurement from DER by distributors; equalizing investments in traditional and new technologies, with reduced lifespan; providing economic signal through dynamic tariffs; ensuring the neutrality of distribution utilities between non-wire alternatives and traditional solutions, assuring the use of DER’s flexibility as an operating resource; reviewing the benchmarking model based on backward looking; and adjusting the market design to a new decentralized context.

Conclusions

According to the 28 stakeholders consulted in the research, in Brazil the utilities role as distribution system operators will be crucial in the power sector transition. Although about 60% of the interviewees believe that in the future the distributors will have to focus on the operation of the system, tending to Model A, the competitive regime with the distributor's performance was elected by the majority as the most appropriate for the development of new activities, associated with DER. It is possible to note, therefore, the presence of a hybrid model, in which, although the distributor is focused on the operation of the network, its performance in new areas, competing with new players, is allowed. The creation of mechanisms for flexibility procurement at the distribution level was identified as crucial for DER to become, in fact, an alternative to traditional investments in the network. However, there are still several regulatory gaps to be filled, which indicates the need for a broader discussion on the subject. Besides that, the democratization of access to consumer data was pointed out as an essential feature to the virtuous development of the distribution sector. Finally, it is a consensus that the current economic regulation of distributors imposes a series of challenges that must be mitigated in order to support the modernization of the distribution system and the evolution of Brazilian distribution utilities’ business model.

References

Cross-Call, D., Gold, R., Guccione, L., Henchen, M., & Lacy, V. (2018). Reimagining the utility: Evolving the functions and business model of utilities to achieve a low-carbon grid. Rocky Mountain Institute: Boulder, USA.

Ruester, S., Schwenen, S., Batlle, C., & Pérez-Arriaga, I. (2014). From distribution networks to smart distribution systems: Rethinking the regulation of European electricity DSOs. Utilities Policy, 31, 229-237.

Efficient Use of Energy for Cooking Food in the Residential Sector in Panama: Challenges & Opportunities.

Uso Eficiente de Energéticos para Cocción de Alimentos en el Sector Residencial de Panamá: Retos & Oportunidades.

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***Abstract* — A policy of efficient use of energy is not only a useful way to save the state money, but it is also an essential ingredient to keep energy resources available for the population. Panama has had a 25-pound LPG cylinder subsidy for 30 years, it is not targeted and since 1998 more than 1,300 million dollars have been allocated to maintain it, but there are still 93,000 families that do not have access to clean fuels to cook their food and are exposed to health and gender risks due to the use of firewood. That is why this work explores the possibilities of using other energy sources for cooking food in the residential sector, such as electricity, since it is expected that due to technological advances to increase the electrification of demand, the urgent need to reduce emissions and improve production and consumption methods that damage the environment will have a prominent role in the residential sector, likewise natural gas is expected to be among the energy sources with the greatest potential to replace derivatives of oil and thus achieve the energy transition with affordable and non-polluting energy. The analysis and projection of different data from the energy sector in Panama is shown here. The results for the scenarios under study are presented: Gris-Business as Usual, where the baseline of consumption to the year 2050 is studied; the blue scenario where the share of electricity for cooking food in the residential sector is increased, and the green scenario where a mixture of different fuels is used in the energy matrix for cooking: Electricity, Liquefied Petroleum Gas and Liquefied Natural Gas. In the three scenarios, the estimation of the main greenhouse gases emitted by the use of fuels for cooking is projected. The results demonstrate the potential decrease in state spending on the LPG subsidy. The planning and implementation of an energy substitution program is presented.**

Keywords—electricity, energy efficiency, climate change, Panama, fuel.

***Resumen* — Una política de uso eficiente de la energía no es solo una manera útil para ahorrar dinero al estado, sino que también constituye un ingrediente esencial para mantener disponibles los recursos energéticos para la población. Panamá cuenta con un subsidio al cilindro de GLP de 25 libras desde hace 30 años, el mismo no está focalizado y desde 1998 se han destinado más de 1,300 millones de dólares para mantenerlo, pero aún así existen 93,000 familias que no tienen acceso a combustibles limpios para cocinar sus alimentos y se exponen a riesgos a la salud y de género debido al uso de la leña. Es por ello que en este trabajo se exploran las posibilidades de utilizar otros energéticos para la cocción de alimentos en el sector residencial, como la electricidad ya que se espera que debido a los avances tecnológicos para aumentar la electrificación de la demanda, a la urgente necesidad de reducir las emisiones y a la eficiencia de los métodos de producción y consumo esta tengan un papel destacado en el sector residencial, así mismo se espera que el gas natural se sitúe entre las fuentes de energía con mayor potencial para reemplazar a los derivados del petróleo y así lograr la transición energética con energía asequible y no contaminante. Aquí se muestra el análisis y proyección de diferentes datos del sector energético en Panamá. Se presentan los resultados para los escenarios en estudio: Gris-Business as Usual, donde se estudia la línea base del consumo al año 2050; el escenario azul donde se incrementa la cuota de electricidad para cocinar alimentos en el sector residencial, y el escenario verde en donde se utiliza una mezcla de distintos combustibles en la matriz energética para cocción: Electricidad, Gas Licuado de Petróleo y Gas Natural Licuado. En los tres escenarios se proyecta la estimación de los principales gases de efecto invernadero emitidos por el uso de combustibles para cocinar. Los resultados demuestran la potencial disminución del gasto estatal en el subsidio al GLP. Se presenta la planificación e implementación de un programa de sustitución de energéticos.**

Palabras claves — electricidad, eficiencia energética, cambio climático, Panamá, combustible.

I. INTRODUCCIÓN

Debido al cambio climático y a las preocupaciones que surgen por sus efectos adversos a la sostenibilidad del planeta, a nivel mundial se le ha dado mayor atención al uso de la energía, ya que la extracción y producción de los energéticos provenientes de fuentes fósiles tienen costos económicos en la sociedad e impactos negativos en el medio ambiente [1]. La cocción de alimentos no escapa de esas actividades que inciden en la calidad de vida de la población y que son del alcance de diversas instituciones en los países de América latina [2] [3].

Los datos históricos del consumo de GLP (Gas Licuado de Petróleo) en Panamá muestran una tendencia creciente del consumo de este energético [4]. En Panamá se importa el 100% de la demanda de GLP para el consumo de los diferentes sectores energéticos, en especial para cocinar en el sector residencial [5].

El uso racional y eficiente de la energía es una necesidad apremiante que beneficia económicamente al estado, ya que permite reducir el costo económico asociado a la energía, dejar de depender de importación de energéticos de otros países y así mitigar las emisiones de gases de efecto invernadero, responsables en gran medida del calentamiento global y cuyas consecuencias son cada vez más visibles y permanentes [6].

Panamá es un mercado importante para la transición energética y adopción de nuevas fuentes de energía si se quiere lograr el ODS 7 en América Latina [7]. El subsidio al GLP está fomentando el apilamiento (uso en paralelo de varios combustibles) y la falta de energía eléctrica en la mayoría de las áreas rurales hace que la cocción eléctrica sea inaccesible [8]- [9].

La contaminación producto del humo de estufas improvisadas ha sido desde hace décadas un problema tanto de calidad de energía como de salud en muchos hogares [10]. Desde la COP21 de París el sector de cocción ha dado grandes avances hacia la reducción de las emisiones, sin embargo, en muchos países aún está pendiente establecer una estrategia nacional para ampliar las opciones de cocción limpia [9]- [11].

Cambiar de estufas de combustibles sólidos o estufas de gas a estufas eléctricas es técnica y económicamente viable en la mayoría de los países, pero enfrenta barreras culturales debido a las preferencias de los hogares, los costos y la organización de las cadenas de suministro y las políticas de cada país [12].

Este estudio está enfocado en ofrecer una perspectiva para promover el uso racional de los recursos, tanto energéticos como económicos del sector, ya que si bien es cierto por un lado se tienen subsidios para el uso del Gas Licuado de Petróleo en el sector residencial, por otro lado existen familias que aún dependen de la leña para cocinar los alimento, ya que no tienen acceso al uso de GLP ni de electricidad en sus hogares, a pesar de que se han destinado cientos de millones de dólares en subsidios tanto para el uso de la electricidad como para la compra del cilindro de 25 libras de GLP [13].

II. PLANTEAMIENTO DEL PROBLEMA

A. Antecedentes

En Panamá existen más de 90 000 familias que no tienen acceso ni a electricidad ni a combustibles limpios para cocinar alimentos, Panamá en 2017 tenía 90% de acceso a electricidad y 93% de acceso a energía y tecnologías de cocción modernas [5].

El Gas Licuado de Petróleo (GLP), tiene gran relevancia en el sector residencial, ya que es el energético más utilizado para la cocción de alimentos [13], pero con deficiencias en el control para la venta del volumen subsidiado, que fomentan el ejercicio de prácticas que distorsionan el mercado.

El GLP doméstico está subsidiado: mientras su precio actual es de US$ 15 por cilindro de 25lb, su precio de venta a los usuarios del sector residencial es de 4.37 US$/cilindro de 25 lb y aunque aumenta su costo por razones del transporte y factores internacionales, cuando se trata de su precio de venta en el sector, permanece invariable, ya que es subsidiado en más del 60% del costo real [13].

B. Descripción del problema

El uso de energéticos ineficientes como la leña y dependiente de importaciones internacionales como el Gas Licuado de Petróleo, es un problema que afecta a las familias de menos recursos y al gobierno. La utilización del Gas Licuado de Petróleo se traduce en un gasto de dinero para el gobierno nacional, ya que este energético se encuentra subsidiado y en la práctica este subsidio no está realmente focalizado hacia los hogares que lo necesitan, lo que provoca gastos innecesarios para el Estado por la indebida utilización de este combustible, además es un combustible que se debe importar, ya que Panamá no es productor de petróleo, por lo que la seguridad energética se encuentra dependiente de factores externos. Con la leña se tiene un problema de salud pública, ya que su utilización como combustible primario no solo indica pobreza energética, si no que causa graves afectaciones a la salud de las familias que la utilizan diariamente.

En teoría el subsidio al GLP se estableció para ayudar a las familias de bajos recursos a acceder a combustibles limpios, sin embargo, a casi 3 décadas de tenerlo, la realidad es otra, han surgido algunos problemas: 1.) Alto costo fiscal; 2.) Contrabando; 3.) Ilusión de bajo precio; 4.) Uso del energético en otras actividades u otros sectores.

C. Justificación

El uso de energéticos limpios para cocinar los alimentos es esencial para el ser humano, sin embargo, aún existe un número importante de hogares en panamá y el mundo que utilizan combustibles contaminantes para el medio ambiente y nocivos para la salud para realizar esta actividad [14] [15]. Es un hecho que existe una problemática que no permite acceder a una energía asequible y no contaminante, y esto aún es una realidad para muchas comunidades en Panamá. Principalmente en las zonas rurales, las personas dependen de leña y carbón vegetal para cocinar sus alimentos impactando gravemente su salud y el ambiente [16]. Subsidiar el GLP se justifica generalmente cuando su uso es para la cocción de los alimentos en el sector residencial, dado que se trata de un bien de uso intensivo, que puede llegar a demandar una importante porción del ingreso en las familias de menos recursos económicos. Con un subsidio, el gobierno busca se incremente el nivel de ingresos de los hogares [17].

Si se quiere aumentar el porcentaje de uso de electricidad en la cocción de alimentos para disminuir el volumen de GLP consumido es probable que se requiera algún mecanismo de apoyo financiero para ayudar a los hogares pobres a adquirir estufas eléctricas y particularmente en casos fuera de la red, sería la adopción de tecnologías limpias para eliminar el uso de la leña y la biomasa [12]. Se debe realizar una evaluación cuidadosa de los esquemas de subsidios e incentivos existentes. Según la experiencia de otros países se puede requerir apoyo para desarrollar modelos comerciales alternativos [18].

La asequibilidad de la energía limpia sigue siendo una barrera crítica para el acceso por el lado de la demanda, y muchas veces la falta de financiamiento eleva el costo unitario de los equipos de cocción eficientes y limpios por el lado de la oferta, ya que las empresas no pueden alcanzar la escala o la rentabilidad financiera. Tanto por el lado de la demanda como de la oferta son 2 barreras financieras que se deben abordar. Esta investigación se enfocará en el estudio del sector residencial sin profundizar en otros sectores como el comercial (hoteles, restaurantes) [19].

D. Objetivo general

Analizar los posibles escenarios de sustitución del GLP por electricidad y por Gas Natural Licuado en la cocción de alimentos en el sector residencial para la cuantificación de las áreas de oportunidad y las variables requeridas, para proponer una política energética por medio de una proyección al año 2050.

III. METODOLOGIA

Se establece una metodología que busca obtener los factores que inciden en el consumo de energéticos en el sector residencial, así como también de los precios del GLP, el Gas Natural Licuado y la electricidad, dentro de los cuales está: la demanda nacional histórica de GLP, precios internacionales, y trasporte marítimo de los combustibles. Para el posible cambio de estufas de gas por estufas eléctricas primero es necesario realizar un análisis cuantitativo y cualitativo del potencial consumo de energético para la cocción y de la potencia eléctrica que se requiere [20].

A continuación, en la figura 1 se muestra un diagrama con los pasos de la metodología a implementar.

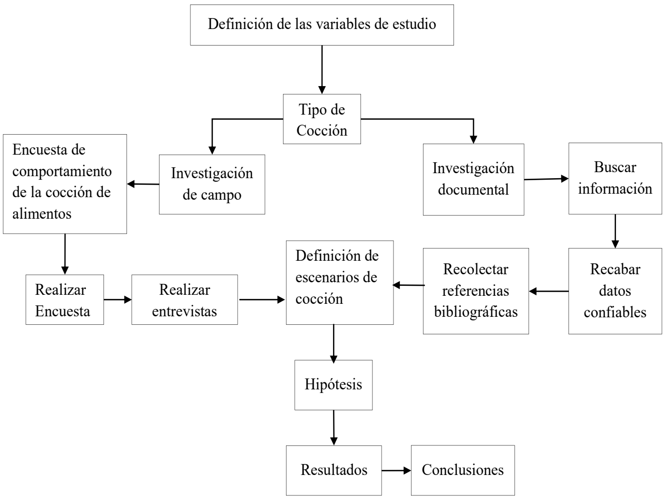


Figura 1. Diagrama de Pasos de la metodología propuesta

A. Etapa Inicial

Desde la perspectiva top-down, recopilación de datos a nivel de políticas e instituciones, se realiza para establecer las principales leyes y políticas relevantes para la cocción en Panamá, se realiza la recopilación y revisión para comprender el estado del marco regulatorio y esfuerzos estatales con respecto a la cocción de alimentos [21].

Para la recopilación de datos a nivel del hogar, bottom-up, como se ampliará más adelante, se realizará utilizando encuestas a una muestra de hogares para obtener información general de cocción, utilización de equipos de la cocina y qué combustible se utiliza para cocinar [21].

- ***Variables de estudio***

- Viviendas ocupadas existentes Panamá.
- Viviendas que cuentan con acceso a energía eléctrica
- Combustible utilizado en la cocción de alimentos.
- Ingreso mensual promedio de las familias.
- Modelos de estufas de inducción existentes en el mercado.
- Precios históricos del GLP.

B. Etapa de investigación de campo

Se realizó una encuesta para tener una noción del comportamiento de las personas en el momento de cocinar sus alimentos y obtener de forma estimada el consumo de energía, para luego proyectar una curva de demanda de potencia. Ello base a los análisis estadísticos aplicados a las encuestas en cuanto al tiempo y horario de uso de las estufas para preparación del desayuno, almuerzo y cena.

La encuesta se estructuró de la siguiente manera:

Formulación de preguntas para estimar el horario en que los hogares cocinan sus alimentos y la intensidad con que lo hacen (número de quemadores utilizados, numero de cilindros usados al mes, tipo de combustible utilizado), y en general otras preguntas sobre los hábitos de cocción de alimentos en el hogar para obtener datos que permitan hacer una estimación de los horarios y por lo tanto los requerimientos de potencia y energía necesarias para la preparación de alimentos.

C. Etapa de selección del caso de estudio

Definida la etapa inicial e identificadas las variables del estudio en base a los datos disponibles, se realiza la selección de los casos que se estudiarán:

- **Hipótesis 1: Escenario Gris: Cocción con GLP, Business as usual.**

Este escenario se basa en la hipótesis de que el uso de energéticos en el sector residencial siga tal como hasta ahora. Las decisiones en materia de políticas públicas se tomen tal como se ha hecho siempre. La escasez de recursos petroleros propios de Panamá y la seguridad de la energía son problemas fundamentales. Los gobiernos intentan seguir importando los suministros, lo que provoca que cambios significativos en el uso de los energéticos en la sociedad sean difíciles de realizar.

- **Hipótesis 2: Escenario Azul: Cocción con Electricidad + GLP**

Este escenario está basado en una política energética que depende de tres factores clave: el acceso a combustibles limpios, la necesidad de crecimiento económico y la reducción de las emisiones.

Contar con un sólido crecimiento económico y reducir las emisiones contaminantes no es una tarea fácil, es más, la evidencia muestra que en muchos países industrializados el crecimiento económico fue posible debido a que los problemas medio ambientales se consideraban irrelevantes [22]. Sin embargo, esta situación ha cambiado debido a los esfuerzos de la comunidad internacional por establecer mecanismos de mitigación para el cambio climático [23].

Un mecanismo para el aprovechamiento de las fuentes renovables de energía y reducir el consumo de hidrocarburos es la eficiencia energética, sumada al desarrollo de otras tecnologías como la movilidad eléctrica y las redes inteligentes [24].

- **Hipótesis 3: Escenario Verde: Cocción con Electricidad + Gas Natural Licuado+ GLP**

Este escenario está basado en un aumento de esfuerzos por electrificar el sector residencial y la reducción de las emisiones contaminantes, aprovechando que el país se ha convertido en un centro logístico de Gas Natural Licuado (GNL).

Actualmente, dentro de los combustibles fósiles, el gas natural se sitúa entre las fuentes de energía con mayor potencial para reemplazar el petróleo.

Dados los resultados de las últimas licitaciones para las contrataciones de energía y potencia realizadas por parte de los encargados de hacer las mismas, el gas natural es una fuente de energía cada vez más importante dentro de la matriz energética a pesar de que el cambio climático es un tema importante dentro de la agenda política.

Panamá inició la integración de GNL en la matriz energética gracias a la puesta en operación de la primera central termoeléctrica a base de gas natural de la región centroamericana: el proyecto “Costa Norte”. La infraestructura asociada mantiene las instalaciones para descarga de GNL en el puerto, almacenamiento y regasificación.

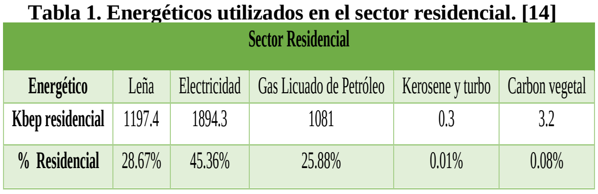
El gas natural presenta ventajas significativas frente a otros energéticos de origen fósil, entre ellas: un bajo factor de emisión y un comportamiento más regular de precios. Estas ventajas incrementan el potencial del país como hub de gas natural de la región y su aprovechamiento como energético en sectores como el residencial y comercial, especialmente para la cocción de alimentos.

Se empleó el consumo histórico mensual de GLP, por provincia, de 2011 a 2016, específicamente de la provincia de Panamá, ya que se considera el área del país con mayor factibilidad para ejecutar proyectos de mini redes de gas natural. Para el cálculo de la demanda de gas natural del sector residencial se determinó un porcentaje de acceso a la tecnología, usando la información de ingresos por habitantes del Área Metropolitana de la provincia de Panamá, periodo 2010 – 2050. Se consideraron los habitantes con ingresos mayores a USD 4,000 por mes.

D. Estadística

La demanda de energía del sector residencial en Panamá es satisfecha por gas licuado de petróleo, electricidad, leña, carbón vegetal y kerosene principalmente para actividades como iluminación, cocción de alimentos y climatización, el porcentaje de participación se puede observar en la tabla 1, se muestra que el más utilizado es la electricidad y luego por la leña [14].

Tabla 1. Energéticos utilizados en el sector residencial. [14]



Sector Residencial					
Energético	Leña	Electricidad	Gas Licuado de Petróleo	Kerosene y turbo	Carbon vegetal
Kbep residencial	1197.4	1894.3	1081	0.3	3.2
% Residencial	28.67%	45.36%	25.88%	0.01%	0.08%

Según el Censo Nacional de Población y Vivienda, el número total de hogares que usaron GLP en el año 2010, como fuente de energía para cocción de alimentos fue de 762,440, de los cuales se estimó que 639,965 corresponden a las viviendas que utilizan cilindros de 25 Lb de GLP subsidiados por el Estado [25]. El GLP tiene un valor importante dentro del uso final de la energía dentro del sector residencial, en Panamá el subsidio al GLP es generalizado, no está focalizado [17].

Se asume que el 100% de toneladas de GLP en el sector doméstico se destina para la cocción de alimentos. En la figura 2 se muestra la evolución de las ventas del cilindro de 25 libras de GLP. Se puede ver que han ido en aumento años tras año, pasando de 5.5 millones a cerca de 12 millones de cilindros.

Figura 2. Ventas nacionales de GLP. Fuente: estadísticas-Secretaría Nacional de Energía [26]

IV. ANÁLISIS DE LOS ESCENARIOS

Los casos de estudio que se presentan son sobre la cocción de alimentos en el sector residencial. Por lo tanto, en esta sección se presenta el análisis de los distintos escenarios de proyección del consumo de GLP, GNL y electricidad al año 2050 como energéticos para la cocción en los hogares panameños, utilizando diferentes premisas como: acceso de la población a combustibles eficientes gracias a su ubicación geográfica, poder adquisitivo de las familias, precios internacionales del combustible [27].

A. Análisis del Escenario Gris: Cocción con GLP, Business as usual

Actualmente, en Panamá se utiliza el GLP como energético para la cocción dentro del sector residencial, por lo tanto, nuestro punto inicial es la tendencia de mantener el uso de GLP dentro de los hogares panameños, por lo que se observa un crecimiento de 1506 KBEP de GLP que representan un aumento del 58% con respecto al consumo residencial del año 2019, como se observa en la figura 3.

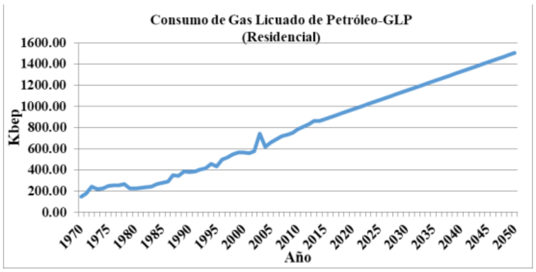


Figura 3. Consumo de GLP, residencial proyectado al 2050

Finalmente, como se ve en la figura 4 para 1,617,481 hogares proyectados en el año 2050 se estima un crecimiento en la demanda de cilindros de GLP de 210 % con respecto a la demanda del año 1998, como se puede observar en la figura 5.

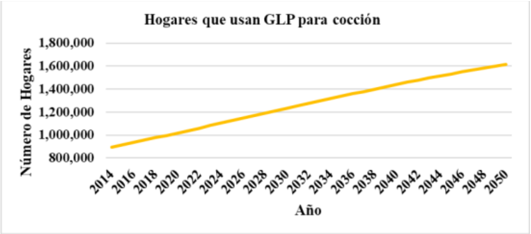


Figura 4. Hogares que usan GLP al 2050.

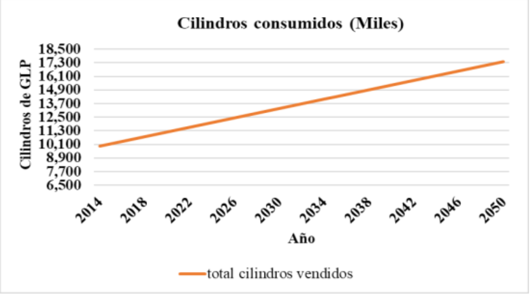


Figura 5. Cilindros de GLP vendidos.

La proyección final obtenida para la cantidad de cilindro es de 17,403 cilindros de 25 libras lo cual permite calcular en el siguiente punto el monto del subsidio en balboas que se tiene que garantizar para cubrir la demanda en el sector residencial.

Una vez calculado el Precio de Paridad de Importación al año 2050, y asumiendo que el precio regulado del GLP permanece sin variación al mismo horizonte de tiempo, se realiza la proyección del gasto público destinado para el subsidio al GLP, el cual asciende a un valor de 198 millones de dólares en el año 2050, tal como se muestra en la figura 6.

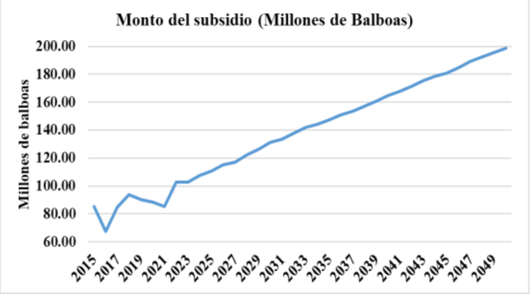


Figura 6. Monto del subsidio

Datos previos nos indican que en el periodo 1998-2020 el costo del subsidio ha sido de 1285.66 millones de balboas. Previo al año 1998 no se cuenta con estadísticas oficiales [28]. Finalmente, el resultado de la proyección realizada del monto acumulado al 2050 del gasto en subsidio al GLP es de 4,458 millones de balboas. Además, si a ese monto le adicionamos lo ya gastado desde el año 1998 asciende a 5,744.5 millones de balboas que se habrían entregado al sector residencial al año 2050.

B. *Análisis del Escenario Azul: Cocción con Electricidad + GLP.*

En esta sección se evaluará la sustitución de gas licuado de petróleo por electricidad de forma progresiva para la cocción de alimentos. Para este análisis se utiliza un modelo estándar de una estufa eléctrica de inducción y una estufa eléctrica de resistencia de 4 “quemadores” ambas. Se utiliza una potencia promedio para cada estufa, la estufa de inducción tiene una potencia media de 1300 W mientras que la eléctrica tiene una demanda media de 1525 W.

La demanda de potencia se calculó en base a la siguiente ecuación (1):

$$P\ (KW) = \left[\left(P_{Q1}\right) * (H) * \left(N_{Q1}\right) * \left(\%_{Q1}\right) + \cdots \left(P_{Qn}\right) * \left(H_n\right) * \left(N_{Qn}\right) * \left(\%_{Qn}\right) \right] \quad (1)$$

En donde:

P es la demanda máxima total para una hora.
P_{Qn} es la demanda de un quemador individual.
H_n es el número de usuarios total
N_{Qn} es el número de quemadores utilizados.
$\%_{Qn}$ es el porcentaje de usuarios en esa hora

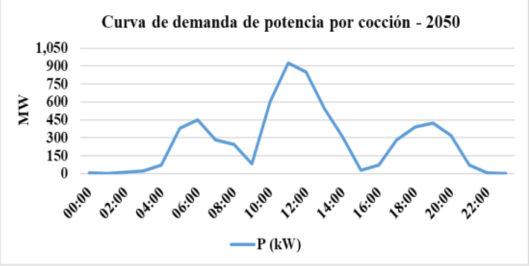


Figura 7 Curva de demanda de potencia por estufas eléctricas al año 2050

Se puede apreciar un considerable aumento en la demanda de potencia al utilizar estufas eléctricas. Como se observa en la figura 7 la demanda máxima ocurre entre las 11 de la mañana y 1 de la tarde, requiriéndose una potencia de 926 MW en el año 2050. estos picos, se presentan en los mismos periodos para los años anteriores al 2050.

En relación con el consumo de energía total, debido al uso de electricidad para cocción, como se muestra en la figura 9, en este escenario se da una disminución del 83 % en el uso de energía fósil proveniente del GLP para cocción con respecto al escenario tendencial al año 2050, se dejarían de utilizar 2,744,000 cilindros de GLP.

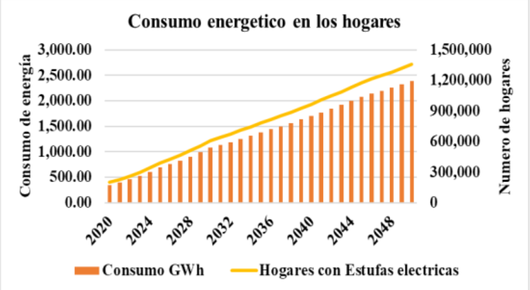


Figura 8 Proyección del consumo de energía por estufas eléctricas

C. *Análisis del Escenario Verde: Cocción con Electricidad + Gas Natural + GLP*

En este escenario se utiliza la evaluación de la sustitución de GLP por electricidad tal como se presentó en el escenario azul y se asume que dada la participación del GNL en la matriz eléctrica también se puede dar su implementación en otros sectores como el doméstico.

Con el fin de determinar la proyección de este sector, se plantearon varias premisas de cálculo:

1.) Suministro de GNL mediante transporte en contenedores criogénicos a mini redes residenciales.
2.) Ingreso familiar.
3.) Distribución espacial de la población.
4.) Implementación escalonada en las residencias, a partir de 2020
5.) Al final del período, el 100% de las residencias escogidas utilizaría gas natural como combustible.

El historial de consumo de GLP en galones de la provincia de Panamá fue analizado por mes, para poder contar con una mayor cantidad de datos y así obtener una línea de tendencia más precisa. Finalmente, los galones resultantes de GLP fueron convertidos a m³ de GNL. Se proyecta una tasa de penetración de tecnología de 9,1% anual.

El consumo de energía eléctrica, debido al uso de electricidad para cocción, como se muestra en la figura 9, es de 2388 GWh en el escenario verde.

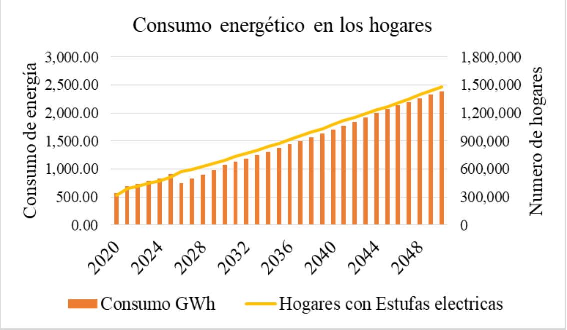


Figura 9 Proyección del consumo de energía por estufas eléctricas

D. *Comparación de escenarios*

- **Consumo de energía total**

El aumento de energía eléctrica en el escenario azul causado por el reemplazo de GLP por electricidad pasa de ser de 13.16 GWh en el escenario gris a 2388 GWh en el escenario azul. A nivel final de energía, esto se traduce en un aumento de 139 Kbep, como se muestra en la tabla 3.

Tabla 3. Consumo de Energía total

Energía total			
Escenario	**Cilindros de GLP**	**Energía cocción (Kbep)**	**Energía (GWh)**
Escenario Gris	**17,403,425**	**1,574**	**2,563**
Escenario Azul	**2,807,864**	**1,713**	**2,790**

La figura 10 muestra la proyección de consumo de gas natural (GNL en m³) del sector residencial durante el período 2025 – 2050, considerando el inicio de conversión también en el año 2025 y los factores calculados: porcentaje de acceso a la tecnología de 2,1% y la tasa de penetración de 9,1%.

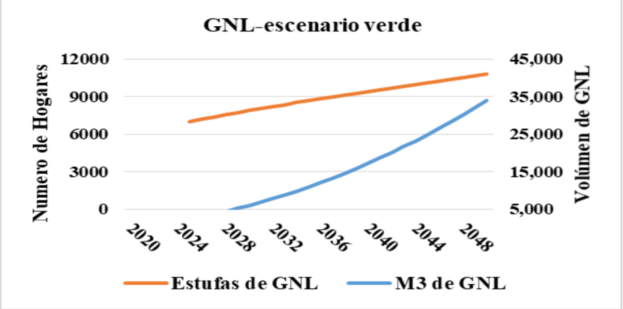


Figura 10. Proyección del número de gas natural escenario verde

En las figuras 11 y 12 se muestra el total de hogares con acceso a combustibles limpios para cocinar en el escenario azul y el escenario verde, respectivamente. Estos incluyen los que utilizan estufas de inducción, de gas natural licuado y GLP, como se observa la utilización del GLP tiende a ir disminuyendo. En la figura 11 se muestra que es ínfimo el consumo de GNL en el sector residencial, respecto a los otros energéticos.

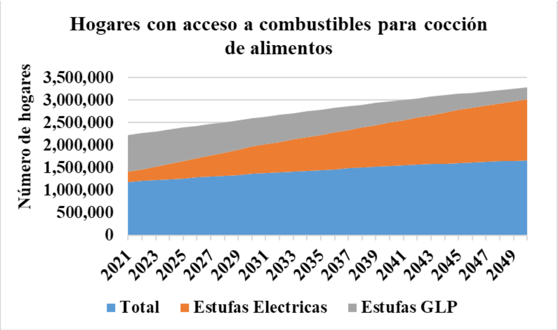


Figura 11. Proyección del número de hogares escenario azul

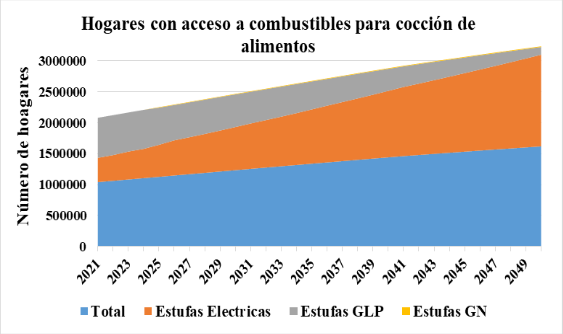


Figura 12. Proyección del número de hogares escenario verde

- **Proyección de consumo de GLP y subsidio.**

Como se puede ver en la figura 13, el monto del gasto público durante el periodo de análisis para el escenario gris va creciendo año tras año a medida que aumenta el número de hogares y estos siguen la tendencia actual de consumo de GLP, mientras que en el escenario azul y verde el gasto va disminuyendo cada año por la penetración de estufas eléctricas y de gas natural que sustituyen el GLP y la leña para cocción de alimentos.

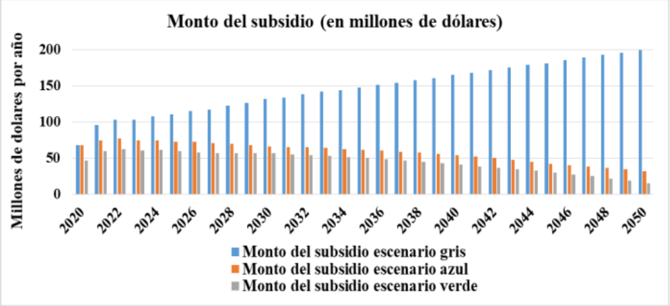


Figura 13 Proyección del desembolso para el subsidio de GLP

En términos monetarios se estimó que en el escenario gris se gastan 4,500 millones de dólares en subsidio para los cilindros de 25 libras de gas licuado de petróleo; mientras que en el escenario azul este monto baja a 1743 millones de dólares y en el escenario verde este monto baja aún más a 1399 millones de dólares, lo que representaría un ahorro de 2716 millones de dólares y de 3,128 millones de dólares para los escenarios azul y verde, respectivamente, como se observa en la tabla 4.

La diferencia entre el escenario verde y azul es de 344 millones de dólares, en reducción del subsidio si se da el escenario verde.

Tabla 4. Gasto total en subsidio 2021-2050

Análisis	Millones de B./ (2021 -2050)
1. Escenario Gris	4,459
2. Escenario Azul	1,743
3. Escenario verde	1,399
Diferencia escenario 2-1	-2,716
Diferencia escenario 3-1	-3,060
Diferencia escenario 3-2	-344

- **Estimación de emisiones de gases de calentamiento global.**

En esta sección se realiza la estimación de las emisiones de gases de efecto invernadero para el escenario gris, el escenario azul y el escenario verde dado el impacto que según investigaciones de la OMS se producen en la salud y el ambiente debido a la contaminación del aire por utilización de combustibles fósiles y sólidos para la cocción de alimentos [29]. En la tabla 5 se muestran las toneladas de Dióxido de carbono (CO_2), Metano (CH_4) y Óxido Nitroso (N_2O) que son producidas en el escenario gris debido a la quema de gas licuado para la cocción en el sector residencial. Al año 2050 se producen poco más de 29 millones de toneladas de dióxido de carbono, 1,387 toneladas de metano y 549 toneladas de óxido nitroso.

Tabla 5. Emisiones escenario gris.

Emisiones escenario gris	
Año	2050
Toneladas de CO_2	29,628,705
Toneladas de CH_4	1,387
Toneladas de N_2O	549

Por otro lado, en la tabla 6 se muestran toneladas de Dióxido de carbono (CO_2), Metano (CH_4) y Óxido Nitroso (N_2O) que son producidas en el escenario azul, hay menor cantidad de hogares que utilizan GLP y el uso de la leña es nulo, debido a los esfuerzos políticos y del mercado para reducir las emisiones y aumentar la eficiencia energética. Al año 2050 se producen cerca de seis millones de toneladas de dióxido de carbono, 289 toneladas de metano y 56 toneladas de óxido nitroso.

Tabla 6. Emisiones escenario azul.

Emisiones escenario azul	
Año	2050
Toneladas de CO_2	6,217,514
Toneladas de CH_4	289
Toneladas de N_2O	56

En la tabla 7 se muestran toneladas gases de nocivos que son producidas en el escenario verde, al igual que en el escenario azul, aquí hay menor cantidad de hogares que utilizan GLP y algunos utilizan GNL, hay mayor utilización de estufas eléctricas. Al año 2050 se producen 4,848,883 millones de toneladas de dióxido de carbno, 225 toneladas de metano y 43 toneladas de óxido nitroso.

Tabla 7. Emisiones escenario verde.

Emisiones escenario verde	
Año	2050
Toneladas de CO_2	4,848,383
Toneladas de CH_4	225.29
Toneladas de N_2O	43.61

Finalmente, en las tabla 8 y 9 se muestra el cálculo de las emisiones evitadas en el escenario azul y verde, con respecto a las producidas en el escenario gris. El país puede dejar de emitir 23 millones de toneladas de CO_2, 1,098 Toneladas de metano CH_4 y 493 Toneladas de N_2O el escenario azul, mientras que en el escenario verde estas cifras aumentan a 24.7 millones de toneladas de CO_2, lo cual es un aporte significativo a los NDC por sus siglas en inglés, compromisos que panamá adquirió ante la Convención Marco de Naciones Unidas sobre Cambio Climático (CMNUCC).

Tabla 8. Emisiones evitadas.

Emisiones evitadas	
Año	2050
Toneladas de CO_2	-23,411,191
Toneladas de CH_4	-1,098
Toneladas de N_2O	-493

Tabla 9. Emisiones evitadas.

Emisiones evitadas	
Año	2050
Toneladas de CO_2	-24,780,322
Toneladas de CH_4	-1,162
Toneladas de N_2O	-506

Al analizar estos resultados es claro que se debe acelerar el acceso a la energía debido a que beneficiará a las familias que no tienen acceso ni a electricidad ni a combustibles limpios para cocinar alimentos. Además, el aumento de la participación de la energía primaria renovable en el uso final, específicamente en el sector residencial, reducirá la emisión de contaminantes que provocan efectos nocivos sobre la salud de la población del país [30]. El aumento en el uso de tecnologías más eficientes reducirá el consumo de energía y las externalidades de los combustibles fósiles y sólidos, esto hará que las personas puedan disponer de recursos económicos y mejor salud para realizar otras actividades productivas [31].

En este análisis no se consideraron las emisiones provenientes del uso de electricidad para cocción, ya que estas dependen del tipo de generación despachada para suplir la demanda.

E. Propuesta de un programa de sustitución

Implementar la cocción limpia es fundamental para lograr los objetivos de desarrollo sostenible en materia de energía asequible y no contaminante, salud pública, igualdad de género, producción y consumo responsable y de acción por el clima [30] [29]. El razonamiento para el desarrollo de una política de energética por parte del estado para trancisionar a tecnologías eficientes es la existencia de fallas en el mercado que hacen que el mismo sea ineficiente en el manejo y uso de la energía [32].

Lo anterior lo podemos ver claramente en el subsidio energético al tanque de 25 libras de GLP, en donde muchas veces no se encuentra destinado a satisfacer las necesidades de cocción de la población más desfavorecida económicamente hablando. Desde el punto de vista del sector estatal, los objetivos para alcanzar el acceso a combustibles limpios de cocción y la eficiencia energética están dentro de las funciones de distintas instituciones:

1.) Secretaría de energía
2.) Ministerio de Salud
3.) Ministerio de ambiente
4.) Instituto de la mujer
5.) Ministerio de Desarrollo Social

6.) Ministerio de Economía y Finanzas
7.) Oficina de Electrificación Rural
8.) Ministerio de Comercio e Industria.

Una intervención estatal estaría dentro de las competencias de varias instituciones, ya que dependiendo del energético que se use para la cocción se tienen diversos impactos en la salud, en el medio ambiente, género (mujeres y niños), economía y financiamiento. Con la implementación de una política de sustitución de energéticos podemos obtener algunos logros:

1.) Reducción del impacto del subsidio frente al alza del precio de importación.
2.) Precio moderado del cilindro.
3.) Focalizar el subsidio.
4.) Uso eficiente de la energía.
5.) Reducción de las emisiones de gases de calentamiento global.

Para lograr la transición hacia una cocina más limpia se requerirán nuevas soluciones determinadas por el mercado e impulsadas por los inversionistas y el estado. Las áreas de trabajo prioritario se enfocan en 3 puntos clave [10]:

1.) Política estatal de largo plazo-compromiso político
2.) Inversión.
3.) Conocimiento e innovación.

Contar con una política estatal es el punto principal, ya que por experiencia de otros países se ha visto que no se puede depender solo del mercado. Transicionar hacia la cocción con energía eléctrica debe contar con el compromiso político, económico y ambiental, apoyado por políticas públicas, asociaciones público-privadas, e inversiones. El Gobierno Nacional, los organismos multilaterales, y otras plataformas tienen un rol clave.

Según datos de la Secretaría Nacional de Energía, el 85.1% de las viviendas declararon utilizar GLP con mayor frecuencia para cocinar, sin embargo este porcentaje baja a 6.7% en la comarca indígena Ngöbe Buglé, donde el uso de leña para cocinar es de 92.7%, mucho más generalizado, incluso cuando se le compara con las otras comarcas: 71.7% y 47.3% usaban leña en Kuna Yala y Emberá, respectivamente [26].

Como se observa en la figura 14, en el área de las comarcas en Panamá es donde se tiene un mayor nivel de mortalidad debido al uso de la leña. La transición hacia tecnologías eficientes para cocinar los alimentos puede ser un dinamizador para aumentar los beneficios en materia económica, cambio climático y de salud pública.

Figura 14 Nivel de Mortalidad y uso de leña; Fuente: Banco Mundial [33]

En Panamá, la venta de GLP tiene una diferencia de precios para los hogares de menores ingresos y los comercios, e incluso en el mismo sector residencial, en comparación con los hogares de mayores ingresos, por medio de tarifas reguladas entre lo pagado, al precio regulado, por el usuario final y según la capacidad del cilindro de GLP. Como se mencionó anteriormente, los tanques de 25 libras son consumidos en los hogares, mientras que los cilindros mayores (100 libras) son para uso comercial u hogares de mayor ingresos [26].

Como parte de la realización del Plan Energético Nacional con horizonte al 2050, en la Secretaría Nacional de Energía se investigó la viabilidad de la sustitución del GLP para cocinar por electricidad, ello como una posible forma de reducir la dependencia de hidrocarburos, de otros combustibles contaminantes como los tradicionales de biomasa, y de reducir el gasto en el subsidio al GLP [13].

V. CONCLUSIONES

Los escenarios se definieron basados en la metodología top down y bottom up que resultaron en proponer el escenario gris y el escenario azul. El escenario gris determinó la línea base del estudio, para cuantificar el consumo tendencial del uso del GLP sin ningún tipo de cambios a nivel de política energética, es decir, BaU. En cuanto al escenario azul donde se da la sustitución de estufas de GLP por estufas eléctricas en el sector residencial, se obtiene el consumo energía eléctrica y de potencia, además se da una disminución del consumo de GLP del 83 % con respecto al escenario gris, donde se dejarían de utilizar 2 744 000 cilindros de GLP.

La proyección del monto del subsidio del GLP al año 2050 para ambos escenarios utilizando las proyecciones del precio dieron como resultado un total de 4,459 millones de balboas como monto acumulado del subsidio al GLP gastados en el escenario gris, mientras que para el escenario azul el gasto en subsidio fue de 1,743 millones de balboas. Por lo tanto, se observó un ahorro en subsidios con respecto al escenario gris de 2,716 millones de balboas cuando se implementa la sustitución de las estufas de GLP a eléctricas en el escenario azul.

En el escenario verde se analizó la sustitución del consumo de Gas Licuado de Petróleo por electricidad y GNL, se observa que en el año 2050, el consumo de GNL sería de 34,000 m³ en las residencias con posibilidad de sustituir el GLP por gas natural. La inserción de este combustible en el sector residencial depende de la construcción de miniredes de tuberías y adecuación de otras infraestructuras para su transporte hasta la demanda final en el sector residencial.

Se calcularon las emisiones de los principales gases de calentamiento global: CO_2, CH_4, y N_2O para el escenario gris, el escenario azul y el escenario verde; que producen al utilizar para cocción combustibles como el GLP. Se estimó que se pueden evitar 24,780,322 Toneladas de CO_2, 1,162 Toneladas de metano CH_4 y 506 Toneladas de N_2O.

Al finalizar esta investigación se ve que es necesaria la implementación de políticas energéticas para la sustitución del GLP y así aumentar la seguridad energética y mejorar el uso racional y eficiente de los recursos energéticos en el País.

Es necesario realizar un estudio económico y de diagnóstico de las fallas de mercado que puedan afectar la implementación: barreras culturales, financieras, institucionales, falta de datos objetivos. El enfoque debe incluir estrategias y tácticas que permitan ejecutarlo con claridad y de manera transparente.

En cuanto al cálculo de los costos de la implementación de un programa, la valuación económica de las posibilidades de la sustitución de energéticos es una manera de alinear la decisión de intervenir en el mercado en términos económicos. Los resultados generados a partir de dicha valuación ayudarán a orientar los objetivos de inversión, priorizar las necesidades y personalizar las evaluaciones a las necesidades de los usuarios finales.

ACKNOWLEDGMENT

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REFERENCES

[1] GEA, «Global Energy Assessment: Toward a Sustainable Future,» IIASA, Cambridge University Press, Viena, 2012.

[2] Agencia Internacional de la Energía, «World Energy Outlook 2011. Panorama Mundial de la Energía,» 2011.

[3] UN Women Watch, «Women, Gender Equality, and Climate Change.,» New York, 2009.

[4] Secretaría Nacional de Energía, «Balances Energéticos-Panamá,» SNE, Panamá, 2016.

[5] Secretaría Nacional de Energía, «ACTUALIDAD ENERGÉTICA – PANAMÁ 2015-2017 - Un Sistema Energético en Transición,» Panamá, 2017.

[6] Comisión Económica para América Latina y el Caribe , «CEPAL,» 2015. [En línea]. Available: https://www.cepal.org/es/temas/. [Último acceso: Agosto 2019].

[7] IRENA, «Evaluación del Estado de Preparación de las Energías Renovables Panamá,» Agencia Internacional de Energías Renovables, Abu Dhabi, 2018.

[8] Smith, K., J. Rogers, and S. Cowlin, «Household fuels and ill-health in developing countries: what improvements can be brought by LP gas?,» World LP Gas Association, Paris, 2005.

[9] Banco Mundial, «Global Tracking Framework 2017: Progress Towards Sustainable Energy,» World Bank, Washington, D.C., 2017.

[10] MECS , «Modern Energy Cooking Services - Publications,» 2021. [En línea]. Available: https://mecs.org.uk/publications/. [Último acceso: 2 Septiembre 2021].

[11] Andrew, P. G., Julian, D. M. and MilindKandlikar, D, «Health and Climate Benefits of Cookstovere Placement Options,» Energy Policy, p. 7530–7542, 2011.

[12] ESMAP, «Cooking with Electricity : A Cost Perspective - ESMAP,» 2020.

[13] Secretaría Nacional de Energía, Plan Energetico Nacional 2015-2050 Panamá el futuro que queremos, Panamá, 2016.

[14] United Nations, Department of Economic and Social Affairs, Population Division, World Urbanization Prospects: The 2018 Revision, New York: United Nations, 2018.

[15] Agencia Internacional de la Energía, “World Energy Outlook 2010.” Panorama Mundial de la Energía., 2016.

[16] T. S. y. S. B. Wood, «Fuelwood and Charcoal Use in Developing Countries,» Annual Review of Energy, vol. 10, pp. 407-429, 1985.

[17] BID - Banco Interamericano de Desarrollo, «SE4ALL Evaluación Rápida y Análisis de Brechas,» BID, Panamá, 2014.

[18] S. Coate, «An Efficiency Approach to the Evaluation of Policy Changes,» National Bureau of Economic Research, Boston, 1999.

[19] International Energy Agency (IEA) and the World Bank, «Sustainable Energy for All 2017—toward Sustainable Energy,» World Bank, Washington, DC, 2017.

[20] The Energy to Cook: An Exploration of Modern Food Systems and Energy Consumption in Domestic Kitchens, «Energies,» 12 4 2021. [En línea]. Available: https:// doi.org/10.3390/en14134004.

[21] ESMAP, «State of the Global Clean and Improved Cooking Sector,» GACC, Washington, DC, USA,, 2015.

[22] California Energy Commission, «California’s clean energy future, – an overview on meeting California’s energy and environmental goals in the electric power sector in 2020 and beyond,» 2010.

[23] International Energy Agency, Key World Energy Statistics 2010, Paris: IEA, 2010.

[24] Coster, Edward J., Distribution Grid Operation Including Distributed Generation, NL: Technical University of Eindhoven, 2010.

[25] Contraloría General de la República, Panamá, «Resultados Finales Básicos,» Instituto de Estadística y Censo, 2010. [En línea]. Available: https://www.inec.gob.pa/publicaciones/Default3.aspx?ID_PUBLICACION=362&ID_CATEGORIA=13&ID_SUBCATEGORIA=59. [Último acceso: Mayo 2020].

[26] Secretaría Nacional de Energía, «https://www.energia.gob.pa/,» Dirección de hidrocarburos, 2015. [En línea]. Available: https://www.energia.gob.pa/archivos/. [Último acceso: 1 Julio 2021].

[27] International Energy Agency, «Energy Access Outlook: from Poverty to Prosperity, World Energy Outlook-2017 Special Report,» IEA, Paris, 2017.

[28] Secretaría Nacional de Energía, «Estadisticas,» Octubre 2019. [En línea]. Available: https://www.energia.gob.pa/archivos/. [Último acceso: 02 07 2021].

[29] WHO (World Health Organization), WHO Guidelines for Indoor Air Quality: Household Fuel Combustion, Geneva: WHO, 2014.

[30] Rosenthal, J., et al., Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals, Energy for Sustainable Development, 2015.

[31] Ministerio de la Presidencia, Secretaría de Energía, SDG7 Energy Compact of Panama, Action Agenda to advance SDG7 on sustainable energy for all.

[32] CPUC (California Public Utilities Commission), «California Standard Practice Manual Economic Analysis of Demand-Side Programs and Projects,» 2001. [En línea]. Available: http://www.energy.ca.gov/greenbuilding/documents/background/07-J_CPUC_STANDARD_PRACTICE_MANUAL.PDF.

[33] Grupo Banco Mundial, «World Bank,» 2014. [En línea]. Available: https://openknowledge.worldbank.org.. [Último acceso: Febrero 2019].

[34] MIT, The Future of Natural Gas, Cambridge, MS: Massachusetts Institute of Technology, 2010.

[35] Censo Nacional de Población y Vivienda, «Provincia-comarca indígena, algunas características de las viviendas,» INEC, Panamá, 2010.

[36] Environmental Protection Agency, «Capítulo 3 (Energy),» de Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018, Washington, D.C., EPA, 2020, p. Emission Factors for Greenhouse Gas Inventories.

Evaluación del potencial de la respuesta a la demanda en Zonas No Interconectadas considerando variables de cambio tecnológico

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Introducción:

A lo largo de la historia se han establecido grandes cambios en la disruptiva tecnológica en materia de generación, consumo y transmisión energética. Este documento nos permite tener una evaluación de potencial sobre respuesta a la demanda (RD) de energía [1], y sus respectivas implicaciones con variable de cambio tecnológico. Disruptiva tecnológica que en muchos casos presenta algunas afectaciones y dificultades desde Zonas no interconectadas ZNI y limitantes propias de cada región como lo son suministro energéticos, gestión energética y variables de cambió tecnológico [2]. El futuro tecnológico de las energías renovables se ha potenciado por una visión de generación a diferentes niveles con políticas impulsadas desde hace varios años relacionadas con descarbonizar y fomentar la generación de electricidad con tecnología limpia [3], y mercados eléctricos competitivos que se han estado regulando tanto políticamente como tecnológicamente desde sus inicios [4]. Ahora en la transición energética por respuesta a la demanda (RD) se han incorporado algunos puntos para tener en cuenta como lo son [5]:

- Cómo reaccionar al cambio de diferente tecnologías y nuevos paradigmas tecnológicos
- Cambios en sectores por servicios en:
    - Hogares
    - Industrias (servicios terciarios)
    - Transporte

El futuro de los servicios públicos cómo las innovaciones tecnológicas en los recursos de energía representan un cambio en la regulación de los incentivos y precios de generación distribuida, revolucionando el sector del mercado de los agregadores de RD [5]. Algunos de los impactos más emblemáticos se han generado con la disruptiva tecnológica e impactan con gran importancia en los mercados reestructurados respondiendo a los precios, a los avances tecnológicos y a las reducciones en los costos de infraestructura con aumento de potencial en la participación tanto en la demanda como en el consumo energético [6]. La gestión energética para la industria genera un enfoque ecosistémico para aumentar sus beneficios acelerando la adopción de soluciones de administración de energía, fortaleciendo los ecosistemas de servicios de transición en procesos de calefacción o enfriamiento y sistemas de cogeneración [7]. La gestión energética en sistemas de RD bajo tecnología de cadena de bloques nos permite descentralizar el sistema de negocio energético y brindar contratos de negocio según los diferentes agregadores de RD y su ruta respecto a su implementación y registro de procesos en escenarios propios de gestión energética, teniendo en cuenta principalmente que la RD nos permite dar una solución para aumentar o fortalecer la capacidad energética y la confiabilidad a la red en constante exigencia y evolución en los servicios de optimización y operación inteligente con tecnología de proyección energética de inteligencia artificial [8]. Desde los hogares inteligentes hasta servicios empresariales o terciarios con operación en horas valle, se analiza y se presentan los resultados en RD que pueden reducir la carga máxima y según [9], los consumos energéticos en la franja de la noche estarían entre un 29,3 % y un 49,3% (con una franja de disminución del 20%). En el día podría reducirse entre un 37,5 % y un 78,2 % [9].

Los servicios descentralizados de energía basados en tecnología IOT se deben desarrollar sobre nuevas herramientas para detectar cambios radicales a la vista y nuevas estrategias para acelerar la disrupción tecnológica [10]. La infraestructura para la entrega de productos básicos evoluciona naturalmente para apoyar una mayor personalización con tecnología de cadena de bloques con modelos de transacción tecnológica a medida que las empresas de servicios públicos buscan convertirse en base para los servicios innovadores. Su evolución finalmente conduce a la utilidad y transformación del sector energético [11]. Transformados para nuevos propósitos, los servicios energéticos permiten nueva infraestructura, plataformas y utilidades tecnológicas. Adicionalmente para estos servicios tecnológicos es necesario analizar diferentes zonas no interconectas (ZNI) donde se presentan retos tecnológicos, climáticos y de disponibilidad propia desde los generadores [12], las ZNI, han tenido incrementos en su cobertura del 25,9%, en nuestra Región [13] lo que supone grandes retos por satisfacer en el sector energético como por ejemplo en ZNI en el sur áfrica, casos similares a nuestra región (Latinoamérica) se pretende la realización de una red dominante de energía renovable en gestión de la demanda que cumpla con los requisitos mínimos de diversificación, accesibilidad e impacto ambiental y tecnológico [14]. Adicionalmente con mecanismo de gestión eficiente con proyección energética se espera garantizar mayor cobertura energética y limitaciones del lugar a través de la planeación de los recursos disponibles con tecnología IA de RD [15], fortaleciendo modelos de transacción energéticos (MTE) y RD [16], además de los diferentes limitantes en cuenta a consumo por habitante o región en ZNI, asumiendo retos y disponibilidades energéticas particulares en sistemas híbridos energía y en sectores como agricultura, piscicultura o propios que se pueden ver formalizados con políticas energéticas limpias[17]. Colombia presenta cerca del 52% de su territorio una cobertura en ZNI lo que genera un impacto en su potencial de trabajo en RD[6]. Una de las regiones con mayor necesidad energética es el departamento del Guaviare donde se tienen aproximadamente cerca de 21.000 usuarios con una población de impacto de cerca de 80.000 habitantes con grandes retos de sostenibilidad energética en ZNI.

Metodología:

Con este trabajo se espera analizar los impactos generales de la evaluación de RD y su composición en el mercado energético en escenarios de trabajo esencialmente programas de RD basados en incentivos [18], (los consumidores reciben incentivos por gestionar con sistemas inteligentes sus patrones de consumo según la disponibilidad de la oferta) y su respectiva ZNI, su incorporación y gestión con tecnologías de proyección energética[8], [19],[20]. Principalmente acelerar los modelos de abastecimiento energético basados en combustibles fósiles (Disel) a sistemas sostenibles renovables operados en ZNI y gestionados desde mecanismos IA con DR donde el consumo es mucho menor que en grandes ciudades pero que presenta grandes retos de suministro, disponibilidad y estabilidad energética en la red[21], [22]. Este documento se desarrolla en 2 fases:

a) Se realizara una revisión general de la literatura dentro del marco de la eficiencia energética en escenario de DR (flexibilidad)
b) Análisis de la información obtenida con una identificación de casos de estudio de RD en sistema de Innovación

Resultados esperados: Principales hallazgos

En este análisis se pretende establecer una propuesta de trabajo (ver figura 1) frente a los temas relacionados y la interacción de los diferentes participantes, quienes con sistemas inteligentes reducen su consumo en las horas pico o durante los eventos programados [23].

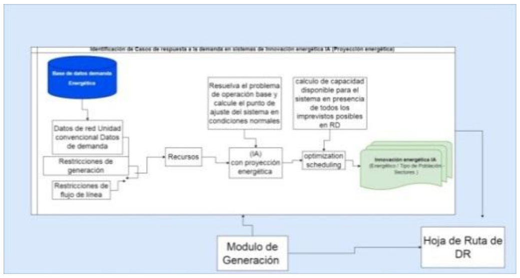

Figura 1 propuesta con implementación de proyección en DR.
Fuente Autores propios

Conclusiones:

Los principales aportes en este documento nos muestran un análisis sobre el impacto tecnológico en escenarios de diferentes casos de gestión sostenible de RD energética, e impactos en casos de estudio (hogares e industria) y se determina que con el análisis de una de gestión de RD se pueden obtener beneficios económicos partiendo de condiciones iniciales en función de las diferentes capacidades y su posterior impacto en la industria como lo serían:

- Sistemas de redes inteligentes de gestión con enfoques adecuados para el modelamiento y optimización en un contexto de RD en el sector terciario con resultados en pagos por incentivos a consumidores y capacidades de aporte a la red eléctrica [24].

- Impactar los costos de facturación disminuyendo el consumo de electricidad del sector terciario. Esto teniendo en cuenta los diferentes escenarios en los cuales se encontrarían dispositivos programables. Se alcanzaría programando los dispositivos en el intervalo de tiempo de tarifa baja [25].
- La reducción de la demanda de carga máxima en el período de tarifa baja. Se establecería la reprogramación de los dispositivos programables dentro de la red [25] .

REFERENCIAS

[1] G. BaseemKhanIssaias, “Chapter 12 - Demand response aggregation,” in *Active Electrical Distribution Network*, 2022, pp. 345–358.

[2] E. E. Gyamfi Samuel, Felix Amankwah Diawuo, Emmanuel Yeboah Asuamah, “Chapter 12 - The role of demand-side management in sustainable energy sector development,” in *Renewable Energy and Sustainability*, Sunyani, Ghana, 2022, pp. 325–346.

[3] F. P. Sioshansi, *Generating Electricity in a Carbon - Constrained World*. 2008.

[4] Fereidoon P. Sioshansi, *Competitive Electricity Markets: Design, Implementation, Performance*. Amsterdam, Netherlands, 2008.

[5] F. P. Sioshansi, *Future of Utilities – Utilities of the Future Edited by United States of America*, Elservier. United States of America, 2018.

[6] Fereidoon Sioshansi, *Chapter 13: New technologies on the demand side*. United States of America, 2021.

[7] Deloitte Insights, “Smart energy management for industrials,” 2021. [Online]. Available: https://www2.deloitte.com/us/en/insights/industry/power-and-utilities/smart-energy-management.html.

[8] V. Sharifi, A. Abdollahi, and M. Rashidinejad, “International Journal of Electrical Power and Energy Systems Flexibility-based generation maintenance scheduling in presence of uncertain wind power plants forecasted by deep learning considering demand response programs portfolio,” *Int. J. Electr. Power Energy Syst.*, vol. 141, no. March, p. 108225, 2022.

[9] B. Yu, F. Sun, C. Chen, G. Fu, and L. Hu, “Power demand response in the context of smart home application,” *Energy*, vol. 240, p. 122774, 2022.

[10] C. Iwendi and G. Wang, “Combined power generation and electricity storage device using deep learning and internet of things technologies,” *Energy Reports*, vol. 8, pp. 5016–5025, 2022.

[11] X. Mao, M. Xue, T. Zhang, W. Tan, Z. Zhang, and Y. Pan, “ScienceDirect Centralized bidding mechanism of demand response based on blockchain,” *Energy Reports*, vol. 8, pp. 111–117, 2022.

[12] N. Oconnell, P. Pinson, H. Madsen, and M. Omalley, “Benefits and challenges of electrical demand response: A critical review,” *Renew. Sustain. Energy Rev.*, vol. 39, pp. 686–699, 2014.

[13] ANDERSON URREGO, “Demanda de energía eléctrica en zonas no interconectadas ha incrementado 25,9%,” *Larepublica*, 2021. [Online]. Available: https://www.larepublica.co/economia/demanda-de-energia-electrica-en-zonas-no-interconectadas-ha-incrementado-25-9-3227491.

[14] O. J. Ayamolowo, P. T. Manditereza, and K. Kusakana, “ScienceDirect South Africa power reforms : The Path to a dominant renewable energy-sourced grid,” *Energy Reports*, vol. 8, pp. 1208–1215, 2022.

[15] V. Sharifi, A. Abdollahi, and M. Rashidinejad, “International Journal of Electrical Power and Energy Systems Flexibility-based generation maintenance scheduling in presence of uncertain wind power plants forecasted by deep learning considering demand response programs portfolio,” *Int. J. Electr. Power Energy Syst.*, vol. 141, no. January, p. 108225, 2022.

[16] J. Han, N. Liu, and C. Gu, “Optimization of transactive energy systems with demand response : A cyber-physical-social system perspective,” no. May, pp. 142–155, 2022.

[17] A. Singh and P. Basak, “Conceptualization and techno-economic evaluation of microgrid based on PV / Biomass in Indian scenario,” *J. Clean. Prod.*, vol. 317, no. March 2020, p. 128378, 2021.

[18] H. Wang, J. Yuan, G. Qi, Y. Li, J. Yang, and H. Dong, “ScienceDirect A data-driven load forecasting method for incentive demand response,” *Energy Reports*, vol. 8, pp. 1013–1019, 2022.

[19] H. Li and S. Wang, “Two-time-scale coordinated optimal control of building energy systems for demand response considering forecast uncertainties,” *Energy*, vol. 253, p. 124204, 2022.

[20] F. Pallonetto, C. Jin, and E. Mangina, “Energy and AI Forecast electricity demand in commercial building with machine learning models to enable demand response programs,” *Energy AI*, vol. 7, no. October 2021, p. 100121, 2022.

[21] L. Alejandro, A. Barragán, E. R. Trujillo, and F. Santamaría, “Respuesta de la demanda en el mercado eléctrico Colombiano : modelado e implementación web Demand response in the Colombian electricity market : modeling and web implementation,” p. 22, 2018.

[22] D. Neves, M. C. Brito, and C. A. Silva, “Impact of solar and wind forecast uncertainties on demand response of isolated microgrids,” *Renew. Energy*, vol. 87, pp. 1003–1015, 2016.

[23] P. Zhang, X. Dou, W. Zhao, M. Hu, and X. Zhang, “Analysis of power sales strategies considering price-based demand response,” *Energy Procedia*, vol. 158, pp. 6701–6706, 2019.

[24] D. K. Hwang and J. Cho, “Feasibility Study on Energy Audit and Data Driven Analysis Procedure for Building Energy E ffi ciency : Bench-Marking in Korean Hospital Buildings,” no. Cop 21, 2019.

[25] M. H. Dadashi-rad, A. Ghasemi-marzbali, and R. A. Ahangar, “Modeling and planning of smart buildings energy in power system considering demand response,” *Energy*, vol. 213, p. 118770, 2020.

Caracterización de las estrategias de gestión de la energía para *Prosumager*s residenciales en el mercado eléctrico colombiano.

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INTRODUCCIÓN

Durante el siglo XXI, el campo fotovoltaico es la rama científica que ha experimentado mayor desarrollo, lo cual se evidencia en que la industria fotovoltaica pasará de ser subsidiada a ser rentable próximamente. Además, se plantea que la energía solar será la única fuente viable de energía limpia en el futuro, sobre la eólica y la hidroeléctrica (Mitrasinovic, 2021). La energía solar, se encuentra entre las fuentes líderes de generación de energía eléctrica en el mundo, creciendo con cada vez más fuerza, representando en el 2021, el 13% de generación (226 GW) del total de generación de energía a nivel mundial, en compañía de la eólica (BP p.l.c., 2022). En el caso colombiano, la capacidad efectiva de generación a partir de la radiación solar, para el año 2020 fue de 114,865 Megavatios (MW) (MNE, 2021) y actualmente se encuentran 885 proyectos registrados en la UPME con una capacidad de 16.446,73 MW. La solar es una fuente energética con una participación del 0,18% en el 2019 (MNE, 2021) .

En particular, los usuarios del sector residencial, han acogido los sistemas de generación solar fotovoltaica bajo la modalidad de Generación Distribuida (GD) (García, López, & Gómez, 2021). Estos sistemas permiten generación de energía limpia y no dependiente de las reservas y precios de los combustibles fósiles. Además de estas ventajas, también son capaces de mejorar el perfil de voltaje, aumentar la confiabilidad del sistema y reducir las pérdidas de línea en los sistemas de distribución (Karadeniz, y otros, 2022). En el caso colombiano, la GD fotovoltaica puede ser una opción viable para diversificar el mercado y poder proporcionar electricidad en áreas remotas y aisladas, donde millones de familias en Colombia carecen de un servicio de energía eléctrica confiable (Hernandez, Velasco, & Trujillo, 2011).

La utilización de los sistemas GD ha requerido del uso de baterías para el almacenamiento, principalmente cuando las instalaciones son aisladas (García P. F., 2021). Las baterías, que son tecnologías de almacenamiento de energía eléctrica, donde ocurren reacciones electroquímicas entre sus componentes: el ánodo (electrodo negativo), el cátodo (electrodo positivo) y el electrolito (medio físico para la transferencia de carga). La reacción es reversible de forma que, una vez descargada, la batería puede recargarse (Iglesias, y otros, 2012). La combinación de sistemas de GD fotovoltaica con baterías permite la gestión y protección de la energía, mejora la integración de las energías renovables a la red eléctrica y favorece el funcionamiento del sistema al reducir la carga máxima y brindar soporte a fallas (Bullich-Massagué, y otros, 2020), además de ayudar a disminuir dificultades de intermitencia de la energía (Salvador, y otros, 2017)

Debido a lo anteriormente expuesto, surge el interés por indagar sobre los consumidores residenciales de energías que cuentan con sistemas de GD fotovoltaica y que hacen uso de almacenamiento de baterías en el sector residencial, es decir, Los *prosumager*s. (Sioshansi, 2019), apoyado por otros autores como (Ajanovic, Hiesl, & Hhaas, 2020), (Reis, Goncalves, Lopes, & Henggeler Antunes, 2022), (Amenta, Sanseverino, & Stagnaro, 2021), describen al *prosumager* como un actor en el sector eléctrico, que invierte en GD fotovoltaica con respaldo y que tiene la posibilidad de no solo consumir energía, sino que también de producirla y de almacenarla. Adicionalmente, puede implementar estrategias de gestión del consumo de energía para mejorar el desempeño financiero del sistema, por ejemplo: utilizar la energía almacenada para necesidades futuras, o compartir su exceso a otros o vender su exceso a otros, como la red (Dal Cin, Carraro, Volpato, Lazzaretto, & Danieli, 2022).

Las tendencias en tecnologías de almacenamiento de energía de batería (BES) para los sistemas fotovoltaicos residenciales de conexión a la red son: batería de plomo-ácido (Pb-A), batería de iones de litio (Li-Ion), batería de azufre de sodio (NaS), y batería redox de vanadio (VRB) (Khezri, Mahmoudi, & Aki, 2022). La Li-Ion es la usualmente utilizada en sistemas residenciales (Khezri, Mahmoudi, & Aki, 2022), con una participación mayoritaria en el mercado global del 59% de la capacidad de potencia operacional (REN21, 2021) .Estas baterías presentan baja auto descarga y alto voltaje de 3,7 V (Pistoia, 2009) además de alta densidad de energía y larga vida útil (Pistoia, 2014) .

Para proporcionar tecnologías de baterías alternativas a las baterías de Li-Ion, las baterías de iones metálicos multivalentes con sus altas capacidades teóricas y su facilidad de preparación, han ganado gradualmente la atención tanto de la academia como de la industria. Por ejemplo, la batería de iones de bismuto (BIB) y la batería de iones de aluminio (Xiong, y otros, 2020).

Dadas las diversas opciones de almacenamiento de baterías, los avances que se están dando en este campo, nos interesa saber cómo las personas pueden beneficiarse de convertirse en *prosumager* al implementar diferentes tipos de estrategias de gestión del consumo de energía.

Considerando lo anterior surge a inquietud sobre qué estrategias de gestión de la demanda han sido reportadas en la literatura y cómo éstas pueden ser clasificadas para los *prosumager*s. Este trabajo se centra en resolver estas preguntas.

METODOLOGÍA

De acuerdo con el problema mencionado y el propósito de la investigación se realizó una revisión sistemática de la literatura (RSL) que tenía por objetivo responder las siguientes preguntas: ¿Qué estrategias de gestión del consumo de energía eléctrica se analizan para el caso de los *prosumager*s? y ¿Cómo se clasifican estas estrategias? La RSL se enfocó en artículos donde se incluyeran sistemas GD fotovoltaicos residenciales con y sin respaldo, incluyendo un rango de fechas del 2015 al 2021 y el filtro de artículos de investigación y artículos de revisión. Se seleccionaron 12 artículos y se utilizó la base de datos Science Direct.

RESULTADOS ESPERADOS Y CONCLUSIONES

A partir de la RSL se logró identificar que las estrategias de gestión del consumo de energía eléctrica para el usuario final, en el sector residencial colombiano y en otros países, no han sido caracterizadas a profundidad. Además, no se ha desarrollado una clasificación de las mismas. Por lo tanto, la descripción, caracterización y posterior clasificación de las estrategias de gestión del consumo de energía eléctrica son el principal enfoque de este trabajo.

REFERENCIAS

Ajanovic, A., Hiesl, A., & Hhaas, R. (2020). On the role of storage for electricity in smart energy systems. *Energy*, 2-18.

Amenta, C., Sanseverino, E. R., & Stagnaro, C. (2021). Regulating blockchain for sustainability? The critical relationship between digital innovation, regulation, and electricity governance. *Energy Research & Social Science*, 2-6.

bp. (17 de mayo de 2022). *bp Statistical Review of World Energy 2022 | 71st edition*. Obtenido de https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

BP p.l.c. (2022). *bp Statistical Review of World Energy 2022 | 71st edition.* BP p.l.c.

Bullich-Massagué, E., Cifuentes-García, F. J., Glenny-Crende, I., Cheah-Mañé, M., Aragüés-Peñalba, M., Díaz-González, F., & Gomis-Bellmunt, O. (2020). A review of energy storage technologies for large scale photovoltaic power plants. *Applied Energy*, 2-18.

Dal Cin, E., Carraro, G., Volpato, G., Lazzaretto, A., & Danieli, P. (2022). A multi-criteria approach to optimize the design-operation of Energy Communities considering economic-environmental objectives and demand side management. *Energy Conversion and Management*, 2-18.

García, C., López, J., & Gómez, T. (2021). Estimación del costo de distribución de la energía eléctrica en Colombia considerando generación distribuida fotovoltaica . *Información Tecnológica*, 79-88.

García, P. F. (2021). *Energía solar fotovoltaica para todos.* MARCOMBO.

Hernandez, Velasco, & Trujillo. (2011). Analysis of the effect of the implementation of photovoltaic systems like option of distributed generation in Colombia. *Renewable and Sustainable Energy Reviews*, 2290-2298.

Iglesias, R., Lago, A., Nogueiras, A., Martínez-Peñalver, C., Marcos, J., Quintans, C., . . . Valdés, M. (2012). Modelado y Simulación de una Batería de Ion-Litio. *SAAEI*, 464-469.

Karadeniz, A., Ozturk, O., Koksoy, A., Atsever, M. B., Balci, M. E., & Hocaoglu, M. H. (2022). Accuracy assessment of frequency-domain models for harmonic analysis of residential type photovoltaic-distributed generation units. *Solar Energy*, 182-195.

Khezri, R., Mahmoudi, A., & Aki, H. (2022). Optimal planning of solar photovoltaic and battery storage systems for grid-connected residential sector: Review, challenges and new perspectives . *Renewable and Sustainable Energy Reviews*, 2-17.

Mitrasinovic, A. M. (2021). Photovoltaics advancements for transition from renewable to clean energy. *Energy*, 1-5.

MNE. (2021). *Boletín Estadístico de Minas y Energía 2016-2020.* Bogotá: Ministerio de Minas y Energía.

Pistoia, G. F. (2009). *Battery Operated Devices and Systems From Portable Electronics to Industrial Products.* Amsterdam: Elsevier.

Pistoia, G. F. (2014). *Lithium-Ion Batteries Advances and Applications.* Amsterdam: Elsevier.

Reis, I. F., Goncalves, I., Lopes, M. A., & Henggeler Antunes, C. (2022). Towards inclusive community-based energy markets: A multiagent framework. *Applied Energy*, 2-21.

REN21. (2021). *RENEWABLES 2021 GLOBAL STATUS REPORT.* Paris: National Technical University of Athens (NTUA).

Salvador, O., José, G., Salvador, S., Pablo, G., Ibán, B., Virginia, P., . . . Alejandro, E. (2017). Instalación Fotovoltaica con Almacenamiento en Baterías de Litio para la Inclusión de los Objetivos de Desarrollo Sostenibles en las Ingenierías. *XIV Congreso de Tecnologías Aplicadas a la Enseñanza de la Electrónica*, 153-160.

Sioshansi, F. (2019). *Consumer, Prosumer, Prosumager, How service innovations will disrupt the utility business model.* Walnut Creek, CA,: AP.

Xiong, T., Vincent Lee, W. S., Du, Y., Yu, J., Xi, S., Wu, H., . . . Xue, J. (2020). Bismuth ion battery – A new member in trivalent battery technology. *Energy Storage Materials*, 100-104.

STRUCTURAL TRANSFORMATIONS OF JOBS UNDER DECARBONIZATION SCENARIOS: AN ASSESSMENT FOR THE BRAZILIAN ECONOMY

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Author keywords

Employment
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Overview

This study analyzes the expected impacts on employment from the anticipated structural changes in the context of the decarbonization of the economy in Brazil and in the world. In addition to general trends, such as greater automation and digitization of some productive sectors, this analysis focuses on key areas in the context of decarbonization: (i) renewable energy sources for electricity generation and (ii) the expansion of electric vehicles, both with effects on the civil construction industry, component manufacturing and the automotive sector.

The unfolding of such trends, alongside other expected transformations in the land use sector, are assessed through the simulation of three scenarios of greenhouse gas emissions for the Brazilian economy until 2050, which derive from the 'Climate and Development' initiative (Unterstell, N. & La Rovere, E. L., coords. et al., 2021). A Current Policies Scenario (CPS) scenario, with no increase in climate ambition in the time horizon considered, is contrasted with two scenarios (Deep Decarbonization Scenarios – DDS) that reach climate neutrality (net zero emissions) in 2050, through the implementation of a series of mitigation measures and an emissions pricing system at the national level. The difference between the two DDS scenarios is the way carbon revenues are recycled: in the DDS_Lab, all revenue is used to replace payroll taxes, mitigating potential recessive effects of carbon pricing. In the DDS_LabDist scenario, a share of the revenues is directed to replace payroll taxes, while a portion is redistributed in the form of a lump-sum transfer to lower-income families, preserving their purchasing power against possible price increases resulting from the pricing system.

Methods

An integrated modeling approach is applied, in which a set of six sectoral models is linked to the computable general equilibrium (CGE) model IMACLIM-BR. The sectoral models consist of four energy demand models (transport, industry, buildings and agricultural energy demand), an agriculture, forests and other land uses (AFOLU) model and an energy supply model (MATRIZ).

The IMACLIM-BR model portrays Brazil as an open economy, with four institutional sectors (Companies, Government, Rest of the World and Households, which are divided into four income classes) and two primary production factors (capital and labor). There are nineteen productive sectors: six energy sectors (Coal, Oil, Natural Gas, (fossil) Liquid Fuels, Biofuels and Electricity), eight industrial sectors (Cement, Steel, Aluminum and Other Non-Ferrous Metals, Chemicals, Beef, Rest of Food and Beverages, Pulp and Paper, and Rest of Industry, which includes manufacturing and the processing industry in general. It also considers Planted Forest, Livestock, Rest of Agriculture, Transport and Rest of the Economy (Services).

Such integration, with greater technological detailment, also allows for a more detailed analysis that considers the employment intensity of different activities within a given sector. Therefore, the results of the Transport, AFOLU, Industry and Energy supply sector models were outlined with official employment data from national surveys RAIS (formal employment only) (MTE , 2021) and PNAD-Contínua (formal and informal employment) (IBGE, 2021) to obtain the granularity to represent sectoral heterogeneity. Subsequently, some assumptions about sectoral transformations found in the literature are applied to obtain a parameterization of the effect of these changes in one or more corresponding sectors within IMACLIM-S BR.

Results

Estimated jobs for the electricity generation, transmission and distribution sector decrease over the study time horizon in all three scenarios due to energy efficiency gains. In the decarbonization scenarios (DDS), the reduction is attenuated due to two main factors: the greater demand for electricity as a result of the electrification of the vehicle fleet, and the fact that this greater demand is met by more renewable energy sources, which are more labor intensive than the fossil-based energy. In the manufacturing industry, the trajectory in both scenarios is also a net reduction in jobs, due to factors such as the deindustrialization and loss of competitiveness, in addition to the effects of automation and digitization. However, in the DDS scenarios, part of this reduction is mitigated by the creation of jobs in two segments: manufacturing of power generation components, and for electric vehicles components, including charging stations.

In terms of overall macroeconomics impacts, results focus on total jobs (all economic sectors, as part of indirect effects) and GDP. Despite the important sectoral transformations shown above, there is little change on the balance of jobs according to the scenario, being slightly higher in the low carbon scenarios, as well as GDP.

Conclusions

The future of the work environment and job creation in Brazil holds a series of uncertainties related to structural changes resulting from observed and anticipated trends. The loss of competitiveness of some sectors leads to the deindustrialization of the economy, and the deterioration of employment in general impose challenges in terms of tax collection, the purchasing power of workers, in addition to social security challenges. Globally, trends such as automation and digitalization make a significant portion of jobs vulnerable (up to 40%, according to Hawksworth et al. (2018)), especially low- and medium-skilled jobs. The necessary transition to a low carbon economy overlaps with these issues. If a transition is to be carried out fairly in its various aspects – social, regional, environmental, with respect for human rights – these concerns deserve due attention.

A planned and gradual transition will make it possible to substantially reduce GHG emissions without major impacts on GDP and employment. Indeed, there will be those “winners” and “losers” sectors, but efforts to reallocate and retrain the workforce can ensure that the aggregate effects balance each other out.

References

IBGE. (2021). PNAD Contínua - Pesquisa Nacional por Amostra de Domicílios Contínua. Instituto Brasileiro de Geografia e Estatística. https://www.ibge.gov.br/estatisticas/sociais/trabalho/17270-pnad-continua.html?=&t=resultados

Hawksworth, J., Berriman, R., & Goel, S. (2018). Will robots really steal our jobs? An international analysis of the potential long term impact of automation. www.pwc.co.uk/economics

MTE. (2021). Relação Anual de Informações Sociais (RAIS). Ministério do Trabalho e da Previdência. http://www.rais.gov.br/sitio/index.jsf

Unterstell, N. & La Rovere, E. L. (coords), et al; “Clima e Desenvolvimento: Visões para o Brasil 2030. Documento de Cenários e Políticas Climáticas”, relatório elaborado pelo Instituto Talanoa e o Centro Clima/COPPE/UFRJ para o Instituto Clima e Sociedade (iCS), o Conselho Empresarial Brasileiro para o Desenvolvimento Sustentável (CEBDS), a Coalizão Brasil para o Clima, a Agricultura e as Florestas, Concertação pela Amazônia, ClimaInfo, Instituto Arapyaú, IPAM e o WWF, 131 p., Outubro 2021.

The effects of renewable energy project cancellation: A case study of the Brazilian wind power sector

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Keywords: Wind energy; Project Cancellation; Agent based modeling; System Dynamics.

1. Introduction

In the last three years, the contract of wind energy in auctions has dropped significantly, from 4.7 GW contracted in 2013 to 2.2 GW and 1.2 GW of power contracted in 2014 and 2015, respectively, until reaching nullity in 2016 (Agencia Nacional de Energía Eléctrica-ANEEL, 2019). The drop in hiring this source directly affects the development of wind technology in the country. Auctions, vital for the development of the Brazilian wind industry (Aquila et al., 2016; Bayer, 2018; Bayer et al., 2018; Juárez et al., 2014), encourage the progress of this technology and reductions in its generation costs.

Given the new cancellation mechanism in the electricity sector of Brazil and the importance of the development of wind power, this paper assesses the influence of guidelines adopted in the contract of electricity for the wind power diffusion. The guidelines analyzed include the establishment of different ceiling prices in energy auctions and the adoption of the new project cancellation mechanism, in addition to particularities that govern the two Brazilian contract markets

2. Methodology

This research chooses the SD and ABM approaches, given the recognition of using together as a solution approach to model complex energy systems (Brailsford et al., 2019; Köhler et al., 2018). Moreover, both SD and ABM are particularly suitable for generating insights into energy policy. The hybrid model uses data provided by several Brazilian institutions. Two distinct types of agents are used: Regulatory Agent and Entrepreneur Agent. Both act within a continuous and responsive environment to their decisions, called the Hiring Market, which also influences the individual decision criteria of the agents.

3. Results

The results of the simulations indicate that the policies involving variations in the contract ceiling prices are the ones that most influence the expansion of installed wind capacity in the country. Other source incentive policies, which inhibit the development of the wind source in Regulated Hiring Environment, have their potential effects on total wind capacity when combined with project cancellation policies. It should also be noted that the incentive to other sources in the Regulated Hiring Environment causes the migration of some wind enterprises from this market to the Free Hiring Environment, which becomes a more attractive option in comparison.

4. Conclusion

This paper analyzed the effect of guidelines currently applied in Brazilian auctions for the expansion of installed wind capacity in the existing contract markets in Brazil. More specifically, it was explored how the new mechanism of project cancellation and the establishment of different ceiling prices in energy auctions can influence the diffusion of wind generation technology in Brazilian procurement markets. The results of the simulations allow the identification, among the policies tested, of incentive and inhibition measures for the diffusion of wind capacity installed in Regulated Hiring Environment, Free Hiring Environment and both markets simultaneously.

5. References

Agencia Nacional de Energía Eléctrica-ANEEL, 2019. Leilão de geração.

Aquila, G., Rocha, L.C.S., Rotela Junior, P., Pamplona, E. de O., Queiroz, A.R. de, Paiva, A.P. de, 2016. Wind power generation: An impact analysis of incentive strategies for cleaner energy provision in Brazil. J. Clean. Prod. 137, 1100–1108. https://doi.org/10.1016/j.jclepro.2016.07.207

Bayer, B., 2018. Experience with auctions for wind power in Brazil. Renew. Sustain. Energy Rev. 81, 2644–2658. https://doi.org/10.1016/j.rser.2017.06.070

Bayer, B., Berthold, L., Moreno Rodrigo de Freitas, B., 2018. The Brazilian experience with auctions for wind power: An assessment of project delays and potential mitigation measures. Energy Policy 122, 97–117. https://doi.org/10.1016/j.enpol.2018.07.004

Brailsford, S.C., Eldabi, T., Kunc, M., Mustafee, N., Osorio, A.F., 2019. Hybrid simulation modelling in operational research: A state-of-the-art review. Eur. J. Oper. Res. 278, 721–737. https://doi.org/10.1016/j.ejor.2018.10.025

Juárez, A.A., Araújo, A.M., Rohatgi, J.S., De Oliveira Filho, O.D.Q., 2014. Development of the wind power in Brazil: Political, social and technical issues. Renew. Sustain. Energy Rev. 39, 828–834. https://doi.org/10.1016/j.rser.2014.07.086

Köhler, J., De Haan, F., Holtz, G., Kubeczko, K., Moallemi, E., Papachristos, G., Chappin, E., 2018. Modelling sustainability transitions: An assessment of approaches and challenges. J. ofArtificial Soc. Soc. Simul. 21. https://doi.org/10.18564/jasss.3629

Decision tools from index fund finance to explore the path towards a scenario of renewable energy generation with globalization and high specialization of regional electricity markets

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1. INTRODUCTION

Three fundamental characteristics of future energy markets are: i) almost all electricity will be generated by variable renewable energy technologies (VRE) such as wind turbines and solar cells, and by hydropower sources, all of which are directly dependent on weather ii) further transnational integration of energy markets will be required with the aim of diversifying the climate and weather risk to which generation through these technologies is exposed, iii) energy storage, especially green hydrogen technologies, will play a critical role as a way to transfer electricity consumption over time and across dispersed geographic areas. These three points are closely interrelated and emphasize the urgency of establishing clear policy guidelines, legal framework and infrastructure, necessary for an adequate development of future energy markets throughout the world and, in particular, of future energy networks. Such energy networks will consist of extended power 'super' grids (Anaya & Pollitt, 2017; Huber et al., 2014; Santos-Alamillos et al., 2017), but they will be more general than that, as they will also include economic transactions between energy providers and consumers located in very distant areas, using green hydrogen and other innovations in terms of storage. In short, fully integrated, transnational energy markets, operating over large geographic areas and covering neighboring or distant countries in regions as diverse as Western Europe or South America, are likely to be the rule of future energy markets.

Some authors have explored the risk-minimization problem subject to a certain level of reward that a firm wants to achieve, using Markowitz's portfolio theory, and assimilating the problem of deciding on the optimal shares of generation technologies in which the firm can invest to an asset allocation problem (e.g. Awerbuch & Yang, 2008b; Matosovic & Tomsic, 2014; Pinheiro Neto et al., 2017; Unni et al., 2020; Zhang et al., 2022). In the same group, some studies approach the problem changing the perspective from the firm to that of the government or the policy maker. In this case, the policy maker wishes to optimize the generation mix of the country using VRE technologies, and considers the intermittency of this sort of generation due to weather uncertainty (e.g. Ferreira et al., 2014; Mohan et al., 2017; Yu et al., 2019), and to this end a variety of approaches based on classic optimization techniques and fuzzy multi-objective optimization have been proposed.

2. METHODOLOGY

In our empirical application, we use historical weather records and actual locations of Argentinian power plants. Our goal is to preserve as much as possible the configuration of weather risk shaped by the $n = 106$ energy plants in our sample, which consists of solar (34), wind (38) and hydropower plants (34). We show how to select a subset of q plants, with $q \ll n$, which better replicates the observed weather risk configuration in the country. In our example, weather risk is fully described by the correlation matrix (ρ) of the original n series of weather variables that measure the main input used in each case to generate power, according to the respective generation technology in each of the n energy original plants. That is, the correlation matrix between the meteorological series of solar irradiation recorded on the earth's surface, wind speed and precipitation, at different geographical points in Argentina, observed in reality. The reason for working directly with the weather series, rather than with the transformed electricity series, is that in our problem the stochasticity is entirely due to the weather. The generation is simply a deterministic function of the fundamental weather factors. Other potential sources of uncertainty, such as technology malfunctions, are omitted from our analysis because they fall outside the scope of our goals.

3. RESULTS

We find that in Argentina, around 71 power plants diversified across the three generation technologies suffice to preserve the weather risk of the original 106 plants without loss of information. Our results also emphasize that given the sequential nature of the optimization problem at each step the model diversify across technologies and also across locations, guaranteeing a natural diversification of weather risk across the country.

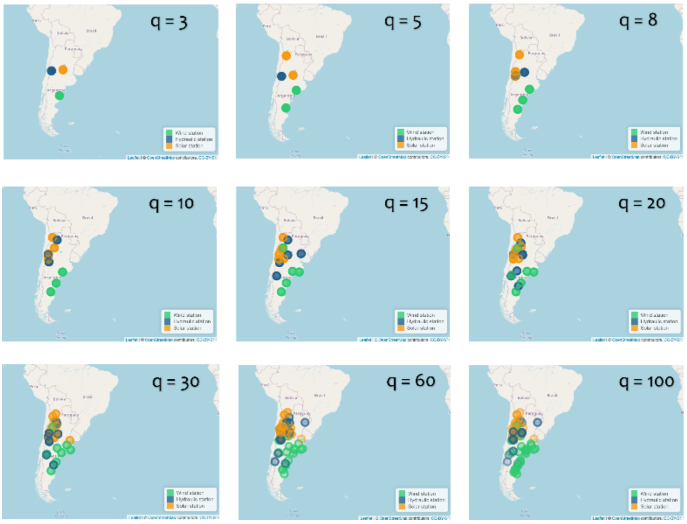

Figure 1. Geographic distribution of plants optimally selected. **Note:** We select some values of q to identify as our model achieves in diversifying climatic variability from a geographic perspective.

4. CONCLUSIONS

We use data for Argentina, consisting of several meteorological series of irradiation recorded on the earth's surface, wind speed, and precipitation associated with each of the 106 power plants in the country. We resort to these fundamental weather factors and show that our model is able to provide the path that could be optimally transited during the transition to a more specialized electricity market in Argentina.

5. REFERENCES

Anaya, K. L., & Pollitt, M. G. (2017). Using stochastic frontier analysis to measure the impact of weather on the efficiency of electricity distribution businesses in developing economies. *European Journal of Operational Research*, *263*(3). https://doi.org/10.1016/j.ejor.2017.05.054

Awerbuch, S., & Yang, S. (2008). Using Portfolio Theory to Value Power Generation Investments. In *Analytical Methods for Energy Diversity and Security*. https://doi.org/10.1016/B978-0-08-056887-4.00003-2

Ferreira, R. S., Barroso, L. A., Carvalho, M. M., & Pereira, M. V. F. (2014). A mean-variance optimization approach to the development of portfolios of renewable generation in transmission-constrained systems. *Proceedings - 2014 Power Systems Computation Conference, PSCC 2014*. https://doi.org/10.1109/PSCC.2014.7038322

Huber, M., Dimkova, D., & Hamacher, T. (2014). Integration of wind and solar power in Europe: Assessment of flexibility requirements. *Energy*, *69*. https://doi.org/10.1016/j.energy.2014.02.109

Matosovic, M., & Tomsic, Z. (2014). Power generation mix optimization using mean-lower partial moments (LPM) portfolio theory. *ENERGYCON 2014 - IEEE International Energy Conference*. https://doi.org/10.1109/ENERGYCON.2014.6850448

Mohan, V., Singh, J. G., & Ongsakul, W. (2017). Sortino Ratio Based Portfolio Optimization Considering EVs and Renewable Energy in Microgrid Power Market. *IEEE Transactions on Sustainable Energy*, *8*(1). https://doi.org/10.1109/TSTE.2016.2593713

Pinheiro Neto, D., Domingues, E. G., Coimbra, A. P., de Almeida, A. T., Alves, A. J., & Calixto, W. P. (2017). Portfolio optimization of renewable energy assets: Hydro, wind, and photovoltaic energy in the regulated market in Brazil. *Energy Economics*, *64*. https://doi.org/10.1016/j.eneco.2017.03.020

Santos-Alamillos, F. J., Brayshaw, D. J., Methven, J., Thomaidis, N. S., Ruiz-Arias, J. A., & Pozo-Vázquez, D. (2017). Exploring the meteorological potential for planning a high performance European electricity super-grid: Optimal power capacity distribution among countries. *Environmental Research Letters*, *12*(11). https://doi.org/10.1088/1748-9326/aa8f18

Unni, A. C., Ongsakul, W., & Madhu M., N. (2020). Fuzzy-based novel risk and reward definition applied for optimal generation-mix estimation. *Renewable Energy*, *148*. https://doi.org/10.1016/j.renene.2019.10.154

Yu, S., Zhou, S., Zheng, S., Li, Z., & Liu, L. (2019). Developing an optimal renewable electricity generation mix for China using a fuzzy multi-objective approach. *Renewable Energy*, *139*. https://doi.org/10.1016/j.renene.2019.03.011

Zhang, M., Tang, Y., Liu, L., & Zhou, D. (2022). Optimal investment portfolio strategies for power enterprises under multi-policy scenarios of renewable energy. *Renewable and Sustainable Energy Reviews*, *154*. https://doi.org/10.1016/j.rser.2021.111879

The contradictions of energy security and energy transition. Index analysis for the case of Mexico, Colombia, and Brazil1980 to 2020

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Keywords: energy security, energy transition, fossil fuels, renewable energies, and climate change.

Since its beginnings in the 1970s, Energy Security has been shaped by various factors that make it complex. At the time, the main concern focused on guaranteeing energy security based on the diversification of sources and suppliers. Over the years, and mainly due to technological change, which allowed for the diversification of sources and suppliers, significant progress was made in guaranteeing access to energy at affordable prices.

However, the effects of climate change, primarily caused by energy consumption in various activities, have led to the inclusion of environmental issues in the discussion on energy security. With the inclusion of these new issues, discussions on energy security have focused on ensuring that energy security is provided, to a large extent, by less polluting sources. In a context where oil and fossil resources, gas and coal, remain central to the energy systems of most nations, this new vision has become more complex.

In this context, this research aims to analyze the contradictions and challenges of energy security and transition in three countries with different energy systems. The analysis is based on the formulation of three indices developed in Puyana and Rodríguez (2020). This methodology was formulated based on an extensive review of the literature on the subject. In methodological terms, the Energy Trilemma and Energy Risk methodologies are considered a reference. The proposal with which we analyze the energy security of these three countries is formulated based on three indices: the oil security index, the energy diversification index, and the energy transition index. Each is constructed and analyzed separately, and their evolution contributes in some direction to energy security.

Regardless of the analysis of each country, the main conclusion of this research is that despite the inclusion of environmental issues and energy equity, the center of energy security

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continues to be oil for several reasons (due to its importance in the energy matrix and the collateral effects it has on the rest of the energy sources).

A principal component analysis is used to strengthen and verify the results of the statistical calculation of the index. Once the information for calculating the indices from 1980 to 2020 in Mexico, Colombia, and Brazil has been gathered, a principal component analysis is applied to calculate the energy security indices for Mexico, Colombia, and Brazil. In this way, the weight of each of the variables on each index is evaluated.

The results show little progress in the different indices and, consequently, little progress for energy security in general. What prevails is a moderate reduction in the use of fossil fuels, despite the diversity of natural resources that the countries possess (water, sun, and air).

The increase of renewable energies and the rise of gas are reflected in an improvement in energy security. In all three cases, progress in energy sustainability can be observed when gas is considered as a source of the energy transition. However, some literature argues that gas cannot be considered a low-emission source because the extraction of this source has adverse environmental effects. In this way, the research shows, in general, the challenges and contradictions of energy security, which can be made more complex by analyzing each country's objectives and strategies in terms of energy policy and climate change, among many other factors that are incorporated and analyzed in this research.

Some reference

Aguilera, R. F., & Aguilera, R. (2020). Revisiting the role of natural gas as a transition fuel. Mineral Economics, 33(1), 73-80. doi:10.1007/s13563-019-00192-5

British Petroleum. (2021). Statistical review of world energy, http://www.bp.com/statisticalreview

Podbregar, I., Šimić, G., Radovanović, M., Filipović, S., & Šprajc, P. (2020). International energy security risk index—Analysis of the methodological settings. Energies, 13(12), 3234.

Cherp, A., & Jewell, J. (2014). The concept of energy security: Beyond the four As. Energy policy, 75, 415-421.

Gürsan, C., & de Gooyert, V. (2020). The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition? Renewable and Sustainable Energy Reviews, 110552.

Hamilton, J. (2008). Understanding crude oil prices. Energy Journal, 30(2), 179-206 OPEC (2021), Interactive data, available at:

Puyana, A (2015), The oil economy in a politicized and global market. Mexico and Colombia. Mexico City: FLACSO.

Puyana Mutis, A., & Rodríguez Peña, I. (2020). Energy security in Mexico, the United States and Canada, 1980-2016: centrality of oil and the inclusion of environmental issues. North America, 15(2), 9-37.

SIE. (2021). Energy Information System. Retrieved from http://sie.energia.gob.mx/

Sovacool, Benjamin K. (2013) "An International Assessment of Energy Security Performance", Ecological Economics, vol. 88, no. 1, pp. 148-158.

Sovacool, Benjamin K. e Ishani Murkherjee (2011) "Conceptualizing and Measuring Energy Security: A Synthesized Approach", Energy, vol. 36, no. 8, pp. 5343-5355.

Valenzuela, J. M., & Studer, I. (2017). Climate Change Policy and Power Sector Reform in Mexico under the Golden Age of Gas. in D Arent, C. Arndt, M. Miller, F. Tarp, & O. Zinaman, The Political Economy of Clean Energy Transitions (pp. 410-429). Oxford, UK: Oxford University Press. doi:10.1093/oso/9780198802242.001.0001

Reliability of generation in an electricity system under different scenarios of participation of wind/solar energy, and hydropower.

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Overview

Variable renewable energies are changing today's energy sectors. Seeking a sustainable future, worldwide efforts are being made to reduce the carbon footprint of economic and energy systems in order to reduce climate impacts (Kerscher & Arboleya, 2022). To contribute to the reduction of polluting emissions from the electricity sector, countries have begun to adopt plans that include the integration of renewable energies and restrictions on generation with fossil fuels (Verástegui et al., 2021).

This growing participation of renewable energies in electricity markets has allowed them to become more independent of fossil resources. But the above makes the market more dependent on solar and wind generation, which depend on variable weather conditions to generate power, such as wind speed and solar radiation. These resources are intermittent and must be constantly monitored (Çiçek et al., 2021) and backed by trustable resources such as fossil fuels, storage or hydropower.

A high share of variable renewable energies in an electricity market requires flexibility to quickly respond to fluctuations of the renewable energy sources that generate intermittency in generation (Sasaki et al., 2022). We use stochastic optimization to prove that the large share of hydro-storage installed in Colombia can allow the introduction of large-scale wind and solar power without reliability risks. However, the current market design cannot guarantee that hydropower will be used in a way that minimizes the loss of load probability.

Methodology

We propose a simulation model to evaluate the effects on LOLP (Loss of load probability) of different scenarios of wind and solar penetration in the Colombian electricity market,assuming that only the currently installed hydropower capacity is in place – i.e., no thermal generation. The model considers the variability of wind, solar and water resources, and the availablestorage capacity of the hydro reservoirs.

Results

The simulations demonstrate that the currently installed hydropower capacity in the Colombian electricity market can provide enough flexibility to face the intermittency of the renewable energies, considering enough wind, and solar power to meet demand for at least the next 10 years. Depending on the mix of wind and solar, as well as their particular locations, the need for flexibility varies and the currently installed hydropower can become insufficient sooner or later.

Conclusions

With the energy transition to renewable energies, it is imperative to have enough flexibility in order to balance the system and guarantee security of supply. Renewable energies are steadily increasing, and they are expected to keep this growth over the years, as they grow their share in electricity markets the need for flexibility will grow with them as well.

We calculate the LOLP in the Colombian electricity market under different scenarios of wind and solar installation, considering only the currently installed hydropower capacity, and conclude that there is enough flexibility to support the growth of the system for the next 10 years. But our conclusions are based on an optimal operation of the hydropower reservoirs, and achieving this will require market reforms in order to give the right signals or incentives for hydropower generators to behave according to the systems' interests.

References

Çiçek, A., Güzel, S., Erdinç, O., & Catalão, J. P. S. (2021). Comprehensive survey on support policies and optimal market participation of renewable energy. *Electric Power Systems Research*, *201*, 107522. https://doi.org/10.1016/J.EPSR.2021.107522

Kerscher, S., & Arboleya, P. (2022). The key role of aggregators in the energy transition under the latest European regulatory framework. *International Journal of Electrical Power & Energy Systems*, *134*, 107361. https://doi.org/10.1016/J.IJEPES.2021.107361

Sasaki, K., Aki, H., & Ikegami, T. (2022). Application of model predictive control to grid flexibility provision by distributed energy resources in residential dwellings under uncertainty. *Energy*, *239*, 122183. https://doi.org/10.1016/J.ENERGY.2021.122183

Verástegui, F., Lorca, Á., Olivares, D., & Negrete-Pincetic, M. (2021). Optimization-based analysis of decarbonization pathways and flexibility requirements in highly renewable power systems. *Energy*, *234*, 121242. https://doi.org/10.1016/J.ENERGY.2021.121242

El rol de las baterías en un mercado eléctrico con alta participación de hidroeléctricas con embalse

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Introducción

Los mercados eléctricos fueron diseñados bajo la premisa de que la electricidad no podía ser almacenada a gran escala, pues los costos del almacenamiento eran prohibitivos hasta hace muy poco tiempo. Sin embargo, la reducción de los costos de las baterías en los últimos años ha permitido que se empiece a considerar la instalación de baterías a gran escala como una posibilidad (Comello & Reichelstein, 2019). Los mecanismos de mercado para su incorporación aún son tema de discusión (Eyer & Corey, 2011; Siddiqui et al., 2019; Sioshansi, 2014) y los posibles efectos de las baterías en los mercados eléctricos no se han estudiado cuidadosamente. En particular, no es claro el rol que podrían tener las baterías en sistemas con alta participación de hidroeléctricas con embalse, que se asemejan a las baterías en algunos aspectos. La generación hidroeléctrica es bastante flexible y su operación puede ajustarse según la estrategia del generador, así que es importante entender las interacciones que podrían resultar al incorporar baterías en el sistema, ya que el comportamiento de los agentes existentes podría cambiar, generando comportamientos contraintuitivos en el mercado eléctrico.

Metodología

Se propone un modelo de simulación basada en agentes para estudiar los efectos de la introducción de baterías en el comportamiento de los generadores en un sistema eléctrico, haciendo especial énfasis en los generadores hidroeléctricos que tienen capacidad de almacenar agua en sus embalses y se asemejan a las baterías en algunos aspectos. Se asume que las baterías son operadas centralizadamente, como un recurso del sistema, para minimizar el costo de operación diario, ya que los autores demostraron en un estudio previo, que este mecanismo es más eficiente que el arbitraje (ver: León et al., 2020). Se modelan dos clases de agentes generadores: térmicos e hidroeléctricos, que ofertan precios y su disponibilidad real diaria. Adicionalmente, el operador del sistema cuenta con cierta capacidad de baterías, y realiza el despacho diario (por hora) de tal forma que se minimice el costo total de operación. Los generadores adaptan sus precios cada día según sus estrategias y los resultados que hayan obtenido en despachos anteriores, además de las expectativas de aportes a los embalses en el caso de las hidroeléctricas.

Resultados

Se parametrizó el modelo para representar un caso similar al sistema eléctrico colombiano, que cuenta con una gran capacidad de generación hidroeléctrica. Se modelaron las características de algunas plantas hidroeléctricas y térmicas representativas, de diferentes tamaños, y se analizaron diferentes escenarios en cuanto a capacidad de baterías y composición de la matriz de generación. Los resultados de las simulaciones mostraron comportamientos contraintuitivos; por ejemplo, que las baterías son más útiles en períodos de alta disponibilidad de agua, que en períodos de sequía cuando el sistema tiene menor margen de disponibilidad. Esto se debe a que no es conveniente perder energía por la eficiencia en la carga y descarga de la batería en períodos de escasez en los que no lograría cargar a precios bajos y disminuir significativamente los costos al descargar en otras horas; en cambio, en períodos de abundancia, la batería permite tener mayor disponibilidad de potencia a bajo precio en horas pico, beneficio que supera las pérdidas de energía. También se observó que el uso de las baterías varía según el tamaño de las plantas térmicas, ya que solamente es conveniente usar las baterías si se logra desplazar completamente la planta que margina (que pone el precio del sistema), pues de no ser así, el beneficio es insignificante.

Conclusiones

Las baterías pueden tener un rol importante para reducir los costos de operación de un mercado eléctrico, incluso cuando existe una alta participación de hidroeléctricas con embalse. Los resultados de este estudio muestran que ambas tecnologías se complementan y bajo ciertas condiciones pueden resultar en un uso más eficiente de los recursos de generación, evitando por ejemplo vertimientos de los embalses y permitiendo que se desplace esa energía para ser usada en horas de mayor demanda. Para definir el tamaño adecuado del almacenamiento en un sistema eléctrico, es necesario tener en cuenta las características de las plantas de generación existentes y las variaciones de la demanda, pues las baterías permiten desplazar energía en el tiempo (con algunas pérdidas) y aumentar la potencia disponible en algunas horas.

Agradecimientos

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Referencias

Comello, S., & Reichelstein, S. (2019). The emergence of cost effective battery storage. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-09988-z

Eyer, J., & Corey, G. (2011). Energy storage for the electricity grid: Benefits and market potential assessment guide. *Lightning in a Bottle: Electrical Energy Storage*, *February*, 1–191.

León, R., Ochoa, C., & Gutiérrez, A. (2020). *ENERGY STORAGE AS A SYSTEM Balancing Investor vs Consumers Benefit* (Issue October). https://doi.org/10.31224/osf.io/bzch8

Siddiqui, A. S., Sioshansi, R., & Conejo, A. J. (2019). Merchant Storage Investment in a Restructured Electricity Industry. *The Energy Journal*, *40*(4), 129–164. https://doi.org/10.5547/01956574.40.4.asid

Sioshansi, R. (2014). When energy storage reduces social welfare. *Energy Economics*, *41*, 106–116. https://doi.org/10.1016/j.eneco.2013.09.027

The volatility of the electricity spot price in Brazil

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Abstract

Electricity is sensitive to extreme price events and spot price volatility is an inherent characteristic of competitive electricity markets. The purpose of this article it to model the realized volatility of electricity spot price in Brazil. The Brazilian electricity industry presents unique characteristics and because of this price varies a lot in a short period. So, we developed a GARCH model using 862 weekly observations to understand the realized volatility in the four different market . We conclude that the spot price in Brazil presents high volatility that presents risk to agents. This high volatility is associated with institutional factors and the increase in the share of renewable energy in the electricity mix.

Keywords: volatility – GARCH model - spot price – Brazilian Electricity Market

C32 - Q40 – Q41

1. Introduction

Market oriented reforms had significant consequences for the electricity industry worldwide. Among these are the impacts on the organization of the industry, on new forms of investment, and on transactions in the industry. In this sense, after deregulation in the industry, spot markets were created to meet some important goals: increase flexibility of transactions, allow adjustments between the contracted power and the energy generated, and to be a reference to long-term contracts. Namely, a spot market is an important adjustment mechanism between demand and supply (Newbery, 1995).

Electricity is much more vulnerable to extreme price events than other commodities because of its non-storability, high transmission costs, high demand price inelasticity, and more recently, due to the increase of the share of renewable energy in the electricity mix (Newbery et al., 2018). Therefore, price volatility is an inherent characteristic of competitive electricity markets. Electricity spot price volatility analysis has been reported in the literature for most competitive electricity markets around the world (Bhattacharya et. al., 2007). Electricity spot price volatility refers to unpredictable fluctuations of the price observed over time. Given the uncertainty associated with electricity prices, and such a wide variety of options, the applications of volatility analysis to competitive electricity markets are undoubtedly useful for market agents (Shahidehpour et al., 2002).

In Brazil, electricity has been traded in competitive wholesale markets for over two decades, following the beginning of electricity sector deregulation in the 1990s. The spot market in the country is a market for differences, as explained in Hunt and Shuttleworth (1996). Spot price is determined by the system operator on a weekly basis. As hydropower plants are responsible for 65% of the electricity produced, the spot price is given by the value related to the point which minimizes both the immediate and future costs of the system operation. The marginal costs of the system depend on the level of water available in reservoirs.

The purpose of this article is to model the realized volatility of the electricity spot price in Brazil. The main motivation for this research was the simple observation of price variations in a short period. For example, in June 2019, the price rose three times in a period of two weeks. Therefore, understanding price volatility is crucial for market players and policy makers.

2. Background

Sadorsky (2012) points out that modelling and forecasting volatility lies at the heart of modern finance, because good estimates of correlation and volatility are needed for derivative pricing, portfolio optimization, risk management, and hedging. According to Bello et al. (2017), electricity prices are more volatile than other goods affected by extreme values. Electricity prices vary according to the demand, weather patterns, regulation patterns, market power, and other reasons. Price fluctuations are a specific feature inherent to liberalized electricity markets. The stochastic properties of volatility in spot electricity prices present substantial modelling challenges. There are a variety of research papers which deal with price volatility in electricity markets that can be found in the literature.

Angelus (2001) and Mount (2001) consider that forecasting electricity prices is a difficult task due to factors such as the uncertainty about demand and supply, climate change, and the non-storability of electricity. In Alvarado and Rajaraman (2000), the periodic part of the price variations for an unknown market is separated out using a frequency-domain method, and volatility of the remaining part is analyzed. Dahlgren et al. (2001) used a value at risk methodology to study the volatility of prices in the Californian market. Li and Flynn (2004) analyzed price volatility of fourteen markets worldwide, with widely varying price volatility behaviors being observed across different markets.

Worthington et al. (2005) developed a multivariate GARCH model to understand the interrelationship among prices and price volatilities in the five Australian electricity markets. Volatility features of the Nord Pool day-ahead electricity market were studied in Simonsen (2005) for a 12-year period up until the year 2004, and the research concludes that electricity shows a higher level of price volatility when compared to other financial markets. Tashpulatov (2013) estimated the volatility of prices in England and Wales and found that the introduction of price-cap regulation did achieve the goal of lowering the price level, albeit at the cost of higher price volatility.

Karakatsani and Bunn (2010) developed and applied three complementary modelling approaches using GARCH, in order to uncover fundamental and behavioral price volatility drivers over time, and across intra-day trading periods. They found that GARCH effects diminish when each of the sources of volatility are accounted for. There are therefore several studies using a univariate GARCH approach to estimate volatility in electricity and energy markets, as in Zareipour et al. (2007), Hadsell et al. (2004), Higgs (2009), Chan and Gray (2006), Girish (2016), and Qu et al (2018). However, no significant GARCH study modelling the volatility of Brazil’s electricity market has been published. In sum, volatility of electricity spot prices depends on the characteristics of each market. Additionally, electricity supply is inelastic at high output levels. Every region’s generation capacity is composed of a unique mix of technologies, which differ by marginal cost and by their ability to quickly change the level of output.

3. The Brazilian electricity spot market

The Brazilian electricity sector is a large-scale hydro-thermal system characterized by the presence of large reservoirs, high capital intensity, and large interconnections. The main institutional feature of the Brazilian electricity sector is the predominance of hierarchy as a governance structure. Until the 1990's in Brazil, Eletrobras, the state owned holding, was at the top of the hierarchy. Eletrobras controlled nearly 90% of supply and was responsible for planning and operating the whole system. This governance structure was created in the 1950's, based on state monopoly. The governance structure became more relevant in the 1970's, when efficiency gains from the interconnection of the system and economic growth resulted in a virtuous cycle, with decreasing short and long-term marginal costs. The increase in demand was linked to the increase in supply. This was a consequence of the centralized coordination of the electric system's operation and growth (Santana e Oliveira, 1988 and 1999).

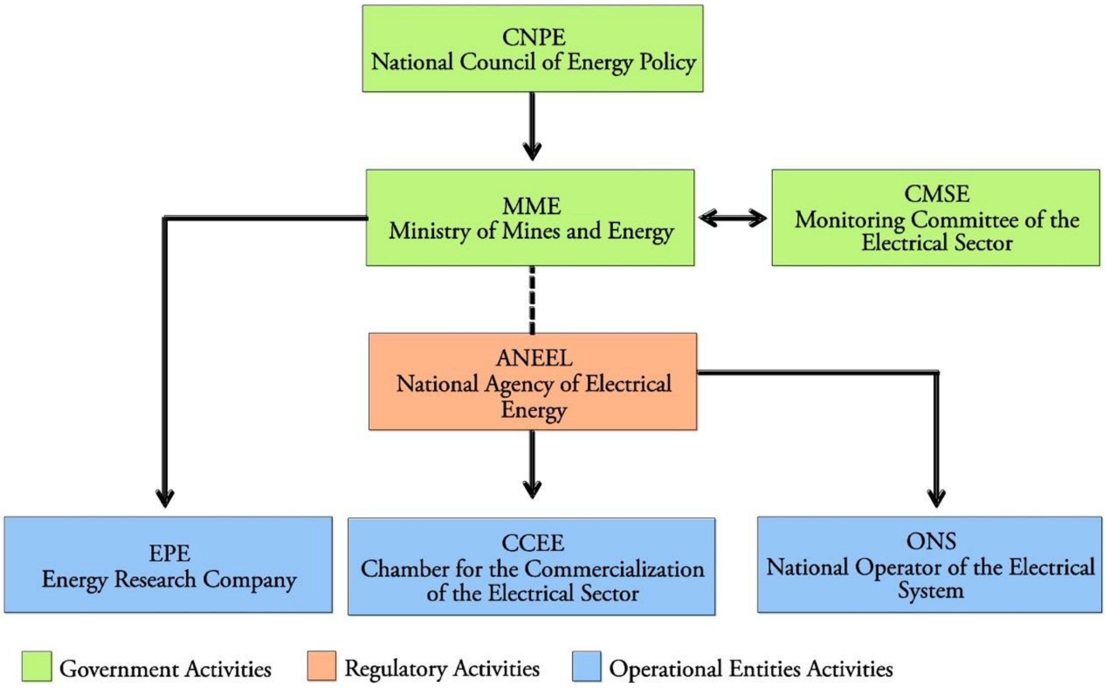
The Brazilian electricity sector has faced two important institutional reforms in previous decades. In 1996, the Brazilian electricity industry (BEI) was restructured for the first time, with the main purpose being to introduce competition and enhance investments in the industry. Nearly 80% of the distribution companies and 20% of the generation companies were privatized. Some companies remained state-owned, and two (CEMIG and COPEL) were not unbundled. The 2001 supply crisis made clear that both private and public investments in electricity had decreased. After 2003, the government designed a new model for the Brazilian Electricity Industry that strengthened the role of the state in the industry.

Although these reforms tried to introduce competition in generation, it is possible to say that the BEI is far from being a competitive market. As Araujo (2001) states, in a hydroelectric system like in Brazil, coordination is far more important than competition. The most important feature of the short-term Brazilian market is the existence of two market operators, with different functions. On one hand, the physical system operator—the National System Operator (ONS)—is responsible for the coordination and control of the installation operations for the generation and transmission of electric energy in the national interconnected system, under the supervision and regulation of the National Electric Energy Agency (ANEEL). On the other hand, the Electric Energy Trading

Chamber (CCEE) is responsible for energy purchase and sale transactions. Figure 1 shows the BPS institutional agents. It is important to notice the significance of the government in the planning of the industry, which also includes the methodology used to determine prices.

Regarding the commercialization of electricity, two distinct markets were created for the negotiation of energy trade contracts: the Regulated Contracting Environment (ACR), in which the agents of generation and distribution of energy participate; and the Free Contracting Environment (ACL), in which generators, electricity dealers, importers, and free consumers of energy participate (CCEE, 2019). The institutional model of the electricity sector provided a set of measures to be observed by the agents, such as the requirement to meet all demand by the distributors and free consumers; as well as permanent monitoring of the continuity and security of supply to detect conjunctural imbalances between supply and consumption (CCEE, 2019).

Fig 1. Brazilian electricity industry institutional agents



Source: (MME, 2013)

The Brazilian energy grid is diversified, with many sources of generation (hydraulic, biomass, wind, photovoltaic, amongst others), with smaller projects alongside larger ones, distribution across the various geographic regions of the country (Vahl et al., 2013), and increased private sector participation (Rego and Parente, 2013). However, hydropower is responsible for approximately 65% of electricity produced, which has an impact on price.

The commercialization of electricity occurs in two different markets: the ACR, subject to the rules established by the regulatory agency and government directives; and the ACL, which allows generators and traders to freely commercialize energy (Rendeiro et al., 2011).

The Brazilian electricity sector exhibits unique characteristics. Approximately 65% of the electricity is generated by hydroelectric plants, almost 15% comes from wind farms, and nearly all generation, transmission, and distribution systems are nationally interconnected. Unlike other countries, in Brazil there is no electricity market *per se*. The short-term electricity price in Brazil is known as the settlement difference difference price (PLD) and it reflects the difference between what was contracted and what was really consumed. This concept is well described in Ferreira et al. (2015).

The PLD reflects, for instance, the opportunity costs for short-term electricity:

i. For the generator, who can sell non-contracted electricity.
ii. For consumers, who can buy or sell the differences between what was contracted and what was effectively consumed.

The PLD is not determined by demand and supply, but by a computational program that takes into account the availability of water for immediate use and for future use. Balanced operation of the system involves a compromise between depleting (using water) and not depleting (using thermal plants) the reservoirs. The decision variable is the volume of water stored at the end of the operational period (Ferreira et al. 2015). This decision is associated with the immediate cost function (ICF) and the future cost function (FCF); in this case, the cost to use or to store water in reservoirs.

In the case of the Brazilian electricity sector, the spot price of electricity is a function of the characteristics of the industry, i.e., the availability of water in reservoirs and the precipitation level, the marginal costs of thermal plants, and transmission constraints. In most systems, the hydroelectric energy prices tend to be somewhat volatile in the short term and more volatile in the medium term. This is because in the short term, there is a transfer of electricity from low-load to high-load periods by modulating the supply and reducing price volatility. While in the medium term, the price of energy is more volatile because the hydraulic systems were designed to ensure the supply of electricity in adverse hydrological conditions.

The Brazilian electricity sector is divided into four subsystems: Southeast/Midwest, South, North, and Northeast, which represent the geographic regions of the country. The system operator defines, according to stochastic programming, the price for each subsystem on a weekly basis.

The electricity contracts are registered at CCEE, which measures the amounts actually produced or consumed by each agent. The differences established are settled in the short-term market, or spot market, at the PLD (CCEE, 2019). The PLD is determined on a weekly basis for each load level, with a cap and a minimum price, and is used to value the energy that was not contracted by the agents of CCEE (surplus or difference) in the spot market (Araujo et al., 2008). The PLD reflects the marginal cost of new electricity in the system. In the rainy season, when supply and demand for electricity in the country are balanced, the price of electric power is lower, as is, consequently, the PLD. When the water reservoirs are low, there is a lack of energy, and the thermal plants are linked to a high marginal cost, pushing up the energy price and the PLD (Dalbem et al., 2014). The PLD, due to the way it is defined, does not give accurate economic signaling for the agents. Moreover, in situations of prolonged drought, the PLD tends to reach and park for many months at extreme values, clearly without adherence to the average cost of energy. This contributes to exacerbating financial risk in the commercialization of energy, bringing in return only very limited benefits in the form of signaling for the restriction of consumption by consumers.

4. Data, the model, and results

The data used in this article is the weekly price for medium load of the four sub-systems data on wholesale electricity prices obtained from the Electric Energy Trading Chamber’s website (www.ccee.org.br). The time period covered is from January 1, 2003, to September 21, 2019, totalizing 886 observations. Prices before 2003 were disturbed by the 2001-2002 supply crisis, so they were not used in this research.

4.1 The GARCH model

A GARCH Model is a useful generalization of the ARCH model developed by Engel (1982), and was first introduced by Bollerslev (1986). This model is also a weighted average of past squared residuals, but it has declining weights that never go completely to zero. It gives parsimonious models that are easy to estimate, and even in its simplest form, has proven surprisingly successful in predicting conditional variances. It describes volatility clustering and excess kurtosis (although not entirely). The most widely used GARCH model asserts that the best predictor of variance in the next period is a weighted average of the long-term average variance, the variance predicted for this period, and the new information in this period that is captured by the most recent squared residual. Such an updating rule is a simple description of adaptive or learning behavior and can be thought of as Bayesian updating (Engel, 2001)

The basic principle of GARCH is that great changes are followed by great uncertainties, and small changes are followed by small uncertainties. In the standard GARCH model, a series of returns is usually represented by a constant average C plus Gaussian innovation, as described in Bollerslev (1986).

As the literature suggests, the benchmark model for capturing this principle is a simple first order autoregressive model (AR (1)), as in Cuaresma et. al (2004). AR (1) process is given by:

$$p_t = \alpha + \beta p_{t-1} + \eta_t \qquad (1)$$

Linear ARMA models have an assumption of constant variance and covariance functions, or homoskedasticity. In the case of electricity prices, autoregressive conditional homoskedasticity (ARCH) models, given by Engle (1982), usually yield better results, as the literature suggests. However, as electricity spot prices are usually volatile, the generalized autoregressive conditional homoskedasticity (GARCH) model fits better because it models the time-varying volatility process (Engle, 2001).

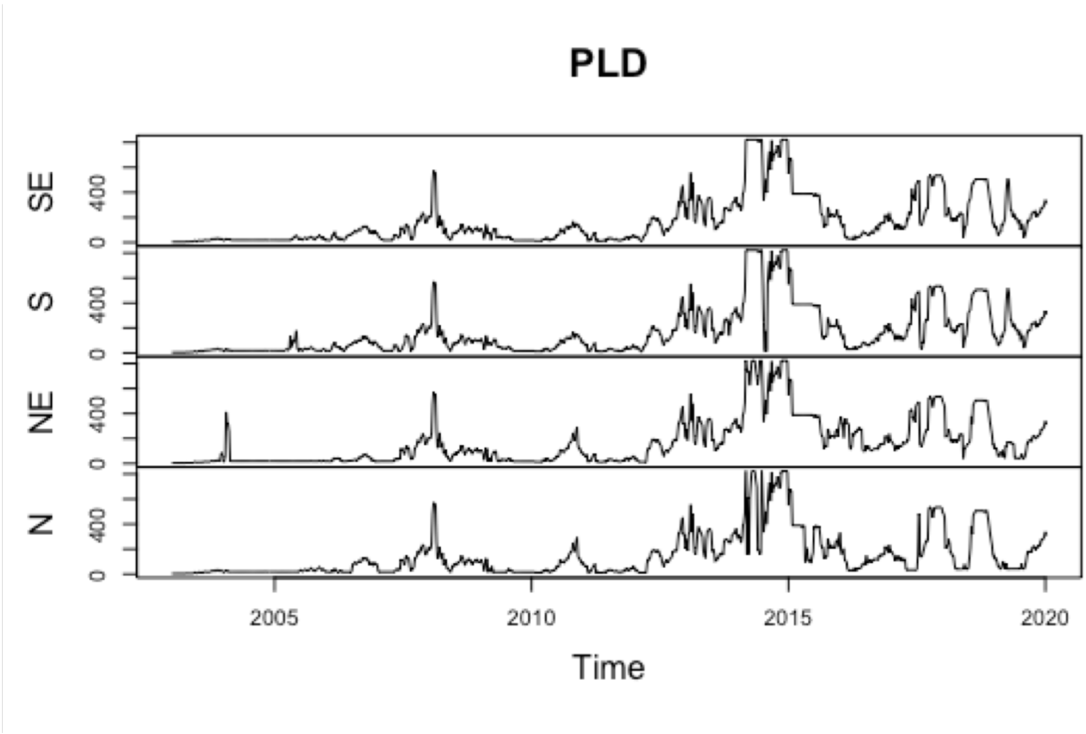
The standard GARCH (1.1) model is represented by:

$$y_t = \mu + \varepsilon_t \qquad \varepsilon_t \sim N(0, \sigma_t^2),$$

$$\sigma_t^2 = \alpha_0 + \alpha_1 \varepsilon_{t-1}^2 + \beta_1 \sigma_{t-1}^2$$

Where, ε_0 and σ_0^2 are constant. The conditional variance is a deterministic function of the model parameters and past data. Figure 2 presents the data from January 2003 up until September 2019, for the four subsystems.

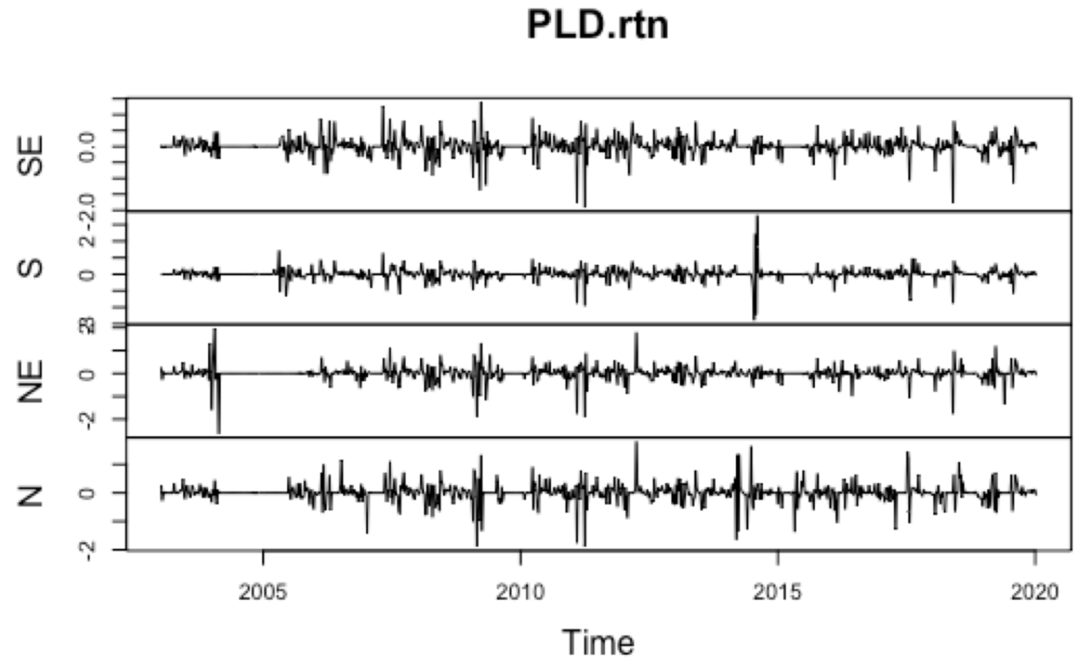
Figure 2 – PLD of the four subsystems in Brazil, from 01/2003 until 09/ 2019 – (R$)



Source: data from www.ccee.org.br

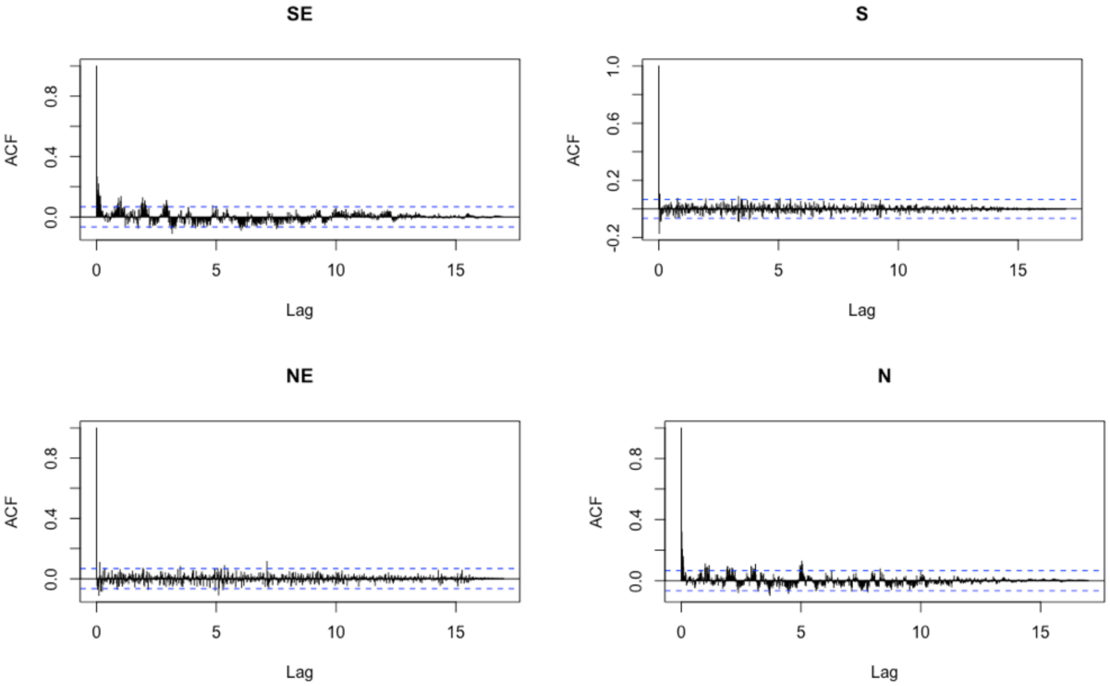
Most volatility analysis studies consider the logarithmic return over arithmetic return (Jorion, 2001; Christoffersen, 2003), hence, logarithmic return is also used in the present work. The log return for each subsystem was calculated and shown in Figure 3, where it can be asserted that the series are non-stationary, and serially uncorrelated.

Figure 3 – PLD log return for the four subsystems



Source: data from www.ccee.org.br

Figure 4 – Autocorrelation function of the four subsystems in Brazil



The conditional mean equation is estimated using the autocorrelation function (ACF), which helped to identify and specify AR and MA terms for capturing and representing the spot price dynamics. The first difference was rendered for all four subsystems in Brazil, as shown in Figure 4.

The series of log returns for the four sub-markets is stationary, however, the autocorrelation functions suggest a non-significant serial correlation, with the exception of 1 lag. Thus, the log returns of the series of spot electricity prices are shown to be serially uncorrelated, however, dependent. Thus, for the four subsystems, volatility models were developed based on the weekly price log-returns. The models developed for all subsystems were GARCH (1.1) and generated the following equations, respectively:

- Southeast

$$r_t = 0.003 + \alpha_t, \quad \alpha = \sigma_t \varepsilon_t, \quad \varepsilon \sim N(0{,}1)$$
$$\sigma_t^2 = 0.01119 + 0.154\alpha_{t-1}^2 + 0.718\sigma_{t-1}^2$$

- South

$$r_t = -0.003838 + \alpha_t \quad \alpha = \sigma_t \varepsilon_t, \ \varepsilon \sim N(0{,}1)$$
$$\sigma_t^2 = 0.0299 + 0.418\alpha_{t-1}^2 + 0{,}3763\sigma_{t-1}^2$$

- Northeast

$$r_t = 0.00349 + \alpha_t \quad \alpha = \sigma_t \varepsilon_t \quad \varepsilon \sim N(0{,}1)$$
$$\sigma_t^2 = 0.00775 + 0.17784\alpha_{t-1}^2 + 0.7685\sigma_{t-1}^2$$

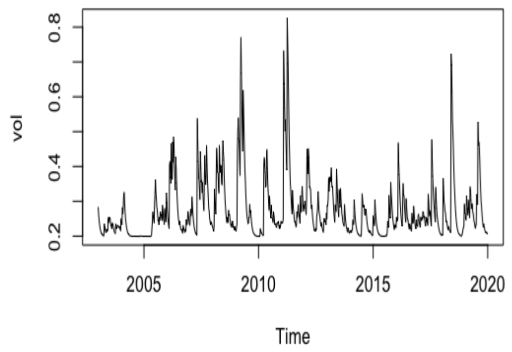
- North

$$r_t = 0.00536 + \alpha_t, \quad \alpha = \sigma_t \varepsilon_t, \quad \varepsilon \sim N(0{,}1)$$
$$\sigma_t^2 = 0.0169 + 0.1610\alpha_{t-1}^2 + 0.6958\sigma_{t-1}^2$$

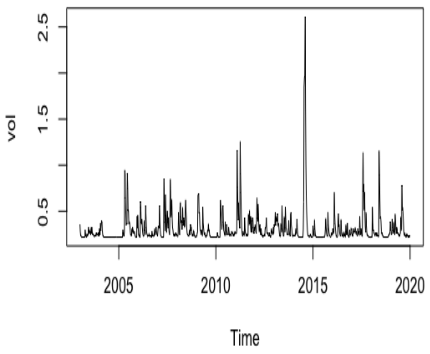
As all equations are statistically significant, it was possible to model realized volatility series for the four subsystems , as shown in Figure 5.

Figure 5 – Realized volatility for the four subsystems in Brazil

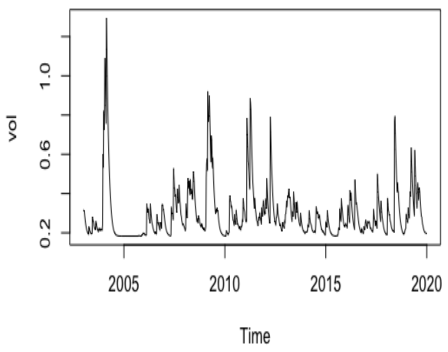
Southeast



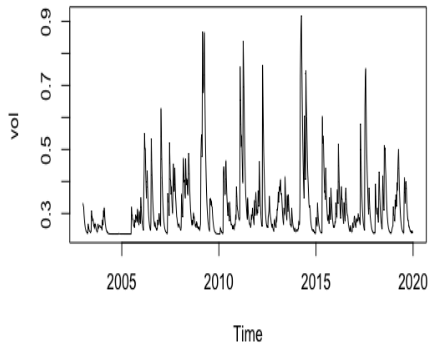
South



Northeast



North



For the four markets, volatility was high in some periods and low in others, and it is possible to notice the presence of volatility clusters. As can be seen, for all the markets the PLD is very volatile, which represents high risk to players in the electricity industry.

The main cause of this volatility is related to the characteristics of the industry. Approximately, 65% of the energy generated in Brazil comes from hydro plants. In the past, before the reforms, hydro plants were responsible for 100% of the electricity produced in the country and large reservoirs were used to act as a hedge to guarantee the generation of electricity in dry periods. However, after the promulgation of the Federal Constitution was edited in 1988, and environmental concerns which prevented the construction of new reservoirs, it is not possible to build large reservoirs anymore.

Nowadays, the backup is from thermal plants, especially oil and natural gas; but to determine the price, the system operator uses the same computational program as used when the system was a vertically integrated monopoly. In addition, since 2014, the share of intermittent sources in the electricity mix, especially wind, has increased. This has contributed to the high volatility in the spot price.

Spot prices are meant to give incentives. In the short run, spot prices give incentives to sellers and buyers. In the long run, spot prices give signals to investors. The increased participation of the run-of-river hydro plants will reduce the performance of the strategic reserve system and will require greater operational flexibility of existing reservoirs. This is in addition to requiring increased installed capacity of back-up plants, i.e., flexible thermal plants, especially during dry seasons.

5. Concluding remarks

The purpose of this article was to model the realized volatility of the electricity spot price in Brazil. The PLD, corresponding to the spot price, has been very volatile, and by consequence, substantially unpredictable. These characteristics reduce the degree of certainty of the electricity sector's economic agents to considerably increase the economic and financial risks.

To do so, a GARCH model was built with 862 observations. The model showed that the price is very volatile, and this represents a risk to agents as it is more difficult to forecast the electricity price.

The main cause of this volatility is related to the characteristics of the industry. Approximately 90% of the energy generated in Brazil comes from hydro plants. The price is calculated on an ex-ante weekly basis through dual stochastic dynamic programming models that analyze the current flow and the flow rates in the short, medium, and long terms. Thus, the spot price is the result of computer models, and by failing to take into account the demand side, the spot price is inadequate and gives an inconsistent signal for future investments and providing long-term contracts. In relation to the volatility of the spot price, three factors were examined: a shortage of investment in the period after crisis, the end of the construction of new reservoirs. It was noted that these elements are interdependent, which implies that there is an increasingly explicit trend, which is that the PLD will become an even more volatile variable, contributing to instability in the Brazilian electricity market.

References

Alvarado, F., Rajaraman, R. (2000). Understanding price volatility in electricity markets. in: Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, pp. 1–5.

Angelus A. (2001) Electricity Price Forecasting in Deregulated Markets. *The Electricity Journal*, 4, pp. 32–41. https://doi.org/10.1016/j.ijepes.2008.09.003

Araujo, J. L. R. H.; Costa A.M.A.; Correa T.; Melo E. (2008). Energy contracting in Brazil and electricity prices. International Journal of Energy Sector Management, V. 2, n. 1, p. 36-51. DOI: https://doi.org/10.1108/17506220810859088.

Bello, A.; Bunn, D.; Renesses, J.; Munõz, A. (2017). Medium-Term Probabilistic Forecasting of Electricity Prices: A Hybrid Approach. *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 334-343. DOI: 10.1109/TPWRS.2016.2552983.

Bhattacharya, K., Bollen, M.H., Dallder, J.E. (2001). Operation of Restructured Power Systems. Kluwer Academic Publishers, Boston.

Bollerslev T. (1986). Generalized autoregressive conditional heteroskedasticity. Journal of Econometrics, 31, pp. 307–327. https://doi.org/10.1016/0304-4076(86)90063-1.

CCEE, 2019. Arquivo 2019. (disponível em Câmara de Comercialização de Energia Elétrica: http://www.ccee.org.br).

Christoffersen, P.F. (2003). *Elements of Financial Risk Management*. Academic Press.

Cuaresma, J.C., Hlouskova, J.; Kossmeier, S., Obersteiner, M. (2004). Forecasting electricity spot-prices using linear univariate time-series models, Applied Energy, 77, 87-106. DOI: 10.1016/S0306-2619(03)00096-5.

Dahlgren, R.W., Liu, C.C., Lawarree, J. (2001). Volatility in the California power market: source, methodology and recommendations. *IEE Proceedings on Generation, Transmission and Distribution*, 148 (2), https://doi.org/10.1049/ip-gtd:20010339.

Dalbem, M.C.; Brandao L.E.T.; Gomes L.L. (2014). Can the regulated market help foster a free market for wind energy in Brazil? *Energy Policy*, v. 66, pp. 303-311. https://doi.org/10.1016/j.enpol.2013.11.019

Efimova, O., Serletis, A. (2014). Energy markets volatility using GARCH. Energy Economics, V. 43, pp. 264-273. **DOI:** 10.1016/j.eneco.2014.02.018

Engle, R. (1982). Autoregressive Conditional Heteroscedasticity with Estimates of the Variance of United Kingdom Inflation. *Econometrica*, 50(4), pp. 987-1007. DOI: 10.2307/1912773.

Engle, R. F. (2001). GARCH 101: The Use of ARCH/GARCH Models in Applied Econometrics. *Journal of Economic Perspectives*, 15(4), 157-168. *DOI: 10.1257/jep.15.4.157*

Ferreira, P.G.C.; Oliveira, F. L. C.; Souza, R.C. (2015). The stochastic effects on the Brazilian Electrical Sector. *Energy Economics*, 49, pp. 328–335. https://doi.org/10.1016/j.eneco.2015.03.004

Girish, G.P. (2016). Spot electricity price forecasting in Indian electricity market using autoregressive-GARCH models. *Energy Strategy Reviews,* 11-12, pp. 52 - 57. https://doi.org/10.1016/j.esr.2016.06.005

Hadsell, L., Marathe, A., Shawky, H.A. (2004). Estimating the volatility of wholesale electricity spot prices in the US. Energy Journal25 (4), pp. 23–40.

Higgs, H. (2009). Modelling price and volatility inter-relationships in the Australian wholesale spot electricity markets. *Energy Economics*, 31(5), pp. 748-756. https://doi.org/10.1016/j.eneco.2009.05.003

Hunt, S. and Shuttleworth, G. (1996). **Competition and choice in electricity**, West Sussex, England: Willey, 1996.

Jorion, P. (2001). *Value at Risk*. McGraw-Hill, New York.

Karakatsani, N. V. & Bunn, D. W. (2010). Fundamental and behavioral drivers of electricity price volatility. *Studies in Nonlinear Dynamics & Econometrics*, De Gruyter, vol. 14(4), pp. 1-42. https://doi.org/10.2202/1558-3708.1657

Li, Y.; Flynn, P. (2004). Deregulated power prices: comparison of diurnal patterns. *Energy Policy*. Vol. 32 (5), p. 657-672. https://doi.org/10.1016/S0301-4215(02)00331-2

Mount, T. (2001). Market power and price volatility in restructured markets for electricity. *Decision support systems*, vol. 30 (3), pp. 311-325. DOI: https://doi.org/10.1109/HICSS.1999.772841.

Newbery, D. (1995). Power Markets and Market Power. *The Energy Journal*, v. 16 (3), pp. 39-66. DOI: 10.5547/ISSN0195-6574-EJ-Vol16-No3-2.

Newbery, D.; Pollitt, M.; Ritz, R.; Strielkowski, W. (2018). Market design for a high-renewables European electricity system. *Renewable and Sustainable Energy Reviews*, 91, pp. 695-707. https://doi.org/10.1016/j.rser.2018.04.025

Qu, H., Duan, Q., Nil, M. (2018). Modeling the volatility of realized volatility to improve volatility forecasts in electricity markets. *Energy Economics*, 74, 767-776. https://doi.org/10.1016/j.eneco.2018.07.033

Ryan, R.; Lidderdale, T. (2009). *Energy price volatility and forecast uncertainty*. Energy Information Administration Energy Information Administration/Short-Term Energy Outlook Supplement.

Sadorsky, P. (2012). Correlations and volatility spillovers between oil prices and the stock prices of clean energy and technology companies. *Energy Economics*, 34(1), pp. 248-255. DOI: 10.1016/j.eneco.2011.03.006

Shahidehpour, M., Yamin, H., Li, Z. (2002). *Market Operations in Electric Power Systems*. Wiley Interscience, New York.

Simonsen, I., 2005. Volatility of power markets. *Physica* A, 335 (1), 10–20. DOI:10.1016/j.physa.2005.02.062.

Tashpulatov, S. N. (2013). Estimating the volatility of electricity prices: The case of the England and Wales wholesale electricity market. *Energy policy*, v. 60, pp. 81-90. https://doi.org/10.1016/j.enpol.2013.04.045

Vahl, F. P.; Rüther, R.; Casarotto Filho. (2013). The influence of distributed generation penetration levels on energy markets**.** *Energy Policy*, v. 62, p. 226-235.

Worthington, A., Kay-Spratley, A., Higgs, H. (2005). Transmission of prices and price volatility in Australian electricity spot markets: a multivariate GARCH analysis. *Energy Economics*, 27 (2), pp. 337–350. https://doi.org/10.1016/j.eneco.2003.11.002

Zareipour, H., Bhattacharya, K. & Cañizares, C. A. (2007). Electricity market price volatility: The case of Ontario, *Energy Policy*, 35 (9), 4739-4748. DOI:10.1016/j.enpol.2007.04.006

PROSPECTIVA PARA EL DESPLIEGUE DE LA ECONOMÍA DEL HIDRÓGENO EN COLOMBIA: UNA ESTRATEGIA NACIONAL DE HIDRÓGENO

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INTRODUCCIÓN

A partir de la legislación existente para el hidrógeno de bajas emisiones[1], se ha generado un gran interés nacional en las prospectivas de inserción de este vector energético como habilitador de la transición energética y su contribución a la mitigación de emisiones de gases de efecto invernadero (GEI). Sumado a esto, el lanzamiento de la Hoja de ruta del hidrógeno en Colombia[2] por parte del Gobierno Nacional ha movilizado a los actores del sector energético a tomar acción para posicionarse dentro de la cadena de valor del hidrógeno. En este punto se requiere el diseño y la implementación de políticas y normativa específicas que incentiven el despliegue de la economía del hidrógeno en Colombia.

Este estudio, financiado por la UPME y Minciencias, generó recomendaciones de política pública y medidas complementarias como parte de una Estrategia Nacional de Hidrógeno que contribuya a la construcción del Plan Nacional de Desarrollo 2022-2026.

METODOLOGÍA

Para el diseño de una Estrategia Nacional de Hidrógeno para Colombia se incorporaron metodologías para la planeación a largo plazo como la prospección tecnológica, los escenarios de transición energética y el modelado de sistemas energéticos. A partir de la prospección de las tecnologías de producción y uso de hidrógeno, y los recursos de FNCER y combustibles fósiles del país, se realizó una evaluación de los potenciales nacionales de producción de hidrógeno por diferentes fuentes y las prospectivas de demanda de hidrógeno de los sectores transporte e industria.

Con base en los potenciales de producción y prospectivas de demanda, se construyeron escenarios de inserción y despliegue de tecnologías de hidrógeno de bajas emisiones para Colombia hacia el 2050. Luego, se evaluaron los escenarios de demanda para el transporte y la industria utilizando la herramienta LEAP (*Low Emissions Analysis Platform*) para determinar las demandas anuales totales hacia el 2050 de manera integrada al modelo energético nacional del PEN 2020-2050[3]. Seguidamente, se utilizó la herramienta NEMO (*Next Energy Modeling system for Optimization*) para obtener la matriz de producción de hidrógeno optimizada económicamente a partir del potencial de producción de hidrógeno de bajas emisiones y precios al carbono de US$9,85/t CO_2-eq a partir del 2025. A este escenario se le denominó como “Economía del Hidrógeno”.

Finalmente, a partir de los resultados de escenario de “Economía del Hidrógeno”, se generaron recomendaciones de política pública y medidas complementarias como parte de una Estrategia Nacional de Hidrógeno para Colombia.

RESULTADOS

A partir de la evaluación del escenario de “Economía del Hidrógeno” para el modelo del sistema energético nacional, se obtuvieron los siguientes resultados:

- Colombia tiene un potencial de capacidad instalada para producción de hidrógeno de 23,4 GW al 2050, equivalente a ~6,1 Mt de hidrógeno al año.
- En 2050, la demanda interna de hidrógeno puede alcanzar ~1,87 Mt/año, de los cuales ~1,2 corresponderían al transporte terrestre pesado, ~0,61 a la industria, y ~0,06 al residencial y terciario.
- Suplir la demanda interna con el menor costo requeriría 7,59 GW de capacidad instalada al 2050 a partir de tecnologías bajas en carbono, con una participación de 65,8% de energía solar fotovoltaica, 28,1% de energía eólica, y 6,1% a partir de gas natural con captura de carbono (ver Fig. 1).

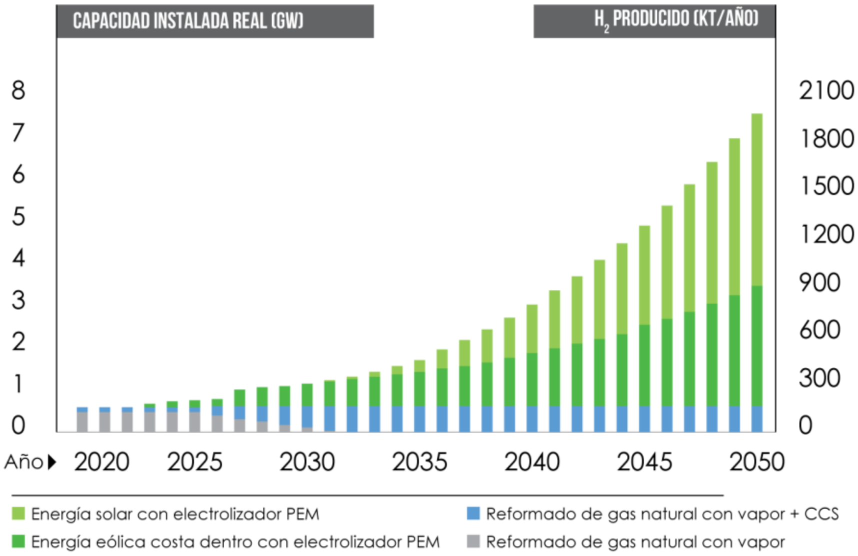

Figura 1. Matriz de producción de hidrógeno optimizada para el periodo 2020 a 2050 del escenario "Economía del Hidrógeno".

- Al 2050, se podrían mitigar ~733 Mt CO_2-eq de emisiones de GEI respecto al escenario tendencial del NDC de Colombia[4], de los cuales ~624 Mt CO_2-eq corresponden al sector transporte y ~109 Mt CO_2-eq al sector industrial. Esta reducción de emisiones representaría un 56% de la mitigación de GEI de estos sectores en 2050.
- La inversión anual requerida para la transición varía desde US$ 882 millones en 2030 y US$ 10 892 millones en 2050. Para el 2030, la inversión necesaria para el despliegue del escenario se debe a los costos de producción (71%), los costos de demanda (23%) y los costos de infraestructura de suministro de hidrógeno (6%).
- Colombia cuenta con un potencial de exportación de hidrógeno 4,2 Mt para el 2050. Esto representaría ingresos de US$ 12,8 billones para un precio de venta de US$ 3/kg H_2.

CONCLUSIONES Y RECOMENDACIONES

Los resultados del escenario "Economía del Hidrógeno" proveen los insumos necesarios para definir dos de los componentes principales de una estrategia nacional de hidrógeno[5]: (i) los objetivos clave de producción, infraestructura y uso de hidrógeno, y (ii) la línea de tiempo de la estrategia.

Finalmente, las recomendaciones de (iii) políticas públicas para la oferta, la demanda y la infraestructura de hidrógeno y de (iv) medidas complementarias[5] buscan ser coherente con el marco de política energética actual para la implementación integrada de la Estrategia Nacional de Hidrógeno así:

Recomendaciones para la oferta:

- Subastas de contratación de largo plazo para proyectos de producción de hidrógeno de bajas emisiones.
- Sello ambiental colombiano para la certificación de origen del hidrógeno.
- Estándares de intensidad de emisiones para el Sistema Interconectado Nacional.
- Mercado de certificados de reducciones y absorciones de emisiones de GEI.

Recomendaciones para la demanda en el transporte pesado:

- Cuotas anuales crecientes de fabricación local e importación de vehículos de cero emisiones.
- Estándares promedio corporativos de emisiones de gases efecto invernadero y de eficiencia de combustible.
- Incremento de US$5/t CO_2-eq al impuesto nacional al carbono (INC) a partir de 2025 con destinación a subsidiar adquisición de vehículos de cero emisiones.

Recomendaciones para la demanda industrial:

- Tasación de los permisos transables de emisión del Programa Nacional de Cupos Transables de Emisión de Gases de Efecto Invernadero (PNCTE) a US$ 9,85/t CO_2-eq a partir del 2025.
- Extensión de incentivos tributarios de la Ley 2099 de 2021 a proyectos de producción de fertilizantes, combustibles sintéticos y otros productos de valor agregado que utilicen hidrógeno de bajas emisiones como insumo.

Mecanismos de financiación de la infraestructura:

- Habilitación del fondo para la promoción de ascenso tecnológico de los sistemas de transporte y del parque automotor de carga y del Fondo de Energías No Convencionales y de Gestión Eficiente de la Energía (FENOGE) para la destinación de los recursos recaudados por concepto del incremento del INC, y la venta de permisos de emisión y sanciones por incumplimiento del PNCTE, respectivamente.
- Diseño de mecanismos de créditos blandos a la inversión público-privada en infraestructura de hidrógeno, respaldados por fondos públicos de garantías.
- Desarrollo de acciones enfocadas en la diplomacia del hidrógeno para la gestión de recursos internacionales por medio de mecanismos como el Fondo Climático Verde (GCF, por sus siglas en inglés), y el *Climate Investor One* (CIO) y el *GET-invest* de la Unión Europea, entre otros.

Medidas complementarias:

- Creación de una Agencia Nacional del Energías Renovables que articule la institucionalidad para la inserción y despliegue de las Fuentes No Convencionales de Energía Renovable y el hidrógeno de bajas emisiones.
- Desarrollo de un marco de gobernanza participativa con enfoque territorial para la transición justa e inclusiva hacia la economía del hidrógeno, de acuerdo con las mejores prácticas a nivel internacional.
- Definición de los aspectos técnicos y normativos para el licenciamiento ambiental de proyectos de hidrógeno.
- Impulso a la investigación, el desarrollo tecnológico y la innovación en la producción y uso de hidrógeno de bajas emisiones.

REFERENCIAS

1. Congreso de Colombia. *Ley 2099 de 2021*. 1–25 (2021).

2. Ministerio de energía de Colombia. Hoja de ruta de hidrógeno en Colombia. *Ministerio de energía de Colombia* 5–24 (2021).

3. Unidad de Planeación Minero Energética. *Plan Energético Nacional 2020 - 2050*. https://www1.upme.gov.co/DemandaEnergetica/PEN_documento_para_consulta.pdf (2019).

4. Gobierno de Colombia. *Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC)*. 1–45 (2020).

5. IRENA. *Making the breakthrough: Green hydrogen policies and technology costs*. (International Renewable Energy Agency, 2021).

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PAPER

Environmental impacts associated with hydrogen production in La Guajira, Colombia

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Abstract

The global push to decarbonize sectors of the economy and phase-out coal use has attracted a renewed interest in hydrogen. At the forefront of this debate, Colombia, the world's 6th largest coal exporter, must consider strategies to support a just transition for regions that depend economically on coal exports. However, the role of hydrogen as a part of the energy transition has yet to be examined from an environmental justice lens. A full-chain life-cycle assessment of hydrogen production is yet to be considered in Colombia. Using life-cycle assessment (LCA) methodology, we examine the greenhouse gas emissions, water consumption, and trace metal emissions associated with six potential Colombian liquid hydrogen production strategies: (1) electrolysis powered by the country's national electricity grid, (2) on-site electrolysis powered by electricity produced by a wind farm, (3) off-site electrolysis powered by electricity produced by a wind farm, (4) electrolysis powered by electricity produced from a coal-fired power plant, (5) coal gasification without carbon capture and storage (CCS), and (6) coal gasification with CCS. Upstream conversion has an outsized influence on the sustainability of a hydrogen transition in Colombia. Impact levels for wind-powered electrolysis are lower than those of the coal- and grid-powered scenarios for every impact category analyzed, apart from emissions of aluminum to air, nitrogen emissions to water, and phosphorous, nitrate, and nitrite emissions to soil. The grid-based electrolysis scenario is found to consume the largest amount of water, while coal-fueled scenarios pathways raise concerns of greater life-cycle mercury, nickel, and arsenic emissions. While coal gasification with CCS reduced gasification CO_2 emissions by 35%, the CCS scenario's VOC emissions were 37% greater than gasification without CCS, given that increased levels of coal inputs were required to account for the loss of efficiency associated with the addition of CCS technology. For Colombia to benefit most from a hydrogen-based decarbonization transition with minimal environmental impacts, community-focused planning and wind-based hydrogen systems should be prioritized.

1. Introduction

Colombia occupies a unique position as the largest coal exporter in South America, placing it at the international center of a changing industry. With increasing international pressure to reduce coal exports, Colombia may seek to diversify its energy economy. Much of the country's coal production takes place in its northern department of La Guajira, which is home to El Cerrejón, South America's largest open pit coal mine. The mining industry is a foundational part of La Guajira's economy, comprising 37.6% of the region's economy in 2019 (Departamento Administrativo Nacional de Estadística, Colombia 2021). The department also has some of the best potential wind resources in South America, with class 7 winds that are only matched by those in the Patagonia region of

Chile and Argentina (Vergara *et al* 2010). Despite these vast primary energy resources, the department maintains the highest poverty levels of the Caribbean region, with a 51.4% incidence of multidimensional poverty, an index Colombia uses to measure quality of life based on household education, childhood conditions, health, work, access to public services, and living conditions (Departamento Administrativo Nacional de Estadística, Colombia 2019). The department is also home to many indigenous and Afrocolombian communities, which have been historically marginalized throughout Colombia's history and have suffered greatly from the development and operation of the mine (Boeder 2013). Ninety-eight percent of the country's Wayuu tribe lives in La Guajira and comprises 38% of the population (Sistema Nacional de Información Cultural (SINIC) 2021).

According to the El Cerrejón mine, the mine directly employs or contracts with 5,282 residents of La Guajira and has invested $15 billion COP (~ $4 million USD) into the community (Cerrejón 2021). As such, contraction of the mining industry could pose a great risk to communities that depend economically on the mine. With global demand for coal decreasing as countries strengthen the ambitions of their decarbonization goals, materialization of these risks become more and more likely. To aid coal-mine-adjacent communities through these predicted economic contractions, government officials must consider policies that promote a 'just transition' to provide economic support to the communities economically affected from the transition towards zero-emissions energy production.

At the start of August of 2021, Colombia launched its own Hydrogen Roadmap that detailed its plans to invest heavily in hydrogen production, with a goal to develop 1 GW of electrolysis infrastructure and produce 50 kt of blue hydrogen by 2030 (Minenergía 2021). Hydrogen has the potential to serve as a key step in the country's climate change mitigation goals, where Colombia pledges to reduce its 2030 baseline greenhouse gas emissions by 51%, specifically reducing its energy sector emissions by 35% of 2015 emissions (Gobierno de Colombia 2020).

Hydrogen can be produced by various fuels and technologies and is often characterized using colors to describe its emissions and mode of production (Dawood *et al* 2020). 'Grey hydrogen', for instance, is created from fossil fuel sources without any carbon capture mechanisms to reduce the process' emissions. 'Blue hydrogen', on the other hand, is produced from fossil fuels with carbon capture technology. Hydrogen also has the potential to be produced entirely from zero-emission energy sources, like wind or solar, using techniques like water electrolysis to produce 'green hydrogen.' La Guajira has been noted as a location of particular interest for hydrogen production, in large part given its significant wind resources. However, the country notes in its hydrogen roadmap that production will not be entirely 'green', particularly in the earlier stages of the industry's development (Minenergía 2021).

Producing 'green' over 'grey' or 'blue' hydrogen may have important economic, environmental, and human implications. For instance, should the country consider exporting locally produced hydrogen, especially to account for contracting coal demand, potential importers may seek to employ carbon border adjustments, increasing demand for green H_2 over that for blue and grey H_2. The fuels consumed throughout the life-cycle of the process, as well as their resulting emissions, are also likely to have important implications on the country's climate change goals and the health and wellbeing of the indigenous, Afrocolombian, and mining communities living near potential hydrogen production sites. This study examines the differences between the impacts of six potential hydrogen production scenarios in the region, using a life cycle assessment (LCA) to quantify each scenario's greenhouse gas, air, and water pollution emissions; water consumption levels; and trace metal leakage.

2. Literature review

Studies have found that decarbonization of Colombia's energy sector will be important for insulating its economy from contractions in international coal markets, reducing the greenhouse gas emissions that contribute to international climate change, mitigating carbon lock-in, and responding to political pressures for decarbonization through pledges made in international venues, like the Paris Agreement (Falkner 2016, Lazarus and van Asselt 2018, Oei and Mendelevitch 2019, Delgado *et al* 2020, Gobierno de Colombia 2020). Substantial research has been conducted on sustainability energy transitions in Latin America (Bataille *et al* 2020, Pye *et al* 2021., Vergara *et al* 2010, Ramirez *et al* 2020), but the role of hydrogen as a part of this energy transition has yet to be examined from an environmental justice lens. Recent work on long-duration energy storage established potential techno-economic benefits of liquid hydrogen and hydrogen as a form of long-duration or seasonal energy storage on the path toward energy system decarbonization (Shan *et al* 2022). Other studies have developed alternative energy strategies to analyze environmental and economic effects of producing hydrogen and other products from coal, integrating findings into policy roadmaps for a hydrogen industry. One common methodology utilizes backcasting, which first identifies desired transition goals or targets as an endpoint and assesses the necessary transition steps and intervention pathways needed to achieve policy goals (Giurco *et al* 2011). Other research has demonstrated sustained improvement of hydrogen production efficiency (Kaskun

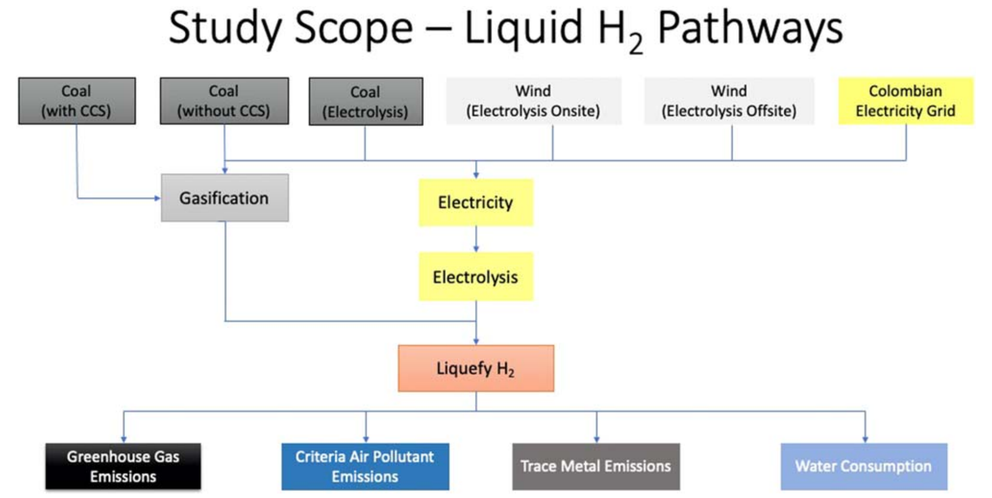

Figure 1. Study scope.

and Kayfeci, 2018, Kaskun 2020, Kaskun *et al* 2020) and noted economic synergies and greenhouse gas reduction benefits for hydrogen production in regions with substantial wind capacity (Scolaro and Kittner 2022). However, just one study has examined the transition to hydrogen production potential in Latin America, and has done so primarily through an economic lens (Moreira dos Santos *et al* 2021). Other research that has been conducted on hydrogen production as a transition strategy has instead focused on the transition under the lens of the transportation sector (Iannuzzi *et al* 2021). This study will build off this previous work by examining the prospective environmental and health impacts of hydrogen as a tool in Colombia's energy transition.

Examination of the health and environmental impacts of prospective hydrogen development scenarios in Colombia is extremely important given the country's acceleration of hydrogen technology development. This study uses a life-cycle framework to examine these impacts. Past studies have used life-cycle assessment to determine the greenhouse gas emissions from various hydrogen scenarios (Utgikar and Thiesen 2006, Bouvart and Prieur 2009, Cetinkaya *et al* 2012, Dufour *et al* 2012, Muresan *et al* 2014, Verma and Kumar 2015, Wang *et al* 2019). A limited number of papers have also expanded their impact assessment beyond greenhouse gas emissions to include other environmental effects, including acidification, eutrophication, smog, and water resource depletion (Koroneos 2004, Delpierre *et al* 2021). However, trace metals, which could be a key environmental indicator for particular production pathways, are often omitted. A full-chain life-cycle assessment of hydrogen production is yet to be done in Colombia, a major potential exporter, and has so far not included a holistic examination of environmental factors that would affect Colombia's coal-mine-adjacent communities, like trace metal leakage, air and water pollution, and water consumption.

Given Colombia's large amounts of coal exports and documented environmental and health detriments that have risen from its coal production, it is important that energy transitions research in the country include analysis of the transition on coal mine-adjacent communities (Weber and Cabras 2021). Impact analyses of the mine have documented detriments to vegetation from oxidation of surrounding soil, desertification of nearby rivers and contamination of local water sources, and detriments to air quality that have resulted in pulmonary disease amongst young and elderly community members resulting from the mine's operation (Virgüez 2011, Aggregocés *et al* 2018). Past work on just transitions centered their framework on the political and economic components of the transition (Healy and Barry 2017, Cardoso and Turhan 2018, Strambo and Atteridge 2018, Jakob *et al* 2019, Strambo and González Espinosa 2020). It is essential to include management of water consumption, air and water emissions, and trace metal leakage as part of the discussion of just transitions given their impacts on air pollution and public health—and they are often excluded from the economic or jobs analysis. This study can aid planners in assessing the environmental and health implications of various hydrogen production scenarios and facilitating discussion on hydrogen's role as a viable just energy transition strategy.

3. Methods

3.1. Life cycle inventory

This study uses a life cycle assessment approach to compare the environmental impacts of six hydrogen production methods in La Guajira, Colombia. The objective of this approach is to compare the impacts of producing 1 ton of liquid hydrogen (LH_2) through the following six pathways: (1) gasification of coal with CCS,

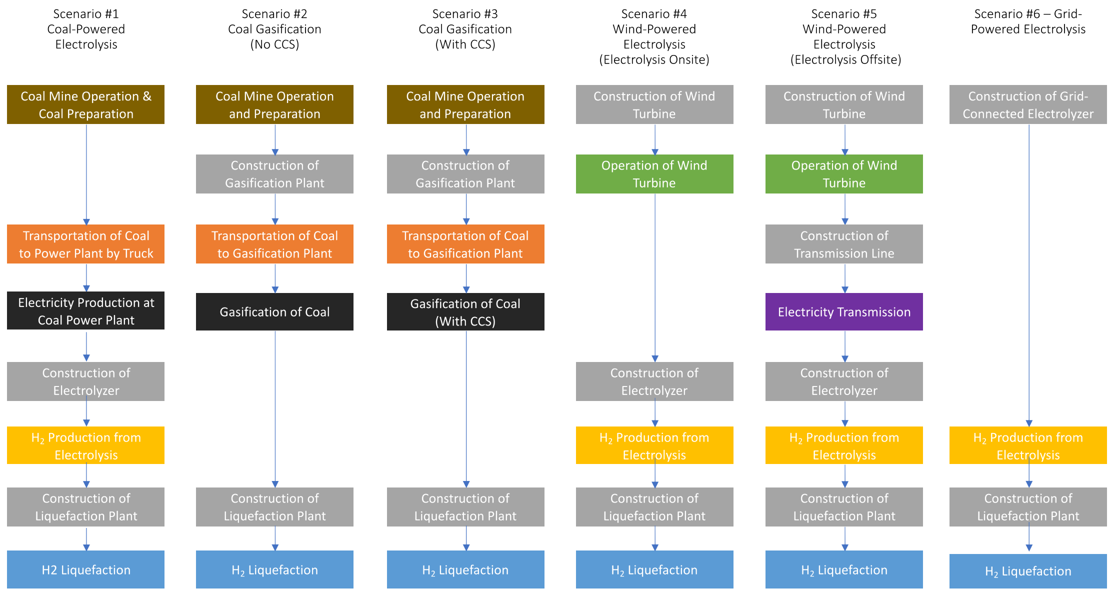

Figure 2. Study boundaries.

Table 1. Life cycle assessment impact category indicators.

Indicator	
Greenhouse Gases	CO_2, CH_4, Non-methane VOC
Criteria Air Pollutants	NOx, PM < 2.5, PM 2.5–10, PM > 10, SO_2
Trace Metal Leeching	Aluminum, Arsenic, Cadmium, Copper, Dissolved Solids, Fluoride, Inorganic Solids, Iron, Lead, Manganese, Mercury, Nickel, Nitrate, Nitrite, Oils, Strontium, Sulfate, Zinc
Water Consumption	Tonnes water consumed

(2) gasification of coal without CCS, (3) electrolysis using electricity produced from a thermal coal plant, (4) electrolysis using electricity powered by wind turbines in the La Guajira region with an onsite electrolyzer and liquefaction plant, (5) electrolysis using electricity powered by wind turbines in the La Guajira region with an offsite electrolyzer and liquefaction plant, and (6) electrolysis powered using electricity from Colombia's national electricity grid (Spanish acronym SIN) with assumed completion of the HidroItuango hydroelectric dam. These pathways are summarized in figure 1.

The study calculates and presents an overview of the greenhouse gas, criteria air pollutant, and trace metal emission impacts associated with each production method and calculates each method's estimated life-cycle water consumption. The impact categories, along with their corresponding indicators, are shown table 1. After the LCA per ton impacts were characterized, they were also compared with full scale-up of meeting Colombia's 2030 low-emissions hydrogen production targets, assumed to be 50 ktonnes of LH_2, based on the blue hydrogen production goals stated in Colombia's Hydrogen Roadmap (Minenergía 2021).

3.2. Study boundary

A summary overview of each included step is shown in figure 2.

3.3. Coal gasification

Since the El Cerrejón mine was established more than 30 years ago, the exploration and development steps of the coal production are excluded from the analysis. Both coal gasification pathways begin with extraction of coal from the El Cerrejón mine. Coal is extracted using a 63.5-ton bucket excavator and 35% of the extracted coal is sent to the mine's stockpiles. The coal is then cleaned and washed, a process that is assumed to have a 73% coal recovery rate (Fueyo Editores 2015). Once the coal is prepared, it is transported 150 miles from the mine to Puerto Bolivar via the mine's proprietary diesel-powered train. This study assumes that the coal gasification process will take place at a gasification plant constructed adjacent to Puerto Bolivar. During the gasification process, hydrogen is produced through pressure swing absorption (PSA), with an assumed 1.57 GJ/GJ-H_2 gas to feedstock ratio for gasification without CCS, and a 1.69 GJ/GJ-H_2 gas to feedstock ratio for gasification with CCS (Gray and Tomlinson 2002). In the gasification with CCS scenario, carbon capture and storage (CCS) takes

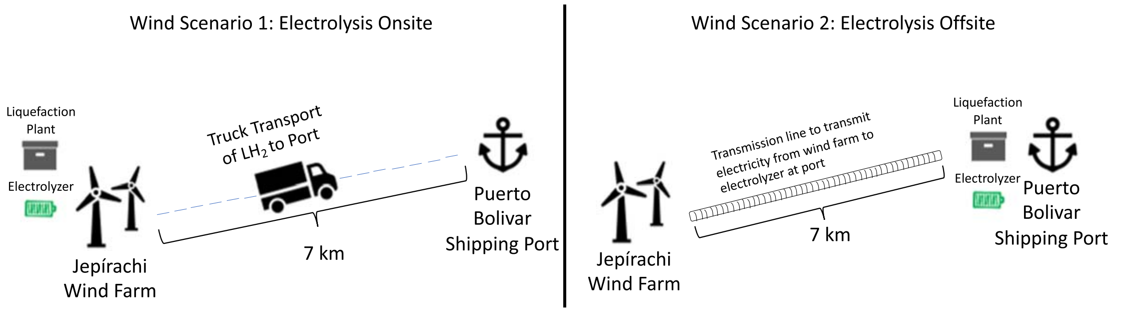

Figure 3. Representation of onsite and offsite electrolysis scenarios.

place concurrently with the PSA process. The produced hydrogen is then liquefied at an 85% efficiency rate, accounting for boil-off during the liquefaction process. For reference, a 50 tpd liquefaction plant is estimated to cost $80 million USD (Connelly *et al* 2019). The study assumes the 85% efficiency rate and an electricity consumption rate of 8 kWh for liquefaction of 1 kg of hydrogen in every scenario (Gardiner 2009, Petitpas 2018). The amount of coal required to produce this hydrogen is calculated using the following equation:

Coal Gasification with PSA & Liquefaction:

$$\sum CMP_{ef} * C + Tra_{ef} + \frac{GPC_{ef}}{GP_L * P} + G_{ef} + \frac{LC_{ef}}{L_L * P} + LO_{ef}$$

Where CMP_{ef} is the coal mine operation and coal preparation emission factor, C is the amount of the coal mined (8.55 tonnes), Tra_{ef} is the coal transport by train emission factor, GPC_{ef} is the gasification plant construction emission factor, GP_L is the gasification plant project lifetime (20 years), P is the scenario hydrogen production potential, G_{ef} is the gasification emission factor, LC_{ef} is the liquefaction plant construction emission factor), L_L is the liquefaction plant project lifetime (20 years), and LO_{ef} is the liquefaction plant operation emission factor.

3.4. Coal-powered electrolysis

The coal extraction and preparation steps taking place in the coal electrolysis pathway are equivalent to that of the coal gasification pathway. Once the coal has been extracted and prepared, it is transported 71 miles from the El Cerrejón mine to the Termoguajira power plant via a 40-ton semi-truck. The power plant produces electricity, which is then transmitted to a 1 MW polymer electrolyte membrane (PEM) electrolyzer, estimated to cost $300,000 ($300/kW) (DOE Hydrogen and Fuel Cells Technologies Office 2021). The electrolyzer is installed at the Puerto Bolivar site using the current SIN grid system transmission network, with an assumed 10% transmission loss (International Energy Agency 2018). This will be the same electrolyzer and transmission loss used across all scenarios involving electrolysis. Powered by the transmitted electricity, the electrolyzer produces hydrogen, assumed to require 50 kWh of electricity to produce 1 kg hydrogen (DOE Hydrogen and Fuel Cells Technologies Office 2021). A similar liquefaction process is performed using the same efficiency and electricity requirements of previous steps. Outputs resulting from production of liquid hydrogen from coal-powered electrolysis is calculated using the following equation:

Coal − powered electrolysis & liquefaction:

$$\sum CMP_{ef} * C + CE_{ef} * CE + Tru_{ef} + \frac{EC_{ef}}{E_L * P} + \frac{LC_{ef}}{L_L * P} + LO_{ef}$$

Where CMP_{ef} is the coal mine operation and coal preparation emission factor, C is the amount of coal mined (59 tonnes), CE_{ef} is the coal electricity production emission factor, CE is the amount of coal-powered electricity required to produce 1 ton of liquid hydrogen ($59 * 10^3$ kWh), Tru_{ef} is the coal transportation by truck emission factor, EC_{ef} is the electrolyzer construction emission factor, E_L is the electrolyzer lifetime (20 years), P is the scenario hydrogen production potential, LC_{ef} is the liquefaction plant construction emission factor, L_L is the liquefaction plant project lifetime (20 years), and LO_{ef} is the liquefaction plant operation emission factor.

3.5. Wind-Powered electrolysis

The wind-powered electrolysis pathway begins with construction of the Jepirachi wind farm, to account for the embodied emissions and water consumption of the recently constructed park. Operation of the turbines produces electricity to power the PEM electrolyzer, however it is assumed that there are no emissions or water consumption associated with operation of the turbines. Two wind-powered electrolysis scenarios are considered in this study: 1) where electrolysis and liquefaction are co-located at the wind farm site and 2) where the

Table 2. Emissions and water consumption impacts of producing 1 tonne of liquid hydrogen.

		Wind (Electrolysis Onsite)	Wind (Electrolysis Offsite)	Coal Electrolysis	Coal Gasification without CCS	Coal Gasification with CCS	Grid-Powered Electrolysis
Emissions to Air	CO_2 (tonne)	6.1	6.1	66	31	11	18
	Methane (g)	1.9E + 03	1.9E + 03	3.3E + 04	1.6E + 04	1.9E + 04	7.1E + 04
	Non-methane VOC (g)	1.3E + 02	1.3E + 02	6.8E + 05	2.1E + 05	2.9E + 05	1.74E + 02
	NOx (g)	1.3E + 04	1.3E + 04	1.9E + 05	1.6E + 04	1.7E + 04	3.5E + 04
	PM 2.5 (g)	9.7E + 02	9.7E + 02	2.0E + 04	1.3E + 03	1.3E + 03	2.9E + 03
	PM 10 (g)	9.5E + 02	9.5E + 02	1.3E + 04	4.3E + 03	5.6E + 03	1.2E + 03
	PM 2.5–10 (g)	3.8E + 02	3.8E + 02	2.9E + 03	4.2E + 02	4.2E + 02	7.1E + 02
	SO_2 (g)	7.7E + 03	7.7E + 03	6.1E + 05	1.4E + 04	1.4E + 04	7.1E + 04
	Arsenic (g)	0.77	0.76	7.5	3.6	3.8	1.5
	Cadmium (g)	0.14	0.14	0.85	0.41	0.43	0.27
	Lead (g)	1.5	1.5	27	19	20	4.4
	Manganese (g)	0.53	0.53	25	40	43	2.9
	Mercury (g)	0.32	0.32	2.2	0.34	0.34	0.50
	Nickel (g)	3.0	2.8	17	36	38	8.8
	Aluminum (mg)	4.2E-03	4.2E-03	3.6E-03	3.4E-03	3.4E-03	3.6E-03
Emissions to Water	Aluminum (g)	1.5	1.5	28	10	13	1.5
	Copper (mg)	4.8E + 02	4.8E + 02	4.8E + 02	4.8E + 02	4.8E + 02	4.8E + 02
	Dissolved Solids (g)	11	11	4.1E + 02	1.4E + 02	1.8E + 02	11
	Fluoride (g)	10	10	90	35	45	13
	Iron (g)	5.3	5.3	59	22	28	7
	Manganese (g)	1.5	1.5	28	9.8	13	1.5
	Nickel (g)	0.18	0.18	2.9	1.1	1.4	0.49
	Nitrogen (mg)	42	41	57	33	33	31
	Oils (mg)	5.1	5.1	5.1	5.1	5.1	5.1
	Inorganic Solids (g)	73	73	2.7E + 03	9.1E + 02	1.2E + 03	73
	Strontium (g)	3.6	3.6	1.4E + 02	45	61	3.6
	Sulfate (g)	5.4E + 03	5.4E + 03	1.9E + 04	1.0E + 04	1.1E + 04	8.9E + 03
	Zinc (g)	9.2E + 02	9.2E + 02	3.5E + 04	1.2E + 04	1.6E + 04	9.2E + 02
	Mercury (m)	2.0	2.0	2.2	2.2	2.2	4.1
	Arsenic (mg)	29	29	29	29	29	29
Emissions to Soil	Iron (mg)	4.0E + 02	4.0E + 02	4.0E + 02	8.3E + 03	8.3E + 03	4.0E + 02
	Lead (mg)	10	10	10	10	10	10
	Cadmium (mg)	0.42	0.42	0.42	0.42	0.42	0.42
	Phosphorous (mg)	1.20E-02	1.3E-02	2.9	1.2E-02	1.2E-02	1.2E-02
	Nitrate (mg)	7.6E-03	8.2E-03	1.8	7.6E-03	7.6E-03	7.5E-03
	Nitrite (mg)	6.3E + 03	6.3E + 03	6.2E + 03	6.2E + 03	6.2E + 03	6.2E + 03
Water Consumption (tonne)		53	52	3.3E + 02	2.2E + 02	2.2E + 02	1.6E + 03

electricity produced from the wind farm is transmitted 7 km to Puerto Bolivar for electrolysis and liquefaction using a proprietary transmission network. These scenarios are represented in figure 3 below:

The electrolysis and liquefaction process performed is assumed to use the same efficiency and electricity requirements of previous steps. Outputs resulting from production of liquid hydrogen from wind energy-powered electrolysis is calculated using the following equation:

Onsite wind electrolysis & liquefaction:

$$\sum \frac{EC_{ef}}{E_L * P} + \frac{T * TC_{ef}}{T_L * P} + Tru_{ef} + \frac{LC_{ef}}{L_L * P}$$

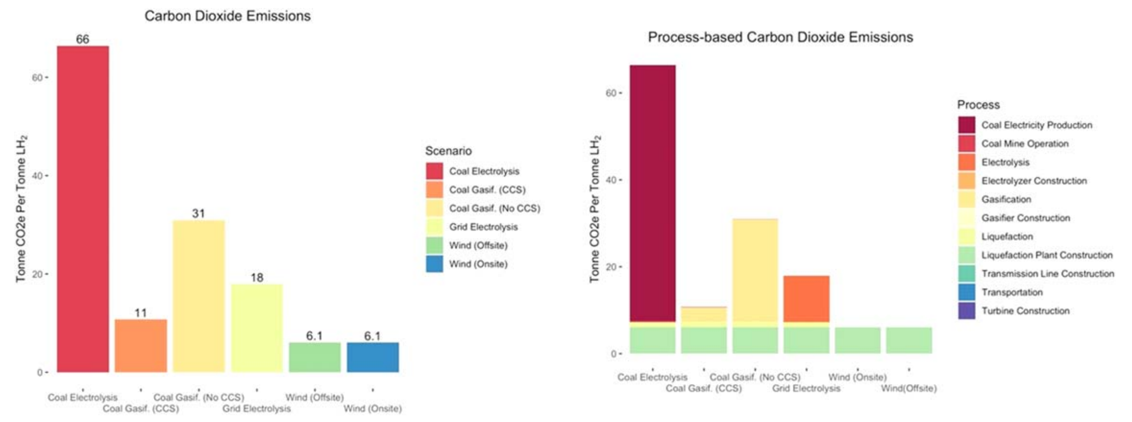

Figure 4. Carbon dioxide emissions per tonne liquid hydrogen produced (Left) and process-based carbon dioxide emissions (Right).

Offsite wind electrolysis & liquefaction:

$$\sum \frac{EC_{ef}}{E_L * P} + \frac{T * T_{ef}}{T_L * P} + \frac{TraC_{ef}}{Tra_L * P} + \frac{LC_{ef}}{L_L * P}$$

Where P is the scenario hydrogen production potential, EC_{ef} is the electrolyzer construction emission factor, E_L is the electrolyzer lifetime (20 years), T is the number of turbines (15 turbines), TC_{ef} is the turbine construction emission factor, T_L is the turbine lifetime (20 years), Tru_{ef} is the cryogenic truck operation emission factor, LC_{ef} is the liquefaction plant construction emission factor, L_L is the liquefaction plant project lifetime (20 years), Tra_{ef} is the transmission line construction emission factor, and Tra_L is the transmission line project lifetime (20 years).

3.6. Grid-powered electrolysis

In the grid-powered electrolysis pathway, Colombia's national electricity grid is used to power the electrolyzer. The study assumes that the HidroItuango dam will be constructed and in operation by the time this process occurs, and that the electricity produced from the dam will supply 17% of the country's electricity consumption. It is assumed that all 2019 levels of electricity production from the country's natural gas, coal, oil, and non-hydro renewables will remain constant. Hydrogen electrolysis and liquefaction are performed using the same assumptions detailed in previous sections. The amount of grid electricity required to produce this hydrogen is calculated using the following equation:

Grid − connected electrolysis & liquefaction:

$$\sum \frac{EC_{ef}}{E_L * P} + EO_{ef} + \frac{LC_{ef}}{L_L * P} + LO_{ef}$$

Where P is the scenario hydrogen production potential, EC_{ef} is the electrolyzer construction emission factor, E_L is the electrolyzer lifetime (20 years), LC_{ef} is the liquefaction plant construction emission factor, L_L is the liquefaction plant project lifetime (20 years), and LO_{ef} is the liquefaction plant operation emission factor.

3.7. Life cycle impacts

Emissions of greenhouse gases, water consumption, and trace metal leeching are calculated through the life cycle inventory ecoinvent database, which provides an open-access and transparent range of environmental life cycle inventory datasets in sectors such as building and construction, energy, and metals (Wernet *et al* 2016). The datasets are supplemented by context specific variables and equipment manuals. Water consumption was calculated to reflect net water consumption based on water outputs deducted from water inputs. Primary materials for the PEM electrolyzer included 528 kg of titanium, 200 kg of stainless steel, 54 kg of aluminum, and 9 kg copper, along with 10,720 kWh of construction electricity requirements. (Evangelisti *et al* 2017, Bareiß *et al* 2019)

4. Results

Clear patterns emerge when comparing the results of the six scenarios against one another (Table 2). Grid-powered water electrolysis has the largest water consumption and methane emissions levels, while coal-powered water electrolysis has the largest emissions of trace metals, air pollutants, and greenhouse gases in almost every other scenario. On-site and off-site wind-powered electrolysis were the lowest emitters in every category, apart

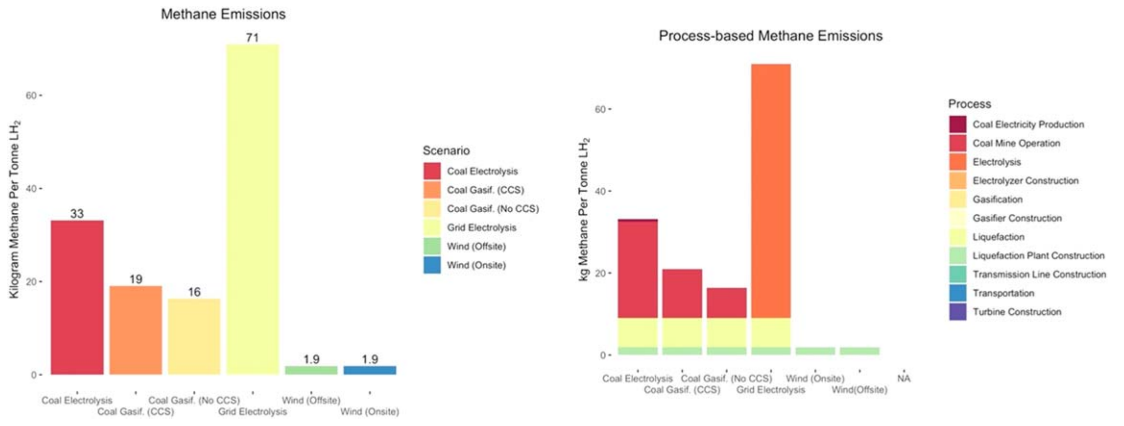

Figure 5. Methane emissions per tonne liquid hydrogen produced (Left) and process-based methane emissions (Right).

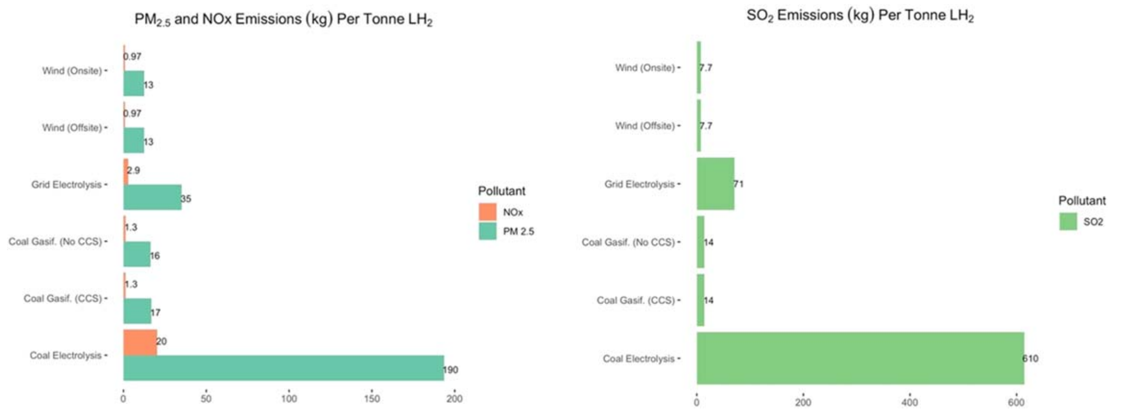

Figure 6. $PM_{2.5}$ and NOx emissions (kg) per tonne liquid hydrogen (Left) and SO_2 Emissions per tonne liquid hydrogen (Right).

from emissions of aluminum to air; nitrogen emissions to water; and phosphorous, nitrate, and nitrite emissions to soil. Siting of the electrolyzer on- or offsite made little difference in all categories.

4.1. Greenhouse gas emissions

The coal electrolysis scenario has the highest estimated carbon dioxide emissions of the five scenarios, emitting an estimated 66 tonnes of carbon dioxide per tonne of liquid hydrogen produced, as shown in figure 4 (left). This is almost eleven times greater than the emissions from the wind electrolysis scenarios. Including carbon capture and storage (CCS) in the coal gasification scenario lowered CO_2 emissions by over 65%, from 31 tonnes to 11 tonnes emitted per tonne LH_2 produced. As shown in figure 4 (right), a process-based emissions analysis indicates that in the coal electrolysis scenario, the electricity production step accounts for 89% of these emissions.

Methane emissions are highest in the grid-powered electrolysis scenario, which produces 71 kg of methane per tonne of liquid hydrogen produced, as shown in figure 5 (left). This due to the natural gas-powered electricity production that comprises 11% of Colombia's national grid mix. As shown in figure 5 (right), the electrolysis process in the grid electrolysis scenario, which is powered by the national grid mix, accounts for 87% of the scenario's methane production. The grid electrolysis scenario produces over twice the amount of methane produced by the coal electrolysis scenario and over thirty-seven times that produced by the wind electrolysis scenarios. Coal gasification with CCS produced 19 kg of methane, about 3 kg more methane per tonne liquid hydrogen than that produced in the coal gasification without CCS scenario. This difference can be attributed to the increased coal inputs required in the CCS scenario, which account for the efficiency losses associated with the CCS process.

4.2. Air pollutant emissions

The coal electrolysis scenario's NOx emissions were almost twelve times greater than that of coal gasification and over fifteen times greater than that of wind electrolysis (see figure 6 left.) It also produced far more SO_2 emissions

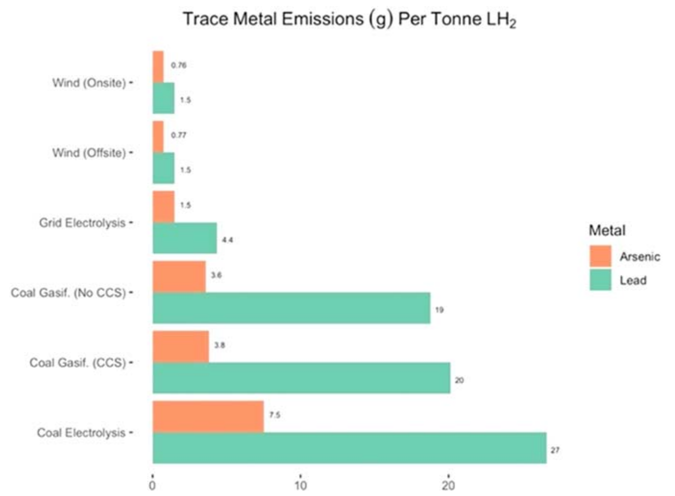

Figure 7. Trace metal emissions per tonne liquid hydrogen.

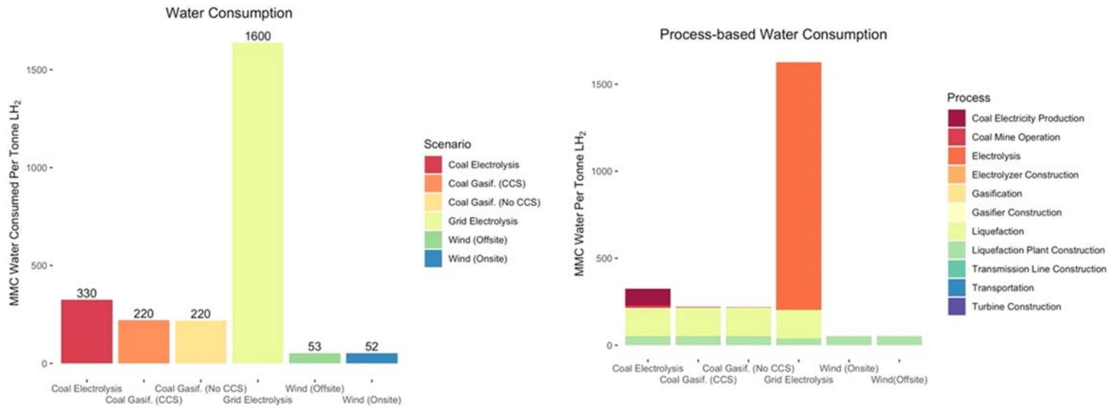

Figure 8. MMC water consumed per tonne liquid hydrogen.

than any other scenario, producing almost nine times the amount of SO_2 produced by grid-powered electrolysis and about eighty times that of the wind-powered electrolysis scenarios, also shown in figure 6 (right). Construction of the liquefaction plant was a large contributor of NOx and SO_2 emissions to all scenarios, comprising almost the entirety of the 13 kg of NOx emissions and the 7.7 kg of SO_2 associated with offsite and onsite wind electrolysis. All coal-powered scenarios produced higher levels of non-methane volatile organic compounds (VOC) and airborne particulate matter. The grid-powered electrolysis scenario also emitted high levels of fine particulate matter, emitting about two times that of the coal gasification scenarios.

4.3. Trace metals leakage

As shown in figure 7, the coal-based scenarios produced the highest levels of arsenic and lead emissions to air, with arsenic emissions from the coal electrolysis scenario that were ten times greater than those of the wind electrolysis scenarios, and lead emissions almost eighteen times greater. Cadmium emissions were also relatively high amongst the coal-based scenarios, with gasification emissions with CCS three times greater than those of the wind-powered electrolysis and coal-based electrolysis emission that were six times greater. Coal-based scenarios were associated with dissolved solids emissions to water that were almost thirty-eight times greater than those of the wind and grid-based electrolysis scenarios.

4.4. Water consumption

Water consumption was highest in the grid-powered electrolysis scenario, which consumed about 1600 million cubic meters (MMC) of water per tonne liquid hydrogen produced, as shown in figure 8 (left). This is due to Colombia's heavy reliance on hydroelectricity to power their national grid mix, assumed to comprise 77% of electricity production after incorporation of the HidroItuango dam. As shown in figure 8 (right), the electrolysis process in the grid electrolysis scenario, which is powered by the national grid mix, accounts for 88% of the scenario's water consumption. While the coal gasification scenarios water consumption levels were far less than that of the grid-powered electrolysis scenario, their consumption levels (~220 MMC) were about four times greater than those of the wind-powered electrolysis scenarios (~ 53 MMC and 52 MMC). It should be noted, however, that while this is the best water consumption data available, there is some uncertainty with regard to the net water consumption figures made available within the ecoinvent database.

5. Discussion

As international coal markets contract with the increasing ambitions of climate change mitigation strategies and internalized social costs of carbon, coal mining communities like those in La Guajira may be tempted to find domestic strategies to consume their remaining coal reserves (Mercure *et al* 2021). One such strategy may be to produce liquid hydrogen using coal as a primary energy source. However, the above results pose serious concerns for the impacts on water consumption, the various trace metals, air pollutants, and greenhouse gasses that liquid hydrogen (LH_2) production could emit depending on the mode through which it is produced, particularly cautioning against coal-based and grid-based LH_2 production scenarios.

Among all categories, coal electrolysis is the least efficient production scenario that Colombia might elect to use for LH_2 production. In terms of its effects on climate change, coal electrolysis produces the most carbon dioxide emissions and second-most methane emissions, amounting to 66 tonne CO_2 eq/tonne LH_2 (US EPA 2015). This is about 35 tonne CO_2 eq/onne LH_2 greater than the CO_2 eq of the coal-gasification without CCS scenario, and 48 tonne CO_2 eq/tonne LH_2 greater than the CO_2 eq of the grid-powered electrolysis scenario (US EPA 2015). To illustrate this impact, if Colombia were to produces 50 tons of hydrogen using coal-based electrolysis, total CO_2 eq emissions could increase by 3.3 Mtonne per year. The study's least emissions-intensive scenarios, the offsite and onsite wind electrolysis scenarios, in contrast would produce approximately 0.3 Mtonne CO_2 eq per year. This difference is significant, considering that Colombia recently declared its increased climate change mitigation ambitions of reducing the intensity of its energy production by 35%, capping the level of its energy sector emissions at 56 CO_2 eq per year. (Gobierno de Colombia 2020).

An analysis of the air pollution impacts of the five scenarios also reveals significant concerns for $SO_{2,}$ NO_x, and PM emissions from scenarios using coal as their primary fuel source. Both SO_2 and NO_x contribute to photochemical smog formation, which not only has detrimental impacts on local ecosystems and agricultural crops, but also contributes to increased incidence of respiratory disease amongst communities (Harte *et al* 1991, US EPA 2015). Previous studies have also documented the annual impact of particulate matter released from operation of the mine, associating it with over 325,000 respiratory symptom cases a year (Aggregocés *et al* 2018). Continued or increased prevalence of these health issues is of great concern, given that they have the potential to affect some of Colombia's most vulnerable communities. Additionally, the prospective agricultural detriments associated with the SO_2 and NO_x emissions could exacerbate the Wayuu's historical agricultural losses from operation and expansion of the El Cerrejón mine (Observatorio Latinoamericano de Conflictos Ambientales 2018).

Disparities between the arsenic, lead, and mercury emission to water levels of the coal-powered scenarios versus the grid- and wind-powered scenarios raise further health concerns for communities in direct proximity of the existing mine. High levels of mercury and arsenic exposure are associated with lung cancer, raising further concerns for communities' respiratory health (Harte *et al* 1991). Mercury may also contribute to mental disorder, and damage to nervous systems (Harte *et al* 1991). Lead has been shown to have severe health effects, including brain damage (especially to children), reduced ability to produce blood cells, and reproductive effects, even at low levels of exposure (Harte *et al* 1991). Both lead and mercury exposure have also been shown to affect kidney health, which is concerning given that aluminum exposure (which is also much greater in the coal-powered scenarios) for individuals with kidney failure can lead to toxic levels of aluminum accumulation (Wills and Savory 1989).

Lastly, coal-based scenarios raise significant concerns for consumption of water resources in La Guajira through LH_2 production. Water consumption levels are an especially important consideration in the region, given that over 50% of the municipalities in La Guajira have been shown to be highly vulnerable to climate change-induced desertification and drought (IDEAM 2018). The grid-electrolysis scenario has by far the highest levels of water consumption, largely due to the water losses associated with hydroelectricity, which is assumed to comprise 77% of the country's electricity grid after construction of the HidroItuango dam. It is important to note that these grid-based water losses will not be entirely concentrated in La Guajira, as the impacts will in theory be dispersed across the regions with the electricity sources powering the national electricity grid. However, it is important to note the climate change resiliency concerns of any system that is heavily reliant on hydroelectricity, given the technology's inherent vulnerabilities to climate change. Other scenarios, like the coal-fueled electrolysis and gasification scenarios would affect La Guajira directly, with the potential to consume an annual 6 million cubic meters (MMC) and 4 MMC, respectively. During an average dry year, this would comprise about 1.5% and 1% of the department's available water resources (IDEAM 2018).

By and large, wind-fueled scenarios have the lowest impact levels across the four categories examined in this study. In most cases, the majority of the impacts associated with wind-fueled LH_2 production are associated with the construction of the liquefaction plant. Similar to the case of the grid-based LH_2 scenario's water consumption levels, the localized impacts from the liquefaction construction phase may not be concentrated in the La Guajira region, depending on whether the materials would be imported into Colombia or manufactured locally. Electrolysis of the hydrogen on-site at the wind park or offsite had little effect on the life-cycle impacts, as impacts did not differ greatly between construction of a dedicated transmission line to transmit the electricity produced to power the electrolyzer or transportation of the electrolyzed and liquefied hydrogen by truck between sites. This set-up could offer distinct advantages across sectors of Colombia's economy—from electricity decarbonization and storage to a hydrogen refueling network for ships and heavy duty vehicles (Kittner *et al* 2021).

In its current form, Colombia's Hydrogen Roadmap emphasizes the importance of hydrogen production for achievement of the country's decarbonization goals. While incorporation of renewables into hydrogen production processes is a stated goal, the current plan notes that 60% of hydrogen consumed in the Industrial sector would come from sources that do not qualify under its 'low-emissions' category, even into 2050. (Minenergía 2021) As noted in this study, should this production come from coal-fueled sources, other impacts that aren't directly noted in the Hydrogen Roadmap, like increases in emissions of air pollutants and trace metals, are likely to arise. These impacts would likely take place alongside greater levels of carbon lock-in resulting from investments into fossil-fuel-based infrastructure that could perpetuate use of fossil fuels in the country long after technological advances support large-scale, cost-efficient adoption of renewable technologies. This possibility is particularly noteworthy when considering that coal-based hydrogen consumption would likely result in larger levels of coal consumption, given that the majority of Colombian coal is currently exported to other countries and therefore not consumed onsite. Future developments to hydrogen strategies and plans to aid communities through a just transition should thus consider these greater holistic implications of any future adopted hydrogen production strategies.

6. Conclusion

This study calculated the greenhouse gas emissions, air pollution, trace metal leakage, and water consumption levels associated with six liquid hydrogen production scenarios using a life cycle assessment to inform hydrogen production's suitability as a just transition strategy. The analysis finds the greatest environmental impacts among scenarios using coal as their primary energy source, especially for CO_2, SO_2, NO_x, mercury, arsenic, and lead emissions. Across all scenarios, localized hazards, like air pollution and trace metal leakage are most concerning for coal-based scenarios, given that most of the processes throughout the life cycle of the liquid hydrogen production would take place locally in the La Guajira region. Other scenarios, like grid-based electrolysis and wind-scenarios, are likely to have their impacts distributed nationally or even internationally. Perhaps the greatest impacts of wind-powered LH_2 production will be those associated with siting decisions for the wind park, particularly given that La Guajira consists of indigenous Wayuu land. Future studies should consider how siting and construction of new wind parks will affect indigenous communities to ensure that future renewable energy development efforts are accompanied by support for Wayuu human rights and general well-being. Further investigation should also be conducted to better inform the hydrogen industry's ability to support a just transition in the wake of a reduction in exported coal, characterizing other factors like potential socio-economic impacts of industry development, as well as its potential to support increased community capabilities and self-sufficiency.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

Aggregocés H A, Rojano R, Angulo L and Restrepo G 2018 Intake fraction of PM10 from coal mine emissions in the North of Colombia *Journal of Environmental and Public Health* **2018** 8532463 (https://hindawi.com/journals/jeph/2018/8532463/)

Bareiß K, de la Rua C, Möckl M and Hamacher T 2019 Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems *Appl. Energy* **237** 862–72

Bataille C *et al* 2020 Net-zero deep decarbonization pathways in Latin America: challenges and opportunities *Energy Strategy Reviews* **30** 100510

Boeder S 2013 At any cost: big coal crushes fragile communities in Colombia *Journal for the Study of Peace and Conflict* **2012** 42–64 (https://www.proquest.com/scholarly-journals/at-any-cost-big-coal-crushes-fragile-communities/docview/1441674763/se-2?accountid=14244)

Bouvart F and Prieur A 2009 Comparison of life cycle GHG emissions and energy consumption of combined electricity and H_2 production pathways with CCS: selection of technologies with natural gas, coal and lignite as fuel for the European HYPOGEN programme *Energy Procedia* **1** 3779–86

Cardoso A and Turhan E 2018 *Political ecology of the new geographies of coal: The coal chain between Colombia and Turkey.* (Quito, Ecuador: Rosa Luxemburg Foundation, Andean Office) (https://diva-portal.org/smash/get/diva2:1273654/FULLTEXT01.pdf)

Cerrejón 2021 Informe de Sostenibilidad(https://cerrejon.com/sites/default/files/2021-08/informe-de-sostenibilidad-2020.pdf)

Cetinkaya E, Dincer I and Naterer G F 2012 Life cycle assessment of various hydrogen production methods—ScienceDirect *Int. J. Hydrogen Energy* **37** 2071–80

Connelly E, Penev M, Elgowainy A and Hunter C 2019 Current status of hydrogen liquefaction cots *DOE Hydrogen and Fuel Cells Program.* **2019** Record #:19001 (https://hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf)

Dawood F, Anda M and Shafiullah G M 2020 Hydrogen production for energy: an overview *Int. J. Hydrogen Energy* **45** 3847–69

Delgado R, Wild T B, Arguello R, Clarke L and Romero G 2020 Options for Colombia's mid-century deep decarbonization strategy *Energy Strategy Reviews* **32** 100525

Delpierre M, Quist J, Mertens J, Prieur-Vernat A and Cucurachi S 2021 Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis *J. Clean. Prod* 299

Departamento Administrativo Nacional de Estadística, Colombia 2019 Pobreza multidimensional Región Caribe 2018 (https://www.dane.gov.co/files/investigaciones/condiciones_vida/pobreza/2019/Boletin_Region_bt_pobreza_multidimensional_19_caribe.pdf)

Departamento Administrativo Nacional de Estadística, Colombia. 2021 *Cuentas nacionales departamentales: PIB por departamento* DANE (https://dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-departamentales)

DOE Hydrogen and Fuel Cells Technologies Office 2021 DOE technical targets for hydrogen production from electrolysis Energy.Gov. (https://energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis)

Dufour J, Serrano D P, Gálvez J L, González A, Soria E and Fierro J L G 2012 Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources *Int. J. Hydrogen Energy* **37** 1173–83

Evangelisti S, Tagliaferri C, Brett D J L and Lettieri P 2017 Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles *J. Clean. Prod* **142** 4339–55

Falkner R 2016 The paris agreement and the new logic of international climate politics *International Affairs* **92** 1107–25

Fueyo Editores 2015 Cerrejón, la explotación de carbón más grande de todo Sudamérica *Fueyo Editores.* (https://fueyoeditores.com/rocas-y-minerales/articulos-tecnicos-rocas-y-minerales/714-cerrejon-la-explotacion-de-carbon-mas-grande-de-todo-sudamerica)

Gardiner M 2009 Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs *DOE Hydrogen and Fuel Cells Program.* (https://hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf)

Giurco D, Cohen B, Langham E and Warnken M 2011 Backcasting energy futures using industrial ecology *Technol. Forecast. Soc. Change* **78** 797–818

Gobierno de Colombia 2020 Actualización de la Contribución Determinada a nivel nacional de Colombia (NDC) (https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Colombia%20First/NDC%20actualizada%20de%20Colombia.pdf)

Gray D and Tomlinson G 2002 Hydrogen from coal (Miretek Technical paper No. 2002–31) (https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.143.5431&rep=rep1&type=pdf)

Harte J, Holdren C, Schneider R and Shirley C 1991 Toxics A to Z: a guide to everyday pollution hazards(https://www.ucpress.edu/book/9780520072244/toxics-a-to-z)

Healy N and Barry J 2017 Politicizing energy justice and energy system transitions: fossil fuel divestment and a 'just transition *Energy Policy* **108** 451–9

Iannuzzi L, Hilbert J A and Silva Lora E E 2021 Life cycle assessment (LCA) for use on renewable sourced hydrogen fuel cell buses vs diesel engines buses in the city of Rosario, Argentina *Int. J. Hydrogen Energy* **46** 29694–705

IDEAM 2018 Reporte de avance del Estudio Nacional del Agua 2018. Instituto de Hidrología, Meterología y Estudios Ambientales (http://ideam.gov.co/documents/24277/76321271/Cartilla+ENA+2018+WEB+actualizada.pdf/ba353c39-b15d-4a76-8ed4-3814c4c35239)

International Energy Agency 2018 Electric power transmission and distribution losses (% of output)—Colombia (https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=CO)

Jakob M *et al* 2019 Green fiscal reform for a just energy transition in Latin America *Economics* **13** 20190017

Kaskun S 2020 An overview of hydrogen-rich gas production from biomass by using thermal technologies *IOP Conf. Ser.: Earth Environ. Sci* **614** 012010

Kaskun S, Akinay Y and Kayfeci M 2020 Improved hydrogen adsorption of ZnO doped multi-walled carbon nanotubes *Int. J. Hydrogen Energy* **45** 34949–55

Kaskun S and Kayfeci M 2018 The synthesized nickel-doped multi-walled carbon nanotubes for hydrogen storage under moderate pressures *Int. J. Hydrogen Energy* **43** 10773–8

Kittner N, Castellanos S, Hidalgo-Gonzalez P, Kammen D M and Kurtz S 2021 Cross-sector storage and modeling needed for deep decarbonization *Joule* **5** 2529–34

Koroneos C 2004 Life cycle assessment of hydrogen fuel production processes *Int. J. Hydrogen Energy* **29** 1443–50

Lazarus M and van Asselt H 2018 Fossil fuel supply and climate policy: exploring the road less taken *Clim. Change* **150** 1–13

Mercure J -F *et al* 2021 Reframing incentives for climate policy action *Nat. Energy* **6** 1133–43

Minenergía 2021 Hoja de Ruta del Hidrógeno en Colombia (https://minenergia.gov.co/documents/10192/24302627/Hoja+de+Ruta+H2+Colombia_Borrador.pdf)

Moreira dos Santos R, Szklo A, Lucena A F P and de Miranda P E V 2021 Blue sky mining: strategy for a feasible transition in emerging countries from natural gas to hydrogen *Int. J. Hydrogen Energy* **46** 25843–59

Muresan M, Cormos C C and Agachi P S 2014 Comparative life cycle analysis for gasification-based hydrogen production systems *J. Renewable Sustainable Energy* **6** 013131

Observatorio Latinoamericano de Conflictos Ambientales 2018 La lucha de los wayuu contra la mina de carbón del Cerrejón (http://olca.cl/articulo/nota.php?id=107340)

Oei P -Y and Mendelevitch R 2019 Prospects for steam coal exporters in the era of climate policies: a case study of Colombia *Climate Policy* **19** 73–91

Petitpas G 2018 Boil-off losses along LH2 pathway (LLNL-TR–750685, 1466121; p. LLNL-TR–750685, 1466121)

Pye S, Hughes N, Rodriguez B S, Tomei J and Marini A 2021 *Shaping fossil fuel extraction strategies in developing countries in a decarbonizing world*. 7(https://www.ucl.ac.uk/bartlett/sites/bartlett/files/shaping_fossil_fuel_extraction_strategies_in_developing_countries_in_a_decarbonizing_world_-_policy_brief.pdf)

Ramirez A D, Boero A, Rivela B, Melendres A M, Espinoza S and Salas D A 2020 Life cycle methods to analyze the environmental sustainability of electricity generation in Ecuador: is decarbonization the right path? *Renew. Sustain. Energy Rev.* **134** 110373

Scolaro Michele and Kittner Noah 2022 Optimizing hybrid offshore wind farms for cost-competitive hydrogen production in Germany *International Journal of Hydrogen Energy* **47** 6478–93

Shan R, Reagan J, Castellanos S, Kurtz S and Kittner N 2022 Evaluating emerging long-duration energy storage technologies *Renew. Sustain. Energy Rev.* **159** 112240

Sistema Nacional de Información Cultural (SINIC) 2021 Colombia Cultural: Polbación—La Guajira. SINIC (http://sinic.gov.co/SINIC/ColombiaCultural/ColCulturalBusca.aspx?AREID=3&SECID=8&IdDep=44&COLTEM=216)

Strambo C and Atteridge A 2018 How Colombia can plan for a future without coal [SEI policy brief] Stockholm Environment Institute (https://sei.org/publications/colombia-can-plan-future-without-coal/)

Strambo C and González Espinosa A C 2020 Extraction and development: fossil fuel production narratives and counternarratives in Colombia *Climate Policy* **20** 931–48

US EPA, O. 2015 Tool for reduction and assessment of chemicals and other environmental impacts (TRACI) [Data and Tools]. (https://epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci)

Utgikar V and Thiesen T 2006 Life cycle assessment of high temperature electrolysis for hydrogen production via nuclear energy *Int. J. Hydrogen Energy* **31** 939–44

Vergara W *et al* (ed) 2010 *Wind energy in Colombia: A framework for market entry*. (World Bank Study: World Bank) (https://openknowledge.worldbank.org/handle/10986/2493)License: CC BY 3.0 IGO

Verma A and Kumar A 2015 Life cycle assessment of hydrogen production from underground coal gasification *Appl. Energy* **147** 556–68

Virgüez J C R 2011 *Análisis del impacto medio ambiental de El Cerrejón a partir de sus informes GRI* **2005–2009** 57 (https://repository.javeriana.edu.co/bitstream/handle/10554/9468/tesis565.pdf)

Wang Y, Li G, Liu Z, Cui P, Zhu Z and Yang S 2019 Techno-economic analysis of biomass-to-hydrogen process in comparison with coal-to-hydrogen process *Energy* **185** 1063–75

Weber G and Cabras I 2021 Environmental justice and just transition in the EU's sustainability policies in third countries: the case of Colombia *The International Spectator* 1–19

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E and Weidema B 2016 The ecoinvent database version 3 (part I): overview and methodology *The International Journal of Life Cycle Assessment [Online]* **21** 1218–30

Wills M R and Savory J 1989 Aluminum and chronic renal failure: sources, absorption, transport, and toxicity *Critical Reviews in Clinical Laboratory Sciences* **27** 59–107

Integrating BECCS and natural gas production for carbon neutrality in the Paraná Basin, Brazil: Favorable areas and regional CO_2 storage capacities

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Abstract

Considering the latest climate commitments pledged by Brazil during the COP26 in 2021, and that the country is currently the second largest CO_2 emitter of Latin America, this study proposes the implementation of a BECCS – natural gas integration strategy for the decarbonization of its most industrial- and carbon-intensive region (the South-Southeastern Region). Further, acknowledging the lower CO_2 emissions contributions of the natural gas and its backup role for renewable energy intermittency, integrating BECCS technologies with this fossil fuel production is a compelling strategy for Brazil that is one of the global leaders in the bioenergy sector. Therefore, to offer exploratory opportunities, this study conducted a site selection of favorable areas for the implementation of BECCS – natural gas integrated systems in reservoirs of the Irati Formation in the Paraná Sedimentary Basin. The study also offers regional estimations of CO_2 storage capacity to help comprehend the CO_2 storage potential of the South-Southeastern Region identifying feasible reservoirs for BECCS systems coupled to natural gas production in the Paraná Basin. The methodology of this study uses ANP well information, machine learning algorithms and spatial data analysis to evaluate the BECCS and natural gas potential of the Paraná Basin and to map the most favorable areas. Also, local CO_2 storage capacities were engaged to calculate regional estimations of CO_2 storage capacities. In addition, an analysis and discussion of the environmental, economic, policy and regulatory aspects is provided. The findings verified the suitability of the Irati Formation as reservoir for BECCS – natural gas integrated systems in a highly prospective area that complies with the technical and environmental requirements; has an extension of 49.500 km^2 covering the states of São Paulo, Paraná and Mato Grosso do Sul (with the state of São Paulo having the biggest potential); and has an average regional capacity of 103.60 $GtCO_2$ (P10 = 93.24; P50 = 51.80; P90 = 10.36). Finally, this study helps comprehend the CO_2 storage potential of the South-Southeastern Region and intends to serve as a guide for decision-makers to anticipate the possible transboundary problems and proper adaptations required for a successful implementation of a BECCS – natural gas integration strategy that also favors the achievement of a Brazilian carbon neutrality by 2050. As recommendation, future studies are encourage regarding public perception and social programs that guarantee sustainable activities in the proposed favorable areas of the Paraná Basin, the most carbon-intensive region of Brazil.

Keywords: BECCS, Natural Gas, CO2 Storage Capacity, Irati Formation, Paraná Basin, Carbon Neutrality, Brazil.

1. Introduction

Our society faces the need of achieving negative CO_2 emissions by 2050 to effectively comply with the climate targets set under the Paris Agreement. To do so, without negatively affecting the global energy supply, it is required a deep decarbonization of the energy sector driven by realistic CO_2 mitigation strategies. In this regard, to accelerate the energy transition and reach negative CO_2 emissions, the international energy experts urge the widespread deployment of the carbon capture and storage (CCS) technologies, together with the increase of natural gas use.

The CCS technologies refer to an array of techniques through which the CO_2 is separated from industrial and energy production sources (including the bioenergy generation); then compressed into a supercritical phase; transported to a safe location; and finally, injected into deep rock formations for permanent storage (IPCC, 2005). Notably, the CCS technologies can be easily integrated and retrofitted into both the oil and gas and the bioenergy operations (GCCSI, 2016).

The integration of bioenergy production and CCS, also known as BECCS, is key to achieve net-negative CO_2 emissions under the IPCC's 2°C scenario (FUSS et al., 2014; IEA, 2019; BABIN et al., 2021). BECCS systems offer an expressive reduction of the elevated costs of the CO_2 capture and treatment process because the bioethanol production effluents are 99% rich in CO_2, which represents an optimization and cost reduction of the CO_2 capture and treatment process (GEF, 2009; SMEETS & FAAIJ, 2010; PELISSARI et al., 2020).

In this context, considering the lower CO_2 emissions contributions of the natural gas and its backup role for renewable energy intermittency, integrating BECCS with natural gas operations is a compelling CO_2 mitigation strategy. Adopting the BECCS – natural gas strategy may help Brazil honor its latest climate commitments pledged during the COP26. Moreover, Brazil may have an advantage for the development of such strategy in its most carbon- and industrial-intensive region; the South-Southeastern Region that encompasses the Paraná Sedimentary Basin and that holds most of the CO_2 emissions from stationary sources of the country, especially from sugarcane and bioethanol mills and thermoelectric power plants (**Figure 1**).

The relevance of the Paraná Sedimentary Basin relies in its total area of approximately 1,100,000 km^2 in Brazilian territory and 100,000 km^2 in Uruguay, Argentina and Paraguay. The basin has an extensive sedimentary stack of approximately 8000 m, with records ranging from the Neo-Ordovician to the Neo-Cretaceous, harboring different types of sedimentary and igneous rocks, which reflect different sedimentation environments throughout the Basin's complex history (MILANI et al., 1998).

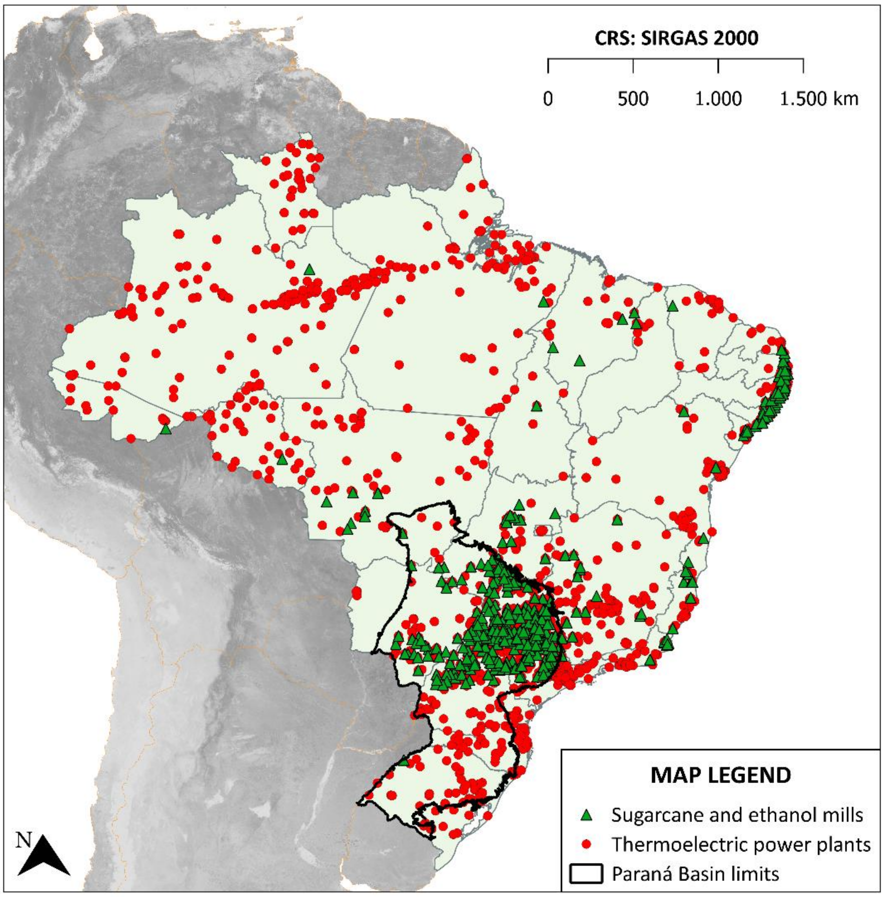

Figure 1. *Map of the location of the sugarcane and bioethanol mills, and thermoelectric power plants in Brazil. Highlighting the boundaries (black line) of the Paraná Sedimentary Basin (area of study). Source: produced by the authors.*

The implementation of BECCS systems in the Paraná Sedimentary Basin could be benefited by the prioritization regarding CO_2 mitigation and environmental impacts adopted by the Brazilian bioethanol sector, with estimations that sugarcane systems could offset 86% of CO_2 emissions compared to oil use (JAISWAL et al., 2017; PELISSARI et al., 2020). However, to develop the BECCS – natural gas strategy, the country still faces the lack of internal natural gas offer near the biggest consumers and the need for a market liberalization (FGV ENERGIA, 2019).

Nevertheless, Brazil already has proper conditions to develop the BECCS – natural gas strategy, especially in the Paraná Sedimentary Basin, as follows:

- It has been the only Latin American nation considered ready for the wide-scale deployment of CCS projects, together with Canada, Norway and United States (GCCIS, 2015);
- It is the second largest CO_2 emitter of Latin America (RITCHIE & ROSER, 2020);
- It has a huge potential for CO_2 geological carbon storage (KETZER et al., 2016; MUSARRA et al., 2022));

- It is the second world’s largest biofuel producer, and together with the United states, is responsible for 70% of the global production (DE SOUZA ABUD & DE FARIAS SILVA, 2019);
- It has reservoirs with high prospectivity for natural gas production (SAN MARTÍN CAÑAS, 2020; ROCHA, 2021; TASSINARI et al., 2021).

Therefore, acknowledging the urgent necessity for Brazil to decarbonize its South-Southeastern Region and to offer exploratory opportunities to address its growing natural gas demand, the purpose of this study is to select the most favorable areas for the integration of BECCS and natural gas production in reservoirs of the Irati Formation in the Paraná Sedimentary Basin. It also offers the regional (basin-scale) estimations of CO_2 storage capacity associated to the most favorable areas. The methodological approach for favorable area selection combined machine learning algorithms and spatial data analysis considering their relevance to address the difficulties for an effective data integration in new frontier basins with insufficient data, as it is the case of the Paraná Sedimentary Basin. Finally, the study intends to identify the main challenges regarding the environmental, economic, policy and regulatory implications regarding the implementation of a BECCS – natural gas integration strategy in the most carbon-intensive region of Brazil.

2. Methodology

The assessment of the potential for an implementation of a BECCS – natural gas integration strategy in the Paraná Sedimentary Basin was based on:

- The analysis of well information from the National Agency for Petroleum, Natural Gas and Biofuels (ANP) and bibliographical sources for the verification of the suitability of the Irati Formation for shale gas (as a source of natural gas) and CO_2 geological storage. These data serve as input for the geological evaluation of the Irati Formation intended to verify the existence of an active petroleum system, and if the unit comply with the minimum requirements for shale gas (as source of natural gas) and CO_2 geological storage.
- The site selection of favorable areas using a spatial data analysis that integrated previous machine learning predictions from San Martín Cañas (2020), that identified the most favorable areas for the co-development of shale gas and CO_2 geological storage in the Irati Formation using the K-Nearest Neighbor and Support Vector Machine algorithms; the georeferenced data of sugarcane and bioethanol mills operating across Brazil; the influence areas of the available infrastructure for natural gas and bioethanol transportation, GASBOL pipeline and LOGUM pipeline system respectively (i.e., the influence areas (100 and 200 km) were set according to the economic feasibility parameters for CO2 transportation and storage costs (NETL, 2019)).
- The calculations of regional estimations of CO_2 storage capacity based on the an extrapolation of the local CO_2 storage capacities proposed by Abraham- A and Tassinari (2021) and De Oliveira et al. (2021) using the application of the

volumetric approach from Bachu et al. (2007). Additionally, considering the P90-P50-P10 probabilistic approach, three risked capacity estimations (i.e., high, medium and lower estimations) were calculated for each regional baseline estimation scenario.

3. The BECCS – natural gas integration strategy in the Paraná Basin

3.1. Favorable areas for BECCS – natural gas systems in reservoirs of the Irati Formation and associated regional CO_2 storage capacity

The ANP well information and relevant bibliographical sources (ROCHA, 2016; MABECUA et al., 2019; PELISSARI et al., 2020; ROCHA, 2021; TASSINARI et al., 2021; DE OLIVEIRA et al., 2022) validated the suitability of the Irati Formation as a reservoir under a BECCS – natural gas integration strategy to be implemented in the Paraná Sedimentary Basin.

The Irati Formation, dating from the Permian, is made up of shales enriched in amorphous organic matter that may contain carbonate lenses and dolomitic limestones. Geochemical analysis revealed that the total organic content (TOC) of the formation varies from 0.1% to 23%, with an average of 2.0% (ROCHA, 2016). The Irati Formation presents a low degree of thermal evolution, with the exception of the depocenter of the basin (central rift), where it can reach high values of maturation due to the influence of intrusive magmatic bodies (ARTHUR & SOARES, 2002; MILANI, 2004; AZEVEDO DA SILVA, 2007). The formation is subdivided into two members: Taquaral and Assistência. The Taquaral Member is composed of silty-clayey, non-bituminous, grayish shales with lenticular carbonate interleaves and silex nodules. It varies from 5 to 10 meters of thickness in the marginal areas of the basin and reaches 30 meters in central portions (HACHIRO, 1996). The Taquaral Member was deposited under low to moderate oxygenation conditions, below the storm wave base (ARAÚJO et al., 2001; GOLDBERG & HUMAYUN, 2016). The Assistência Member consists of clayey, bituminous shales, gray-dark to black, locally interbedded with carbonate beds. Its depositional environment ranged from shallow-water and subaerially exposed to stratified and anoxic conditions (ARAÚJO, 2001; GOLDBERG & HUMAYUN, 2016). The thickness of this package varies between 10 and 20 meters in the margins and reaches approximately 40 meters in the basin depocenter (HACHIRO, 1996; MILANI, et.al., 2007).

The Irati Formation has been proven as the main source rock of one of the main conventional petroleum systems in the Paraná Sedimentary Basin, called Irati – Rio Bonito/Piramboia (I-RB/P). The unit has been proven as the main source rock of the conventional petroleum system Irati – Rio Bonito/Piramboia (I-RB/P) (ARAÚJO et al., 2000; ANP, 2017; EPE, 2019), as well as a highly prospective shale gas reservoir for natural gas production (ROCHA, 2016; MABECUA et al., 2019; ROCHA, 2021; TASSINARI et al., 2021). Furthermore, Rocha (2016) and Tassinari et al. (2021) based on comparative analyses indicate that the Irati Formation exhibit similar characteristics with the Barnett, Marcellus, and Eagle Ford Formations that are excellent shale gas producers in the United States. Additionally, recent studies (SAN MARTÍN CAÑAS, 2020; ABRAHAM-A & TASSINARI, 2021; ROCHA, 2021; DE OLIVERIRA et al., 2021; DE OLIVERIRA et al., 2022; SAN MARTÍN

CAÑAS, 2022) have demonstrated that the Irati Formation comply with the technical and environmental requirements for safe natural gas production and CO_2 storage operations because there is a close relationship between its shale gas and CO_2 geological storage potential resulting in excellent opportunities for the BECCS – natural gas strategy, especially in the central region of the Paraná Sedimentary Basin encompassing the states of São Paulo, Paraná and Mato Grosso do Sul (**Figure 2**).

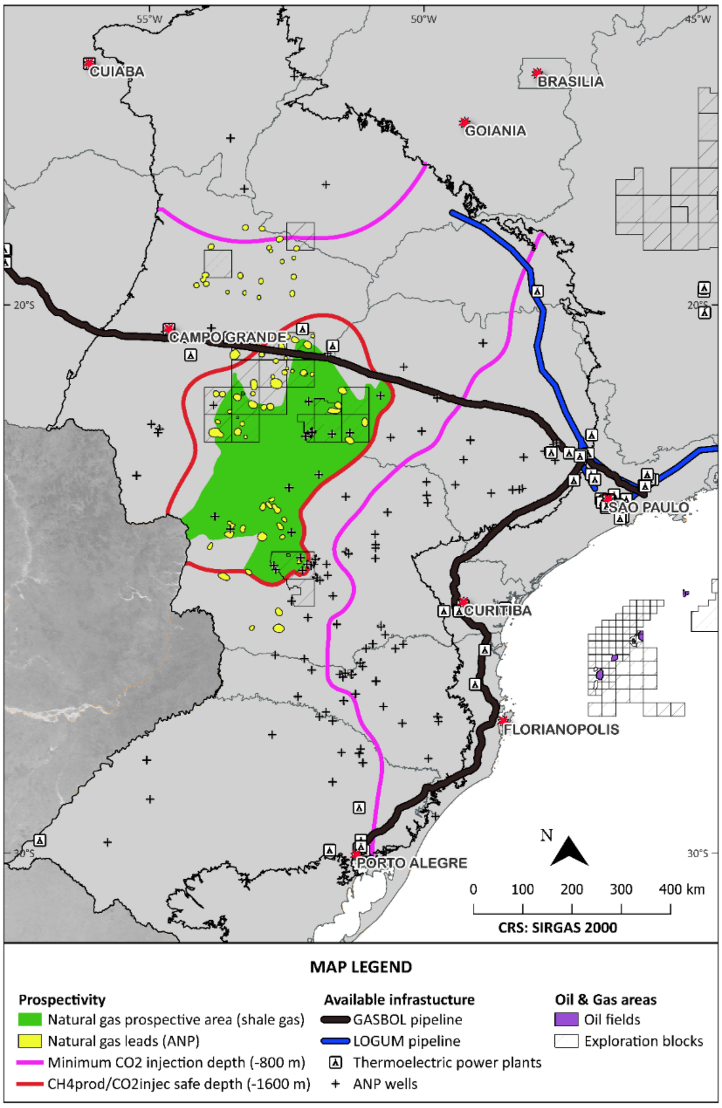

Figure 2. *Map of favorable areas for natural gas production and CO2 geological storage in reservoirs of the Irati Formation based on machine learning algorithms (K-Nearest Neighbor and Support Vector Machine). Source: Produced by the authors based on previous predictive mapping from San Martín Cañas (2020) and (2022), and gas leads from previous ANP bidding rounds 12th(2013), 14th (2017) and 15th (2018).*

In the case of bioenergy potential, the study area holds 270 sugarcane and bioethanol mills in the states of Goiás, Mato Grosso do Sul, Minas Gerais, Paraná, and São Paulo. Moreover, São Paulo has the highest bioenergy potential because its production accounts for around 51% of the total Brazilian sugarcane production (OBSERVATÓRIO DA CANA, 2022). Further, considering the objective of selecting feasible areas for the implementation of a BECCS – natural gas integration strategy, **Figure 3** shows that 244 sugarcane and bioethanol mills are prospective and locate within the infrastructure influence area. It is worth nothing that the prospectivity of these mills was considered under the premise that future BECCS – natural gas systems would be interlinked with the GASBOL and LOGUM pipelines to reduce the overall cost of CO_2 transport, if the pipeline operational requirements are complied.

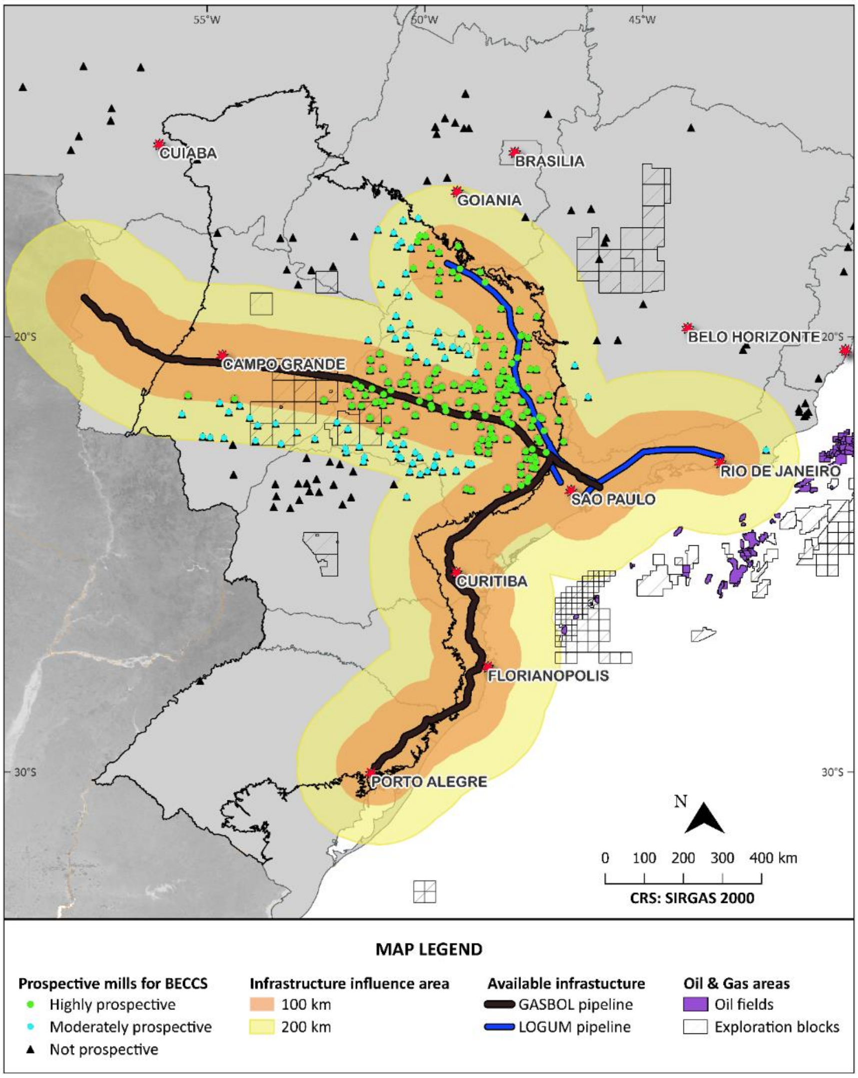

Figure 3. *Map of prospective sugarcane and bioethanol mills for BECCS systems in the Paraná Basin from a logistic point of view. The sugarcane and bioethanol mills that are prospective for BECCS systems are displayed in green colour. Source: Produced by the authors.*

The final site selection of most favorable areas (**Figure 4**) considered that the very high prospective area locates within the infrastructure influence areas of 100 km from the GASBOL and LOGUM pipelines. The high prospective area locates within the infrastructure influence areas of 200 km. in total, the most favorable areas have an extension of 49.500 km^2 and a total average CO2 storage capacity of 103.60 $GtCO_2$ (the estimations for all calculated scenarios are presented in **Table 1**).

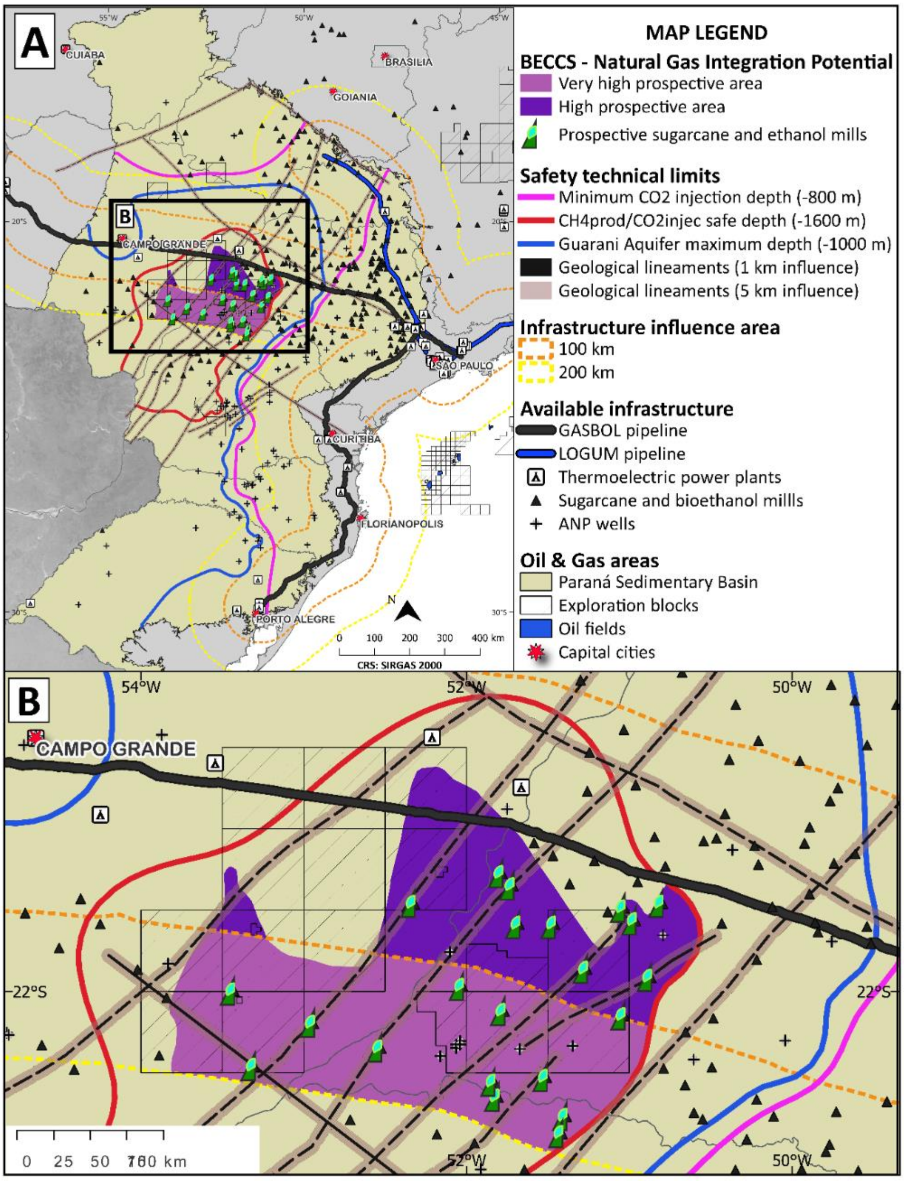

Figure 4. *Feasible areas (very high and high prospectivity) that offer opportunities for a BECCS – natural gas integration strategy in reservoirs of the Irati Formation in the Paraná Sedimentary Basin. A: map of opportunities for the entire Paraná Basin, B: Zoom to the feasible areas located in the states of São Paulo, Mato Grosso do Sul, and a small portion of Paraná. Source: Produced by the authors.*

Table 1. *Scenarios for regional estimations of CO2 storage capacity of the Irati Formation in the most favorable areas of the Paraná Basin. In green: the average value for regional capacity.*

Scenario	**Regional estimations of CO_2 storage capacity**			
	Baseline	**Higher**	**Medium**	**Lower**
	(not risked)	(p10)	(p50)	(p90)
1	156.33	140.70	78.16	15.63
2	50.88	45.79	25.44	5.90
Average	103.60	93.24	51.80	10.36

From all the prospective areas, it is evident that the Southwestern region of the state of São Paulo is the most attractive for an implementation of a BECCS – natural gas integration strategy, considering that offers the most of the extension for natural gas production, its proximity to the GASBOL pipeline, which may guarantee a proper natural gas flow, and holds 15 sugarcane and bioethanol mills (out of a total of 22) with high prospectivity from a logistic point of view. Also, the prospective areas in São Paulo comply with the requirements for safe natural gas production and CO_2 geological storage that technically guarantee the preservation of the Guarani Aquifer System. Further, the economic viability of a BECCS – natural gas strategy in São Paulo may be favored from the optimal infrastructure conditions (e.g., good roads, major highways, railways) that can enable faster project deployments resulting in revenues and future royalties derived from the consolidation of an onshore natural gas market, together with the development of a carbon market.

3.2. Challenges for a BECCS – natural gas integration strategy in the Paraná Basin

Although, as seen in the previous section, there are feasible opportunities to successfully implement a BECCS – natural gas integration strategy in the Paraná Sedimentary Basin, some challenges need to be overcome for both the oil & gas and bioenergy sectors in Brazil, especially the legal challenges considering that the country's CCUS legal framework is still under development and has not been yet implemented. In this context, the REATE 2020 efforts on making onshore petroleum data publicly available have helped the exploratory studies for natural gas and CO_2 geological storage potential, investments are still required for new seismic surveys acquisition, exploratory wells, core samples and bore logging, at least, inside the highly prospective areas delineated in **Figure 4**.

Moreover, these highly prospective areas already indicate that the future legal frameworks must address the transboundary aspects of CCUS projects (i.e., interstate tax regulation, gas pipelines, CO_2 plume and migration) considering that the geological risks and long-term liabilities concerning risk allocation and liability uncertainties are the main regulatory barriers for large-scale deployment of such a decarbonization strategy in Brazil (ROCHA & COSTA, 2021), and specially for the BECCS – natural gas integration strategy proposed in this study regarding the heterogeneities between the jurisdictions of São Paulo, Paraná and Mato Grosso do Sul. Further, as the CCS technologies remain as the most expensive part of the value chain in the BECCS – natural gas strategy, the implementation of fair conditions and incentives from the governmental institutions are required to accelerate the creation of successful Brazilian natural gas and carbon markets. Further, public and private entities must cooperate in favour of a safe legal environment for carbon capture and storage operations in Brazil (NUNES & COSTA, 2019).

Regarding the challenges faced by the bioenergy sector associated to the bioethanol production and the wide scale deployment of BECCS systems, the most important are the use of extensive areas and large volumes of water for irrigation of sugarcane cultures, as well as high demand of fertilizers; the crop production may involve land clearing which can reduce or reverse the expected carbon removal potential; the possibility of competition or overlapping with land for food production and forest creation; the need of innovation, and clear policies and regulations, for biofuels production to increase its share in the fuel markets with competitive prices; the rapid development of capabilities that allow proper integration of CO_2 geological storage operations, together with the need for infrastructure to capture and transport the CO_2 until its final storage site (MARIN et al., 2016; SALLES-FILHO et al., 2017; BORDONAL et al., 2018; CARDOZO et al., 2018; PARENTE & FERREIRA, 2018; GCCSI, 2019; PELISSARI et al., 2020).

Additionally, regarding the policy and economic aspects, the Brazilian bioenergy sector still needs to address the lack of incentives as this constitutes the main barrier for the implementation of BECCS (BELLAMY et al., 2021), and should follow as example the experience of countries like the United States, Sweden and the United Kingdom that are prioritizing the discussion of government-led incentives for BECCS in their political agendas (BRIGHT, 2021; MÖLLERSTEN et al., 2021). In this context, in Brazil, the Renovabio Programme, which is a policy that aims at incrieasing the share of biofuels in the coutnry's energy consumption, determined a 20% bonus on the Decarbonisation Credit (CBio) for the biofuel producers whose product delivered negative emissions (BRASIL – PRESIDÊNCIA DA REPÚBLICA, 2017). However, the lack of clear regulations for the operation of BECCS in the country - for example regarding long-term storage liability - prevents projects from being implemented. Fortunately, this barrier is being addresses under the Future Fuel Programme, in which the goal of the ProBioCCS Subcommittee is to stablish the regulatory conditions for implementing CCS in Brazil (BRASIL – PRESIDÊNCIA DA REPÚBLICA, 2021).

4. Concluding Remarks

The findings verified the suitability of the Irati Formation as reservoir for an integration of BECCS and natural gas production in the Paraná Sedimentary Basin. The most favourable areas comply with the technical and environmental requirements and encompass an area of 49.500 km^2 including the states of São Paulo, Paraná and Mato Grosso do Sul; with the state of São Paulo being the most prospective. Also, the total suitable area has an average capacity of 103.60 $GtCO_2$ (P10 = 93.24; P50 = 51.80; P90 = 10.36) and contains 22 sugarcane and bioethanol mills.

The findings of study help comprehend the potential of the South-Southeastern Region for an integration of BECCS and natural gas production as a decarbonization strategy. Also, it may serve as a guide for decision-makers to anticipate the possible transboundary problems and proper adaptations required for a successful implementation of a BECCS – natural gas integration strategy in the most industrial- and carbon-intensive region in Brazil (the Paraná Sedimentary Basin) that helps honor the country's latest climate commitments pledged during the COP26 and also favor the achievement of a Brazilian carbon neutrality by 2050. As recommendation, future studies are encourage regarding public perception and social programs that guarantee sustainable activities in the proposed favorable areas of the Paraná Basin, the most carbon-intensive region of Brazil.

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References

ABRAHAM-A, R.M., TASSINARI, C. C. G. (2021). CO2 storage algorithms involving the hybrid geological reservoir of the Irati Formation, Parana Basin. International Journal of Greenhouse Gas Control, 112: 103504. https://doi.org/10.1016/j.ijggc.2021.103504.

AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS – ANP (2017). BACIA DO PARANÀ: Sumário Geológico e Setores em Oferta, Superintendência de Definição de Blocos (SDB).

ARAÚJO, L. M., TRIGÜIS, J. A., CERQUEIRA, J. R., FREITAS, L. C. D. S. (2000). The Atypical Permian Petroleum System of the Paraná Basin, Brazil, In: Mello, M. R., Katz, B. J. (Eds.), Petroleum systems of South Atlantic margins: AAPG Memoir 73, pp.377-402.

ARTHUR, P.C., SOARES, P.C. (2002). Revista Brasileira de Geociências. 32 (4), pp.433-448.

AZEVEDO DA SILVA, C. G. (2007). Caracterização geoquímica orgânica das rochas geradoras de petróleo das formações Irati e Ponta Grossa da Bacia do Paraná.

DE OLIVEIRA, S. B., TASSINARI, C. C. G., ABRAHAM-A, R. M., TORRESI, I. (2021). 3D implicit modeling applied to the evaluation of CO2 geological storage in the shales of the Irati Formation, Paraná Basin, Southeastern Brazil. Greenhouse Gas Sci Technol, 11: 1024-1042. https://doi.org/10.1002/ghg.2111.

BABIN, A., VANEECKHAUTE, C., ILIUTA, M.C. (2021). Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review. Biomass and Bioenergy 146. https://doi.org/10.1016/j.biombioe.2021.105968

BELLAMY, R., FRIDAHL, M., LEZAUN, J., PALMER, J., RODRIGUEZ, E., LEFVERT, A., HANSSON, A., GRÖNKVIST, S., HAIKOLA, S. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: Comparing stakeholder policy preferences in the United Kingdom and Sweden. Environ. Sci. Policy 116, 47–55. https://doi.org/10.1016/j.envsci.2020.09.022

BORDONAL, R. O., CARVALHO, J. L. N., LAL, R., DE FIGUEREIDO, E. B., DE OLIVEIRA, B. G., LA SCALA JR, N. (2018). Sustainability of sugarcane production in Brazil. A review, Agronomy for Sustainable Development 38, 13. https://doi.org/10.1007/s13593-018-0490-x

BRIGHT, M. (2021). Surveying the U.S. Federal CCS Policy Landscape in 2021. Global CCS Institute.

CARDOZO, N. P., BORDONAL, R. O., LA SCALA JR, N. (2018). Sustainable intensification of sugarcane production under irrigation systems, considering climate interactions and agricultural efficiency, Journal of Cleaner Production 204, pp. 861-871. https://doi.org/10.1016/j.jclepro.2018.09.004

EMPRESA DE PESQUISA ENERGÉTICA – EPE (2019). Zoneamento Nacional de Recursos de Óleo e Gás, Ciclo 2017-2019 / Ministério de Minas e Energia, Brasília.

DE SOUZA ABUD, A.K., DE FARIAS SILVA, C.E. (2019). Bioethanol in Brazil: status, challenges and perspectives to improve the production. In: Ray, R.C. & Ramachandran, S., Bioethanol Production from Food Crops. Academic Press, 417-443. https://doi.org/10.1016/B978-0-12-813766-6.00021-7

FGV ENERGIA (2019). O novo mercado de gás natural: opiniões de especialistas, perspectivas e desafios para o Brasil, Caderno Opinião – Edição Especial.

FUSS, S., CANADELL, J. G., PETERS, G. P., TAVONI, M., ANDREW, R. M., CIAIS, P., JACKSON, R. B., JONES, C. D., KRAXNER, F., NAKICENOVIC, N., LE QUÉRÉ, C., RAUPACH, M. R., SHARIFI, A., SMITH, P., YAMAGATA, Y. (2014). Betting on negative emissions, Nature Climate Change 4, pp. 850-853. https://doi.org/10.1038/nclimate2392

GLOBAL CCS INSTITUTE – GCCSI (2015). Global Storage Readiness Assessment: an approach to assessing national readiness for wide-scale deployment of CO2 geological storage projects. ISBN 978-0-9871863-7-9.

GLOBAL CCS INSTITUTE – GCCSI (2016) The Global Status of CCS, Special Report: Introducing Industrial Carbon Capture and Storage. Melbourne, Australia.

GLOBAL CCS INSTITUTE – GCCSI (2019). Global Status of CCS 2019, Targeting Climate Change.

GLOBAL ENVIRONMENTAL FACILITY – GEF (2009). TT-Pilot (GEF-4): RCCS – Renewable CO2 capture and storage from sugar fermentation industry in São Paulo State. Retrieved from: https://www.thegef.org/projects-operations/projects/4040

GOLDBERG, K., HUMAYUN, M. (2016). Geochemical paleoredox indicators in organic-rich shales of the Irati Formation, Permian of the Paraná Basin, southern Brazil. Brazilian Journal of Geology, v. 46, p. 377-393.

HACHIRO, J. (1996). O Subgrupo Irati (Neopermiano) da Bacia do Paraná. Tese de Doutorado. Universidade de São Paulo.

INTERNATIONAL ENERGY AGENCY – IEA (2019). The Role of CO2 Storage: Exploring Clean Energy Pathways. Technology Report. Paris, FR.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE – IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

JAISWAL, D., DE SOUZA, A. P., LARSEN, S., LEBAUER, D. S., MIGUEZ, F. E., SPAROVEK, G., BOLLERO, G., BUCKERIDGE, M. S., LONG, S. P. (2017). Brazilian sugarcane ethanol as an expandable green alternative to crude oil use, Nature Climate Change 7, pp. 788-792. https://doi.org/10.1038/nclimate3410

KETZER, J.M.M., MACHADO, C.X., ROCKETT, G.C., IGLESIAS, R.S. (2016). Brazilian atlas of CO2 capture and geological storage. Porto Alegre: EDIPUCRS.

MARIN, F. R., MARTHA, G. B., CASSMAN, K. G., GRASSINI, P. (2016). Prospects for Increasing Sugarcane and Bioethanol Production on Existing Crop Area in Brazil, BioScience 66 (4), pp. 307-316. https://doi.org/10.1093/biosci/biw009

MILANI, E. J. ET AL. (1998). Orogenias paleozóicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. Revista Brasileira de Geociências, v. 28, n. 4, p. 473-484.

MILANI, E. J. (2004). Comentários sobre a origem e evolução tectônica da Bacia do Paraná. Mantesso-Neto, V.; BartorellI, A.; Carneiro, CDR, p. 265-291.

MILANI, E. J. et al. (2007). Bacia do Paraná: Boletim de Geociências da PETROBRAS, v. 15.

MÖLLERSTEN, K., ZETTERBERG, L., NIELSEN, T., TORVANGER, A., SIIKAVIRTA, H., KUJANPÄÄ, L., HANNULA, I. (2021). Policies for the promotion of BECCS in the Nordic countries. Nordic Council of Ministers.

MUSARRA, R.M.LM., TASSINARI, C.C.G., SAN MARTÍN CAÑAS, S. (2022). Perspectives to CO_2 Geological Storage and Greenhouse Gas Negative Emissions in South-Southeastern Brazil: Paraná and Santos Sedimentary Basins, São Paulo: Blucher, pp. 197. ISBN: 9786555501346. 61-72. https://doi.org/10.5151/9786555501346

NATIONAL ENERGY TECHNOLOGY LABORATORY – NETL (2019), Quality guidelines for energy system studies: Carbon Dioxide Transport and Storage Costs in NETL Studies, Report DOE/NETL-2019/2044, U.S. Department of Energy.

NUNES, R. C., COSTA, H. K. M. (2019). Operação e fechamento de instalações de armazenamento para atividades de CCS no Brasil. In: COSTA, Hirdan Katarina de Medeiros (org.). Aspectos Jurídicos da Captura e Armazenamento de Carbono. Rio de Janeiro: Lumen Juris.

OBSERVATÓRIO DA CANA (2022). Histórico da área de cultivo de cana-de-açúcar, moagem e produção de açúcar e etanol: Safra de cana-de-açúcar (CONAB). Retrieved from: https://observatoriodacana.com.br/listagem.php?idMn=4&idioma=1

PARENTE, L., FERREIRA, L. (2018). Assessing the Spatial and Occupation Dynamics of the Brazilian Pasturelands Based on the Automated Classification of MODIS Images from 2000 to 2016, Remote Sensing 10 (4), 606. https://doi.org/10.3390/rs10040606

PELISSARI, M. R., JANOWSKY, S. S. C., CIOTTA, M. R., TASSINARI, C. C. G. (2020). BECCUS: a digital approach for a bioethanol plant in Brazil, Proceedings of the Rio Oil & Gas Expo and Conference 20, 419, Rio de Janeiro, RJ, Brazil. https://doi.org/10.48072/2525-7579.rog.2020.419

BRASIL – PRESIDÊNCIA DA REPÚBLICA (2021). Despacho Presidêncial: Resolução N° 7, de 20 de abril de 2021, Diário Oficial da União. Brasília.

BRASIL – PRESIDÊNCIA DA REPÚBLICA (2017). Lei No 13.576, de 26 de Dezembro de 2017, Secretaria Geral. Brasília, DF.

RITCHIE, H., ROSER, M. (2020). CO2 and Greenhouse Gas Emissions, OurWorldInData.org. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

ROCHA, H.V. (2016). Estudo geológico do potencial de exploração e produção de gás natural não convencional na bacia do Paraná: avaliação da viabilidade no abastecimento a usina termoelétrica de Uruguaiana (RS). Master’s Thesis (Master’s in Science) – Graduate Program in Energy, University of São Paulo, São Paulo, pp. 144.

ROCHA, H.V. (2021). CO2 geological storage in organic-rich shales of the Irati Formation, Paraná Basin, Brazil, Thesis (Doctorate) – Energy Postgraduate Program, Institute of Energy and Environment, University of São Paulo.

ROCHA, H. COSTA, H. K. M. (2021). Chapter 14 – Legal and regulatory barriers to CO2 geological storage in Brazil: Lessons from the European Union. In: COSTA, Hirdan Katarina de Medeiros; ARLOTA, Carolina (Eds.). Carbon Capture and Storage in International Energy Policy and Law. Elsevier, pp. 263–283. https://doi.org/10.1016/B978-0-323-85250-0.00008-6

SALLES-FILHO, S. L. M., DE CASTRO, P. F. D., BIN, A., EDQUIST, C., FERRO, A. F. P., CORDER, S. (2017), Perspectives for the Brazilian bioethanol sector: The innovation driver, Energy Policy 108, pp. 70-77. https://doi.org/10.1016/j.enpol.2017.05.037

SAN MARTÍN CAÑAS, S. (2020). Data mining for prospectivity evaluation: The Irati Formation as a reservoir for the co-development of shale gas and CO2 geological storage in the Paraná Basin – Case study of the State of São Paulo. 2020. Dissertation (Master) – Graduate Program in Energy, Institute of Energy and Environment, University of São Paulo.

SAN MARTÍN CAÑAS, S. (2022). Prospectivity Mapping of the Irati Formation for CO2 Geological Storage in the Paraná Basin, In: Musarra, R.M.LM., Tassinari, C.C.G., San Martín Cañas, S. (Eds.), Perspectives to CO2 Geological Storage and Greenhouse Gas Negative Emissions in South-Southeastern Brazil: Paraná and Santos Sedimentary Basins, São Paulo: Blucher, pp. 61-72. https://doi.org/10.5151/9786555501346-04

SMEETS, E.M.W., FAAIJ, A.P.C. (2010). The impact of sustainability criteria on the costs potentials of bioenergy production – Applied for case studies in Brazil and Ukraine. Biomass and Bioenergy, 34 (3), 319.333. https://doi.org/10.1016/j.biombioe.2009.11.003

TASSINARI, C.C.G., SAN MARTÍN CAÑAS, S., RICCOMINI, C., TAIOLI, F. (2021). 3.4 São Paulo. Cadernos FGV ENERGIA – O desenvolvimento da exploração de recursos não-convencionais no Brasil: novas óticas de desenvolvimento regional, 8 (12), 78-86. Rio de Janeiro: FGV Enegia & Ministério de Minas e Energia do Brasil (MME).

Well-to-wheels emissions and total ownership cost comparison of internal combustion and electric passenger vehicles in Bogota, Colombia

1. Introduction

Various options related to transportation systems have been proposed as solutions for addressing the climate crisis, the increasing transport-related pollution, and fossil fuel energy dependency. Options targeting road passenger transport include improved fossil fuel quality, modal shift due to behavioral changes, and better infrastructure for alternative vehicles, and the development of new vehicle technologies with better performances [1]. Energy-saving and less pollutant vehicle technologies developed by the automotive industry are being analyzed in the scientific literature [2], [3] and are impulsed by public policy [4]. Better information regarding both monetary cost and emissions benefits of current and future trends in vehicle technology adoption is helpful to inform policy action in cities and can increase consumer adoption and behavioral changes [5]–[7].

In this work we estimate well-to-wheel (WTW) emissions from passenger vehicles of Bogotá and their total ownership cost (TOC). Three types of technologies were considered for replacing passenger vehicles: 1) conventional technologies with stricter emission standards (EURO V and VI gasoline and diesel); 2) Compressed Natural Gas (CNG); 3) battery electric vehicles. These three technologies differ in their cost and compatibility with the current infrastructure. A switch to electricity is considered more radical than a switch to natural gas or stricter vehicle emission standards because a large-scale deployment of electric vehicles requires capital and infrastructure investments. It is a disruptive evolution compared to the existing fossil fuel-based technologies.

2. Methodology

Our analysis includes five transportation categories: private cars, motorcycles, taxis, rigid and articulated buses.

2.1. Total ownership cost (TOC)

As indicated in equation (1), the Total Ownership Cost (TOC) is the sum of all costs, which adds the annualized capital cost (C_y^{Cap*}), the operational cost (C_y^{Oper}), and the replacement cost (C_y^{Rep}). A TOC estimation quantifies the costs of buying a vehicle from a specific supplier and includes the overall life costs associated with the ownership of the product. In this study, TOC is estimated in US Dollars per km.

$$TOC = C_y^{Cap*} + C_y^{Oper} + C_y^{Rep} \tag{1}$$

2.2. Cost projection

Costs beyond 2020 up to 2030 (C_y) are defined by equation (2)

$$C_y = (1+\rho)^{\Delta y} C_{2020} \; with \; \Delta y = y - 2020 \tag{2}$$

Where ρ is the annual increase/decrease rate, as mentioned above, costs can either be capital or operational cost. ρ is constant over the whole range of projected years

2.3. Well to wheels emissions

Emissions have been computed for different vehicle categories (i.e., Passenger cars, Taxis, Rigid buses, Articulated buses, and Motorcycles) according to fuel and EURO emission standards (i.e., Gasoline pre-EURO, Gasoline EURO I, Gasoline EURO III, Gasoline EURO IV, Gasoline EURO V, Diesel pre-EURO, Diesel EURO I, Diesel EURO III, Diesel EURO IV, Diesel EURO V, CNG EURO IV, ...). A detailed description of the method to estimate direct and indirect emissions is provided by [8], [9].

3. Results

The total ownership cost (TOC) of electric vehicles (EV) will continue its decrease in the next five years to become cheaper than internal combustion (ICE) vehicles. The annual reductions are roughly 19 percent for passenger cars, 20 percent for taxis, 5% for articulated buses, and 42% for motorcycles. At the same time, it will be equal to IC one for rigid electric buses. We, therefore, foresee a quick substitution of IC vehicles for EVs in the coming years.

However, despite the already competitive TOC for motorcycles, passenger cars, and taxis, Bogota's EV share is still scarce. The following barriers prevent a fast renewal:

- The capital cost of an EV is currently significantly higher than IC. (97% more for a passenger car, 93% for a taxi, 184% for a rigid bus, 100% for an articulated, and 57% for a motorcycle). However, the longer-term maintenance savings for EVs are not fully considered at purchase time.
- EV recharging time is much longer than for ICV.
- The EV autonomy is still significantly lower than for ICV. In addition to the economic decision to buy an EV, consumers have to accept lower autonomies than with ICV. However, the median autonomy currently reaches 200 to 400 kilometers on a single charge (IEA, 2020).
- Charging stations are still scarce and therefore challenging to find in Bogota and, more generally, in Colombia.

4. Conclusions

Here we found that TOC, total ownership cost is already favorable to electric vehicles (EVs). TOC of the EVs will be lower than internal combustion vehicles (ICVs) in less than five years. In some cases, the TOC is already lower than that of ICEVs. An EV requires a high initial investment (purchase price) compared to ICEV, a significant obstacle. However, the cost benefits are not shown to consumers, who are unaware of the savings in operating expenses. It is necessary to show TOC to consmmers to promote the purchase of EVs instead of ICV

References

[1] B. Bednar-Friedl *et al.*, “Transport,” *Springer Clim.*, pp. 279–300, 2015, doi: 10.1007/978-3-319-12457-5_15.

[2] P. Wolfram and N. Lutsey, “Electric vehicles: Literature review of technology costs and carbon emissions,” *Int. Counc. Clean …*, no. July, pp. 1–23, 2016.

[3] M. Tran, D. Banister, J. D. K. Bishop, and M. D. McCulloch, “Realizing the electric-vehicle revolution,” *Nat. Clim. Chang.*, vol. 2, no. 5, pp. 328–333, 2012, doi: 10.1038/nclimate1429.

[4] World Energy Council, *Global Transport Scenarios*. London: WEC, 2011. doi: 10.1177/1077800405284363.

[5] T. A. Gunawan and R. F. D. Monaghan, “Techno-econo-environmental comparisons of zero- and low-emission heavy-duty trucks,” *Appl. Energy*, vol. 308, no. October 2021, p. 118327, 2022, doi: 10.1016/j.apenergy.2021.118327.

[6] L. Langshaw, D. Ainalis, S. Acha, N. Shah, and M. E. J. Stettler, “Environmental and economic analysis of liquefied natural gas (LNG) for heavy goods vehicles in the UK: A Well-to-Wheel and total cost of ownership evaluation,” *Energy Policy*, vol. 137, no. October 2019, p. 111161, 2020, doi: 10.1016/j.enpol.2019.111161.

[7] A. Elgowainy *et al.*, “Cost of ownership and well-to-wheels carbon emissions/oil use of alternative fuels and advanced light-duty vehicle technologies,” *Energy Sustain. Dev.*, vol. 17, no. 6, pp. 626–641, 2013, doi: 10.1016/j.esd.2013.09.001.

[8] Y. Cuéllar-Álvarez, M. A. Guevara-Luna, L. C. Belalcázar-Cerón, and A. Clappier, “Well-to-Wheels emission inventory for the passenger vehicles of Bogota, Colombia [Manuscrito enviado para publicación]. Departamento de Ingeniería Química y Ambiental, Universidad Nacional de Colombia.,” 2021.

[9] Y. Cuéllar Álvarez, A. Clappier, M. Osses, P. Thunis, and L. C. Belalcázar, “Well - to - wheel emissions and abatement strategies for passenger vehicles in two Latin American cities,” *Environ. Sci. Pollut. Res.*, 2022, doi: 10.1007/s11356-022-20885-9.

[10] IEA - International Energy Agency -, “Global EV Outlook 2020,” 2020. doi: 10.1787/d394399e-en.

Price coordination? The influence of criminal groups in gasoline retail in the Rio de Janeiro Metropolitan Area

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Overview

According to the Brazilian Antitrust Authority (CADE), competition is a search, by different economic agents, for strategies that give them advantages. The motivator is the possibility of earning exceptional gains – equivalent to monopoly profits – even if they are temporary. Furthermore, competition in its free form is a factor that conditions supplies to keep their prices as low as possible. By charging higher prices in competitive markets, there is a possibility that companies that do so will lose some of their customers. In this aspect, the only way to maintain a higher level of profitability is to introduce more efficient forms of production to reduce costs. Competition, in this sense, can also be a stimulus to innovation (CADE, 2016).

In the Brazilian Federal Constitution of 1988, several articles deal with the General Principles of Economic Activity. In these Principles, free competition is a fundamental pillar of economic activity. Therefore, any agent that uses its market power to (i) eliminate free competition, (ii) indiscriminately increase its profits, and/or (iii) dominate markets, then it must be restrained. Thus, the State must guarantee that economic agents do not make abusive use of market power and do not manage to harm free competition.

Fuel resale is usually the sector most denounced against a cartel in Brazil (CADE, 2018). CADE defines a cartel as any agreement or concerted practice between competitors to fix prices and divide markets. The presence of cartels has some implications, such as price increases and supply restrictions, which are harmful to consumers. In this sense, the Antitrust Authority considers the practice of cartelization as the most serious anti-competitive conduct of the economic order violation.

Eckert and West (2004) observed two price patterns in gasoline retailing. The first one is price volatility. In general, markets that face volatile prices are the ones with the highest degree of competition between firms. On the other hand, the second pattern is price uniformity. It is more common for gasoline markets characterized by more stable and less dispersed prices to have some degree of market power on the part of firms. Most of the time, this market power is associated with price coordination.

The Rio de Janeiro Metropolitan Area faces a chronic problem of intense activity by criminal groups due to the State's lack of capacity to act in certain areas, especially those with lower income levels. The precarious or absent performance of the State gives space for certain criminal groups, such as the militia and drug trafficking, to exercise control in the urban areas. In several cases, these groups became suppliers of essential services, such as electricity, piped gas, and telecommunications (Melo, 2022). Considering the dominance in these markets, there is a hypothesis that criminal groups also influence fuel retail and act as price coordinators

In this context, there may be a potential loss for consumers in the Rio de Janeiro Metropolitan Area if price coordination is detected. Thus, the objective of this work is to verify the presence of coordinated prices in gasoline retail. Also, we evaluate whether the actions of certain criminal groups affect price dispersion.

Methods

A preliminary step is to analyze some descriptive statistics. According to the Brazilian Oil Regulator (ANP – Agência Nacional do Petróleo), finding an average price variation coefficient (VC Price) of less than 0.01 indicates price coordination. Next, the second step consists of an econometric analysis using panel data with fixed effects. Equation (1), below, presents the model used:

$$VC\ Price_{it} = \beta_0 + \beta_1 Margin_{it} + \beta_2 VC\ Cost_{it} + \beta_3 Margin.Groups_{it} + \beta_4 VC\ Cost.Groups_{it} + \varepsilon_{it} \qquad (1)$$

where: the subscript *i* indicates the neighborhood of Rio de Janeiro Metropolitan Area (observational unit); the subscript *t* indicates the time, in months; βs represent the parameters to be estimated; and ε represents the error term. In turn, each of the variables represents an indicator. The indicators are presented below:

$$Margin = \frac{(Price - Cost)}{Price}$$

$$VC\ Price = \frac{SD\ (Price)}{Mean\ (Price)}$$

$$VC\ Cost = \frac{SD\ (Cost)}{Mean\ (Cost)}$$

$$Group = \begin{cases} 1, & neighbourhood\ with\ criminal\ groups \\ 0, & otherwise \end{cases}$$

According to CADE and ANP methodology, negative correlations indicate price coordination. Thus, the preliminary hypotheses are that the βs are negative and statistically significant. Price dispersion is also expected to be lower in areas where criminal groups operate. Therefore, the second hypothesis is: $\beta_3 < \beta_1$ and $\beta_4 < \beta_2$.

Results

In terms of descriptive statistics, the margins did not show significant differences. In areas where criminal groups operate, the average margin was 10.5%, with a minimum and maximum of 8.1% and 12.7%, respectively. In the areas free of criminal group activities, the average margin was 10.6%, with a minimum of 8.5% and a maximum of 12.8%. In the case of the price variation coefficient (VC Price), the average for areas with group operations was 0.015, and, for areas without group operations, it was 0.013. In both cases, the values are very close to the 0.01 threshold, established by the regulatory agency. Thus, there are indications of price coordination in all areas.

However, concerning the econometric results, all βs are positive, except for β_3, which is not statistically significant. Therefore, the hypothesis of price coordination is rejected both in areas where criminal groups operate and also in the entire sample. However, we confirmed the hypothesis that $\beta_4 < \beta_2$, which is an indication of lower price dispersion. Although there is no price coordination in areas where criminal groups operate, the lower dispersion is compatible with some market power, as pointed out by Eckert and West (2004). Therefore, the are losses for consumers.

Conclusions

The objective of the work was to verify price coordination in gasoline retail in the Rio de Janeiro Metropolitan Area. The preliminary hypothesis was the existence of coordinated prices due to the absence of the State in some neighborhoods, which ended up being dominated by criminal groups. Although there is no evidence for price coordination in the areas where these groups operate, we found a piece of evidence of market power. On average, the price variation coefficient in the areas dominated by criminal groups was 0.015. The regulatory agency establishes that the level of 0.01, there is indicative of coordinated prices.

Furthermore, the low price dispersion found in the econometric model is compatible with Eckert and West's (2004) argument. Thus, there is evidence of the exercise of market power by gas stations. Although the worst situation for consumers is price coordination, low dispersion is also harmful, as prices are above expected.

References

CADE (2016). Conselho Administrativo da Defesa Econômica. Cartilha do CADE. Available in: https://cdn.cade.gov.br/Portal/acesso-a-informacao/perguntas-frequentes/cartilha-do-cade.pdf

CADE (2018). Conselho Administrativo de Defesa Econômica. CADE apresenta propostas para o setor de combustíveis. Available in: http://cade.gov.br/noticias/cade-apresenta-propostas-para-o-setor-de-combustiveis

ECKERT, A.; WEST, D. S. (2004). A tale of two cities: Price uniformity and price volatility in gasoline retailing. The Annals of Regional Science volume 38, pages 25–46.

MELO, Y. E. (2022). As dimensões da pobreza energética no Brasil. PhD Thesis in Economics. Universidade Federal Fluminense.

Capital cost efficiency of US natural gas pipelines and environmental factors influence: A two stage DEA approach

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Abstract

The objective of this paper is to evaluate the relative performance in terms of capital cost gas pipelines projects undertook in United States between years 2003 and 2015 and to acknowledge the effect of differences in the ground where pipelines are buried such as land use, wetlands and crossings. It is performed through Two Stage DEA. The analysis in this article provides through a widespread approved methodology and representative benchmarking figures that helps to evaluate the effect of environmental factors in capital costs. It is a useful tool for regulators who face asymmetric information problems when these important investments are done.

Key words: natural gas pipelines, DEA, efficiency, environmental factors

JEL Code: D24, Q4

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1. Introduction

In several countries gas pipelines investments are made by private companies and regulators must approve the amount of those expenses, so asymmetric information problems arise. Some investors may intend to justify higher costs adducing environmental factors like topographical, soil features or land use factors; disturbs with aborigines; or other kind of difficulties that imply more expenses.

Benchmarking plays a key role in this context; regulators need a comparison with other projects undertook in different states or countries to evaluate costs reasonability and relative efficiency to be sure they are not penalizing consumers with high prices due to inefficiency. But it is also crucial to evaluate the influence of external factors that investors do not control and in consequence must be incorporated as justified cost drivers.

The objective of this paper is to evaluate the relative performance in terms of capital cost of gas pipelines projects undertook in United States between years 2003 and 2015 and to acknowledge the effect of differences in the ground where pipelines are buried such as land use, wetlands and crossings. It is performed through Two Stage DEA.

Since seminal papers of Koopmans [1], Debreu [2], and Shephard [3] literature on productive efficiency has continuously advanced. Farrell [4] used linear programming techniques to estimate efficiency in US agriculture. Research on efficiency estimation continued with the development of Stochastic Frontier Analysis – SFA - [5–7] and Data Envelopment Analysis – DEA -[8]. Each of these techniques has subsequently been extended and developed further. Kumbhakar and Lovell [9] is an interesting textbook about SFA and Cooper et al. [10] for DEA.

Although frontier methods are common in energy literature and incentive regulation of distribution system operators there are few pipeline capital costs relative efficiency evaluating studies. Coelli et al.[11] and Joskow [12] provide some benchmarking experiences review.

The Australian Competition and Consumer Commission Working Paper No. 6 [13] examines five benchmarking methods providing an extensive review of academic literature; and regulatory applications of benchmarking techniques across 15 OECD selected countries. Specifically, DEA has been applied in Finland, Norway, the Netherlands, Germany, Austria, and in Australia. Some regulators have analyzed energy networks using a number of benchmarking techniques. For example, the German regulator used DEA and SFA to determine the comparative performance of gas and electricity distribution networks. Most of them are focused on operating costs. So, unlike capital costs comparisons, operating costs benchmarking are used by regulators country widespread.

Relevant capital cost antecedents are Ederer [14] and Agrell & Bogetoft [15]. The first evaluates capital and operating cost efficiency of European offshore wind farms using Two Stage DEA. The second one is a benchmarking of electricity transmission system operators in Europe and also uses Two Stage DEA.

This article is structured as follows. The second section presents economic model and methodology, including a section about data treatment. In the third section, empirical results are shown. Forth section is focused on the discussion of results and finally, in fifth section conclusions are presented.

2. Methodology

In this article the analysis is based in Two Stage DEA. This methodology seeks to include in the traditional DEA analysis environmental variables to account for the differences in efficiency measurements between firms or DMU (Decision Making Unit). That is, contemplate variables that may be determining an asymmetric environment that conditions the operation of DMU and since such variables are not controllable, they must be considered when measuring relative efficiency, in order to distinguish the efficiency related to the behavior of each DMU.

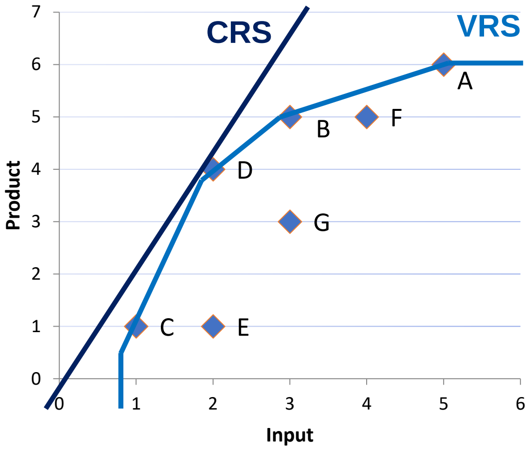
Firstly, DEA (Envelopment data analysis) is performed; then the parametric approach on the second stage helps to explain the effect of certain variables on the efficiency levels achieved by each project. Typically, OLS or Tobit [16] are used.

Some interesting paper using Two Stage DEA are Hoff [17], McDonald [18], Banker &Natarajan [19], Ederer [14] and Agrell & Bogetoft [15].

2.1 First stage DEA

Data Envelopment Analysis is a non-parametric method, which by linear programming constructs an envelope of the most efficient combinations of inputs and outputs. It supports different estimation variants, such as measures oriented to inputs or products, as well as the existence of constant or variable returns to scale[‡‡]. It can be appreciated in Figure 1; for instance, Inefficiency associated to point F can be estimated as the distance to the frontier: If product is fixed: the same amount can be achieved using less inputs as in point B. If, instead, inputs are assumed fixed more output could be achieved in the linear combination of points A and B.

Figure 1: Data Envelopment Analysis



Source: Own elaboration.

Product-oriented models maximize the quantity produced given a fixed amount of inputs, while those oriented to inputs are based on minimizing the use of inputs for a given quantity of product. This second orientation is in line pipeline project reality because in general DMUs do not control the product but the inputs.

[‡‡] As mentioned before Cooper et al. (2007) can be consulted for an understanding of DEA, and also Coelli et. al (2003).

In this first stage a border is calculated by means of DEA and the initial efficiencies of the companies considered.

The linear programming optimization to be solved for each DMU is:

$$\begin{aligned} &\min_{\theta,\lambda} \theta \\ st \quad & -\mathrm{y}_{\mathrm{i}} + Y\lambda \geq 0 \\ & \theta \mathrm{x}_{\mathrm{i}} - X\lambda \geq 0 \\ & \lambda \geq 0 \end{aligned}$$

where:

i: DMU i; i= 1,…,N;
θ: efficiency score (θ ≤ 1);
λ: vector of constants;
xi ≥ 0, input vector Nx1,
yi ≥ 0, output vector Mx1;
X: input matrix
Y: output matrix

Among the advantages of this method are not to require the realization of any assumption about the specification of the production function and the possibility of working with samples of small size. It also allows the incorporation of multiple inputs and products.

However, it is not exempt from disadvantages such as a high sensitivity to the choice of input variables and products, and the fact that it is not flexible in the consideration of environmental factors (obstacle that allows the model to be overcome in two stages).

2.1.1 Scale Returns

Depending on how the quantity produced changes with respect to increases in the use of inputs, it is interpreted that the underlying technology is subject to:

- Constant returns to scale (CRS): increases in the same proportion as inputs
- Variable returns to scale (VRS):
  - Increasing returns to scale (IRS): increases in greater proportion than inputs
  - Decreasing returns to scale (DRS): increases in smaller proportion than inputs

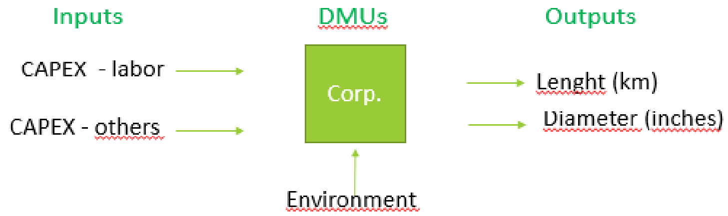
To consider variable returns to scale, the convexity condition N1λ = 1 is added to the optimization problem.

2.1.2 Characterization of DMUs

In a DEA benchmarking framework, a key issue is the selection of inputs and outputs. Thus, a detailed description of the DMUs is really useful.

In the present case of capital cost efficiency, the DMU is the entity that develops and installs the pipelines. As shown in Figure 2, this entity transforms the inputs – Capital costs associated to labor force and other capital costs (machines, material, etc.) – into a pipeline of specific diameter and length

Figure 2: Model for pipeline capital cost efficiency analysis



Source: Own elaboration.

Capital cost comprise all investments for pipeline development, such as soil examinations and all the investments for pipeline deployment, such as the purchase and installation of components and project management.

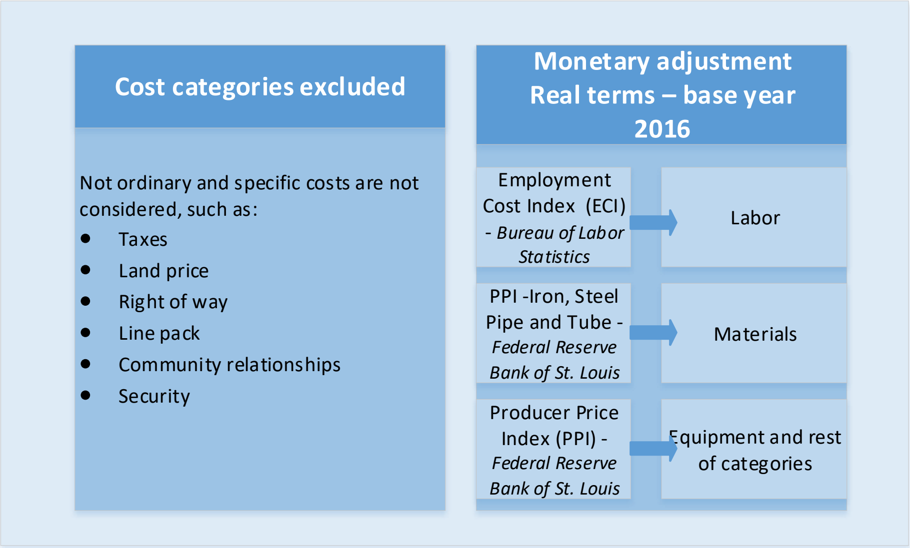
2.1.3 Data harmonization

Our DMUs are gas pipelines projects undertook in United States between years 2003 and 2015 The project data is collected from the Federal Energy Regulatory Commission (FERC).

A reliable cost efficiency model must limit its scope to some core cost components that are in common in all DMUs. This implies setting aside all those items that are not controllable by DMUs and are heterogeneous between states, such as line pack or land expropriation costs. In Figure 3, the full list of not considered items is shown.

All costs are expressed in real terms (base year 2016) correcting for local factor prices and producer prices as is specified in Figure 3.

Figure 3: Capital cost data harmonization



Source: Own elaboration.

2.2 Second stage

When DMUs efficiencies have been estimated in an industry, it is interesting to understand why some firms are more efficient than others. Particularly, one may wonder if the variations in estimated efficiency really reflect variations in performance or if it is due to differences in the operation environment.

To allow fair comparisons and relevant modeling, it is crucial to account for a range of complicating factors, i.e. factors that the DMUs do not control and which may have significant impact on their ability to perform cost-efficient process.

So, in second stage, the most common approach is to investigate if a set of variables (environmental variables) may explain the variations in efficiency. The model would be:

$$E = g(z, a)$$

Whereby efficiency E is explained by variables z and parameters a.

The most frequent strategy is to conduct a Tobit Regression; it is similar to ordinary least square (OLS) regression except that the noise term is truncated.

2.2.1 Environmental variables

As mentioned, to allow fair comparisons and relevant modeling, one also needs to account for a range of complicating properties, i.e. properties that the companies may affect but which are neither inputs nor outputs in the usual sense. The complicating properties for a gas pipeline projects may include: local labor market differences, soil and topographical features, crossings, etc.

In this paper the Z environmental variables included will be:

- As proxy of local labor market characteristics
  - Wage for similar occupations by State
- And, following Agrell, Bogetoft, Beaussant, & Talarmin [20] classification, as proxy of different terrain characteristics:
  - Land use:
    - low difficulty (1): rural, desert, wood, forest and
    - high difficulty (2): urban, industrial
  - Wetland:
    - low difficulty (1): occasionally wet or floodable
    - high difficulty (2): permanently wet or floodable, swampy, peaty
  - Crossing:
    - low difficulty (1): roads, railways
    - high difficulty (2): highways, important railways, rivers, lakes
  - Alternatively, a compressive variable named Total difficulty obtained as the weighted average of Land use, Wetland and Crossing

2.2.2 Ordinary least squares regression

OLS is the simplest regression method. The model is

$$E = az + \varepsilon$$

where ε is a random error term.

In this model it is easy to find the marginal effect on efficiency based on a marginal change in $\mathrm{z_h}$ and it is also easy to interpret it as it does not depend on the value of all the variables.

$$\frac{\partial \mathrm{E}}{\partial \mathrm{z_h}} = a_{\mathrm{h}}$$

Although OLS regressions are widely used, they suffer from a theoretical problem in a benchmarking setting: they do not consider that efficiencies are greater than 0 and less or equal to 1. There is nothing in the method that ensures that fitted values will be within those boundaries. The Tobit model can be used to solve this problem.

2.2.3 Tobit regression

Tobit regression is accurate for models with dependent variable censored, as is the case in which the dependent variable is efficiency that lies between 0 and 1. The model becomes:

$$E = \begin{cases} 0, & if\ az + \varepsilon \leq 0 \\ az + \varepsilon & if\ \ 0 \leq az + \varepsilon \leq 1 \\ 1 & if\ az + \varepsilon \geq 1 \end{cases}$$

where:
ε is a random error term; ε~N(0,σ)
z is a vector of environmental variables
a is a vector of parameters

The challenge is to estimate a based on the observed efficiencies form the N DMUs.

To quantify for the effect of certain variables on the efficiency levels achieved by each project in the Tobit model, it is necessary to know the marginal effect of a change in z in the dependent variable, E. Unlike a linear model estimated by least squares in which this effect is directly measured by the coefficient, in the case of censored variables, the marginal effect responds to the effect of a change in z on the expectation of the variable $\mathrm{EV(E|z)}$; which is determined by the conditional probability that takes into account the three possible states of the variable E. In this case, the marginal effect of the environmental variable h on E is measured by the following expression:

$$\frac{\partial \mathrm{EV(E|z)}}{\partial \mathrm{z_h}} = a_{\mathrm{h}}\ \left[\Phi\left(\frac{1 - az}{\sigma}\right) - \Phi\left(\frac{-az}{\sigma}\right)\right]$$

That is, the marginal effect is equal to the estimated coefficient, a_{h}, corrected by the probability that 0 <E <1.

The marginal effect depends on the value of the environmental variables, then, to calculate the correction of the efficiency levels, it must be done for a specific value of each variable of z[§§].

[§§] The average value of z can be taken as reference. That is, to take into account that companies face different environmental conditions, the deviation from the average is calculated and it is valued according to the marginal effect of z variations in E. Thus, this coefficient allows to obtain the efficiency levels adjusted by environment, that is the "corrected efficiencies".

3. Results

Table 1 provides the results of DEA performed in Stage 1, efficiency scores under VRS and CRS assumptions are shown. Both DEA models have acceptable discriminating capability as relatively small number of pipeline projects are fully efficient: five projects in CRS model and twelve projects in VRS one.

The last column presents scale efficiency estimates[***], and it has relevant implications. The CRS score describes the global technical efficiency of a pipeline project (or DMU), while the VRS score describes the local pure technical efficiency. So, if a DMU is on the VRS frontier it is locally efficient but not globally efficient, only in the segment where both frontiers overlap the most productive scale size is achieved. DMUs satisfying this last sentence are: P23, P34, P41, P56, P61, and they have the maximum scale efficiency score, 100. Meanwhile, project P40 is just locally efficient and its scale efficiency score lies below 100.

Table 1: First Stage DEA efficiency scores under VRS and CRS assumptions

	Efficiency Scores		
DMU	VRS	CRS	Scale
P1	70.22	65.48	93.24
P11	57.90	51.65	89.22
P15	57.01	44.91	78.78
P16	81.22	79.59	98.00
P19	80.02	79.68	99.57
P2	62.84	56.31	89.61
P20	62.83	62.69	99.77
P21	53.57	53.42	99.71
P23	100.00	100.00	100.00
P25	88.43	77.84	88.03
P29	95.83	85.10	88.80
P34	100.00	100.00	100.00
P36	58.13	54.04	92.95
P38	72.90	63.16	86.65
P39	100.00	37.40	37.40
P40	100.00	80.02	80.02
P41	100.00	100.00	100.00
P44	95.44	84.45	88.49
P45	100.00	84.80	84.80
P47	100.00	95.37	95.37
P51	100.00	84.22	84.22
P56	100.00	100.00	100.00
P57	72.20	60.30	83.51
P58	100.00	95.57	95.57
P6	59.38	58.60	98.69
P60	100.00	99.72	99.72
P61	100.00	100.00	100.00
P62	37.01	19.68	53.18
P8	91.93	91.16	99.17

Source: Own elaboration.

[***] Calculated as the ratio between Efficiency Scores under CRS relatively to VRS ones; EE = ECRS/EVRS.

The minimum scores in both models belong to P62, it is a peculiar project because it corresponds to an offshore expansion, so it has a high difficulty grade. Second stage can bring important information to the evaluation of its efficiency under the special circumstances of each project.

Table 2: First Stage - DEA efficiency scores metrics

	Efficiency Scores		
Metric	**VRS**	**CRS**	**Scale**
Mean	82.65	74.66	89.81
St. Dev.	19.42	21.82	14.20
Pctl(25)	62.84	58.603	86.65
Pctl(75)	100	95.37	99.71
MIN	37.01	19.68	37.40
MAX	100.00	100.00	100.00

Source: Own elaboration.

Second stage estimations are presented in Table 3. Dependent Variable in Models (1) to (4) is CRS Eficciency Scores meanwhile models (5) to (8) use VRS Efficiency Scores. Total difficulty results a significant variable, both in Tobit and OLS specifications; Models (1), (2), (5) and (6). In Models (3), (4), (7) and (8) the type of difficulty is discriminated: Wetland and Crossing associated coefficients result to be significant and indicate a negative correlation with efficiency scores. Finally, salary coefficient is not significant in any specification.

Table 3: Second Stage –Tobit and OLS Regressions

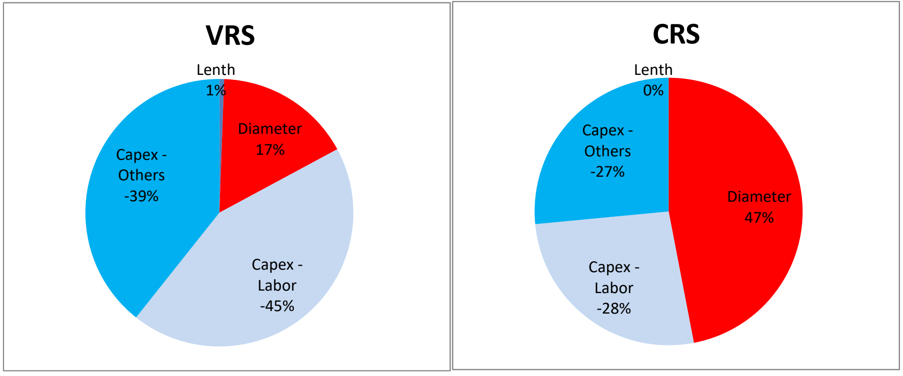
Model	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Dependent variable	**CRS - Efficiency Scores**				**VRS - Efficiency Scores**			
	Tobit	**OLS**	**Tobit**	**OLS**	**Tobit**	**OLS**	**OLS**	**Tobit**
Land use			0.0169	-0.00511			0.0391	0.0333
			(0.149)	(0.134)			(0.172)	(0.112)
Wetland			-1.131*	-0.990*			-1.617**	-1.193**
			(0.586)	(0.546)			(0.668)	(0.456)
Crossing			-0.199*	-0.203**			-0.179	-0.161**
			(0.0998)	(0.0918)			(0.114)	(0.0767)
Salary	6.52e-06	6.35e-06	-1.84e-06	-5.14e-07	1.03e-05	8.49e-06	-2.23e-06	2.26e-07
	(7.93e-06)	(7.01e-06)	(8.09e-06)	(7.37e-06)	(9.70e-06)	(6.28e-06)	(9.46e-06)	(6.16e-06)
Total_difficulty	-0.237**	-0.227**			-0.253*	-0.194**		
	(0.109)	(0.0965)			(0.132)	(0.0865)		
Constant	0.614	0.593	0.928*	0.839*	0.511	0.486	1.071*	0.827**
	(0.495)	(0.439)	(0.504)	(0.462)	(0.603)	(0.393)	(0.589)	(0.386)
Observations	29	29	29	29	29	29	29	29
R-squared		0.177		0.344		0.166		0.422

Source: Own elaboration. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

4. Discussion

As mentioned before, both first stage DEA models (CRS and VRS) have acceptable discriminating capability. They provide interesting information about how inputs (output) should be reduced (augmented) in order to gain efficiency. It does that for each project as it is compared which its peers in the frontier, for example if we are interested in P19, it could reduce costs in 19% using information of its (efficient) peer P4. Also, it is interesting to analyze the total potential improvements chart shown in Figure 4: regarding inputs it is possible to use less labor force and it is also viable to reduce other capital expenditures as material. Perhaps the more interesting recommendation is about the management of outputs: to increase diameter in order to be closer to the frontier, it seems to imply that diameter is not such a critical cost driver as length and of course increases gas transmission capacity. Of course, in general length is determined by supply need.

Figure 4: Total potential improvements based on DEA results in stage 1



Source: Own elaboration.

Second stage estimation allows to evaluate the influence of external factors that investors do not control but are in general relevant cost drivers. Total difficulty results a significant variable, both in Tobit and OLS specifications. It exerts an expected negative sing, implying that part of the inefficiency estimated in first stage is due to an unfavorable operation environment that raises capital expenditures.

When the type of difficulty is discriminated, Wetland and Crossing associated coefficients result to be significant and indicate a negative correlation with efficiency scores. Wetland seems to be the more relevant factor conditioning investment costs among the analyzed. Finally, salary coefficient is not significant in any specification.

5. Conclusion

In this article, the functionality of DEA was exploited with the aim of evaluating the relative capital cost efficiency of gas pipeline projects based on their main specifics.

Both first stage DEA models -CRS and VRS- have acceptable discriminating capability. Analyzing the total potential improvements, the principal efficiency gains could be catch up by reducing labor force use but there is also room to reduce other capital expenditures. Perhaps the more interesting suggestion is about the management of outputs: the recommendation would be, if it is possible, to increase diameter in order to be closer to the frontier, it seems to imply that diameter is not such a critical cost driver as length and of course increases gas transmission capacity.

Finally, OLS and Tobit regression analysis verified and quantified the relationships between efficiency and different terrain characteristics. Evidence indicates that Wetland and Crossing have significant effect on efficiency scores, implying they are key cost drivers.

So, it is a useful tool for regulators facing asymmetric information problems in the moment of planning and evaluating project costs and in the process of costs validation in different kind of surfaces.

6. References

[1] Koopmans TC. An analysis of production as an efficient combination of activities. In: Koopman TC, editor. Act. Anal. Prod. Alloc., Wiley; 1951.

[2] Debreau G. The Coefficient of Resource Utilization. Econometrica 1951;19:273–92.

[3] Shephard RW. Cost and production functions. Princeton University Press; 1953.

[4] Farrell M. J. The Measurement of Productive Efficiency Source. J R Stat Soc Ser A 1957;120:253–90.

[5] Meeusen W, van Den Broeck J. Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error. Int Econ Rev (Philadelphia) 1977;18:435–44.

[6] Aigner DJ., Lovell CAK., Schmidt P. Formulation and estimation of stochastic frontier production function models. J Econom 1977;6:21–37.

[7] Battese GE., Corra GS. Estimation of a production frontier model: with application to the pastoral zone of Eastern Autralia. J Agric Econ 1977;21:169–79.

[8] Charnes A, Cooper WW, Rhodes E. Measuring the efficiency of decision making units. Eur J Oper Res 1978;2:429–44.

[9] Kumbhakar, SC; Lovell C. Stochastic frontier analysis. Cambridge University Press; 2000.

[10] Cooper W, Seiford LM., Tone K. DATA ENVELOPMENT ANALYSIS A Comprehensive Text with Models , Applications , References and DEA-Solver Software. Second Edi. 2007.

[11] Coelli T., Estache A., Perelman S., Trujillo L. Una Introducción a las Medidas de Eficiencia. Banco Mundial y Alfaomega Colombiana S.A.; 2003.

[12] Joskow PL. Incentive Regulation and Its Application to Electricity Networks 2008;7:547–60.

[13] RegulatorAER AC and CCAAE. Benchmarking Opex and Capex in Energy Networks. 2012.

[14] Ederer N. Evaluating capital and operating cost efficiency of offshore wind farms : A DEA approach 2015;42:1034–46. https://doi.org/10.1016/j.rser.2014.10.071.

[15] Agrell PJ, Bogetoft P. International Benchmarking of Electricity Transmission System Operators. 11th Int. Conf. Eur. Energy Mark. (EEM), 2014, Krakow, Poland, Vol. 11, 2014. https://doi.org/10.1109/EEM.2014.6861311.

[16] Tobin J. Estimation of Relationships for Limited Dependent Variables. Econometrica 1958;26:24–36. https://doi.org/10.1016/j.jnoncrysol.2016.02.024.

[17] Hoff A. Second stage DEA : Comparison of approaches for modelling the DEA score 2007;181:425–35. https://doi.org/10.1016/j.ejor.2006.05.019.

[18] McDonald J. Using least squares and tobit in second stage DEA efficiency analyses. Eur J Oper Res 2009;197:792–8. https://doi.org/10.1016/j.ejor.2008.07.039.

[19] Banker RD, Natarajan R. Evaluating Contextual Using Data Variables Envelopment Affecting Analysis. Oper Res 2008;56:48–58. https://doi.org/10.1287/opre.l070.0460.

[20] Agrell PJ, Bogetoft P, Beaussant H, Talarmin J. Benchmarking European Gas Transmission System Operators : A Feasibility Study. 2014.

The increase in demand for LNG in the context of the energy transition in Brazil

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Abstract: The energy transition process has encouraged companies to reduce their environmental impact level by reducing greenhouse gas (GHG) emission in their processes and by increasing the use of energy deriving from renewable sources at global level. Nowadays, Brazil undergoes advanced transition stage from its strong dependence on electricity generation based on water sources to its potential to introduce solar, wind and natural gas-based energy in its matrix. Furthermore, increased LNG supply at global level, national demand for NG and reduced gas price at international level open room for greater likelihood of using natural gas and speeding up the energy transition process in the country, and this process can turn it into a relevant global consumer within the LNG-buying-and-selling scenario in the spot market.

Keywords: energy transition, Natural Gas, LNG, electricity.

1. Introduction

We are living in an era of great transformations, including the way we produce and consume energy. Population increase, global concern with ecosystems' preservation and need to reduce GHG emissions are factors encouraging these changes. Thus, new technology using has increased energy efficiency, the use of energy sources such as natural gas, as well as wind and solar energy using. This change process is called energy transition and its ultimate goal is to decarbonize the global matrix. Natural gas was selected as strategic energy source in this process because it is a low-cost available primary source that has lower environmental impact than other fossil sources – for example, it triggers lower GHG emissions when it is used in combustion processes. The Unites States and China are examples of countries that have successfully reduced GHG emissions based on greater use of this energy source to replace coal.

Brazil has a remarkably "clean" matrix in comparison to other economies worldwide, since it makes significant use of renewable sources. Such a fact places the country in vanguard position in the energy transition process, based on the energy production perspective. However, limitations in increasing hydroelectric power generation and the intermittent nature of solar and wind sources - which have been gradually gaining larger room in our electrical matrix - open room for investments in thermal power generation based on natural gas using as technological alternative capable of providing greater energy security and energy generation at the base. This factor emphasizes the important role played by natural gas in the energy transition process.

Production-pace acceleration in Pre-salt fields mostly depends on the oil market influence than on natural gas market influence, which remains incipient in Brazil. Thus, it is necessary increasing natural gas using rather than reinjecting it in reservoirs. In addition, the country must generate economic, competitive and regulatory conditions to better explore the advantages of natural gas in the transition towards a cleaner matrix. The aim of this chapter is to show the likelihood of using energy generation sources cleaner than coal or oil, such as natural gas - mainly in its liquefied form (LNG - Liquefied Natural Gas) -, in this energy transition process, due to the advantages of buying and selling it and to the flexibility inherent to this Market. In addition, increased natural gas insertion in the national matrix due to its global supply-expansion scenario opens room to increase energy generation through thermoelectric plants powered by natural gas. The current article initially presents an overview of the global energy transition scenario. Next, it provides national data about the topic. Subsequently, it shows traces of LNG supply expansion in the world, as well as possibilities and obstacles faced by the natural gas insertion process in the Brazilian energy matrix.

2. Global energy transition

Most companies have been adapting to the energy transition process driven by market's demand for greater transparency towards stakeholders and investors, both in terms of business risks and environmental impacts generated by it. Thus, energy transition becomes feasible due to technological advances that have enabled using renewable energy to replace the non-renewable ones. Structural and permanent changes based on the supply and demand perspectives, as well as changes in energy input prices, have encouraged the energy transition process, whose aim is to reduce greenhouse gas yenergemissions through the so-called economy decarbonization process.

Nowadays, renewable energy sources have become competitive and economically viable. Solar and wind energy costs have significantly decreased in the USA, UK and Europe. Wind energy has become more economically viable than energy sources used in matrices that operate based on high carbon levels. This economic factor has increased the insertion of this energy source type, as well as of solar energy, in global energy matrices.

The energy market analysis conducted by the International Energy Agency (IEA) has estimated total renewable energy capacity increase by 50% between 2020 and 2024[1]. Consequently, energy companies have started implementing a fast energy transition focused on replacing coal used in their processes. Oil companies are currently making heavy investments and diversifying their

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[1] IEA. *World Energy Outlook 2020*, November, IEA, Paris: IEA Publications, 2021, p. 56.

renewable and low-carbon energy portfolios in response to growing concerns about climate change. The 2021 World Energy Outlook report has pointed out that wind and solar photovoltaic energy will enable more than 50% of the additional energy generated by 2040[2].

According to another WEO scenario, total renewable source rate is expected to increase by 60% - which will result in 940 Mtoe by 2040 - due to substantial increase in bioenergy, biogas, biomethane and biofuel using[3].Wind energy production of approximately 8,300 TWh, and solar energy production of 7,200 TWh expected by 2040, may exceed that of hydropower - which currently corresponds to 6,950 TWh - whereas the energy generated by other renewable sources is expected to increase by 30%.[4]

Energy consumption from renewable sources is expected to increase to approximately 600 Mtoe in the transport sector. Biofuels comprise approximately 60% of such sources, whereas the remaining 40% correspond to renewable sources whose produced energy is used in rail vehicles, as well as in electric cars.

Therefore, based on IEA's projections, the renewable energy market will keep growing in the coming years. Furthermore, large companies have committed to use 100% of energy generated from renewable sources, through the RE100 initiative, which consists in a group of companies that have committed to implement energy transition process by using cleaner energy[5].

Storage is another challenge faced by power generation processes. Despite the mismatch between intermittent renewable energy and system reliability, the energy storage process has been playing an important role in energy transition and it has the potential to increase decarbonization of energy systems. Energy storage has expanded beyond the niche markets it is already used in due to decreased costs with the implementation of more efficient technologies[6].

CO_2 emission increase and future changes in carbon concentrations historically depend on regional aspects influenced by the investment and economic development levels observed in each country. Regions presenting solid economies - such as the European Union, the United States and Japan - have gradually reduced their carbon emissions over the past twenty years.

The United States recorded increased use of renewable sources and replaced coal by natural gas in the energy matrix. This process was driven by increased shale gas production, which reduced CO_2 emissions by 16.6% between 2005 and 2017. However, CO_2 emissions have increased by 2.8% between 2017 and 2018 in the country, due to extreme and adverse weather conditions that have led to increased use of heating systems[7].

The European Union recorded peak in carbon emissions in 2015, which

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[2] Ibid, p. 40.

[3] Ibid, p. 300.

[4] Ibid, p. 303.

[5] WILSON, Adam. The 2020 US Renewable Energy Outlook, December 2019. Available at https://www.spglobal.com/marketintelligence/en/news-insights/research/the-2020-us-renewable-energy-outlook

[6] SPGLOBAL. What is Energy Transition?. ESG Global, Research Insights, February 2020. Available at https://www.spglobal.com/en/research-insights/articles/what-is-energy-transition

[7] IEA. *World Energy Outlook 2021*, November, IEA, Paris: IEA Publications, 2020, p. 240.

was followed by decrease by 3.9% in 2018[8]. Such a decrease was influenced by coal power generation and by increased use of renewable sources. Carbon emissions in Japan have decreased for the fifth consecutive year in 2018, due to investments in technologies capable of increasing energy efficiency and to the activation of new nuclear reactors, which boosted nuclear power generation.

High economic and population growth in emerging economies such as China and India in the last fifteen years has significantly boosted energy consumption, mostly energy deriving from fossil fuels. In addition, capital investments and political efforts were made to implement projects focused on generating energy based on renewable sources, as well as to increase energy efficiency.

CO_2 emissions worldwide have increased by 1.7% in 2018 in comparison to the previous year. It was the second consecutive year of CO_2 emission increase after a curve-stagnation period. The drive to increase these emissions lied on the increased energy consumption boosted by countries' economic development, besides the climatic factor, which consequently increased the energy demand by cooling and heating systems.

Germany is another country to be taken into consideration. The German government initially took an active stance in energy transition – the ***Energiewende*** – based on an interventionist state policy and took the lead in decarbonizing the matrix. Germany basically depends on two sources to generate electricity, namely: coal and uranium. However, there has been strong popular pressure to discontinue nuclear energy using after the accident in Fukushima, Japan, in 2011[9].

Nowadays, according to the German Federal Ministry of External Relations (Energiewende), 35% of energy produced in the country is based on water, solar and wind sources[10], with emphasis on the price drop observed for wind sources at level lower than that of energy generated by fossil fuels. Despite the benefits arising from this active decarbonization policy, from high investment cost of approximately 150 billion euros in its implementation and from greater incentive to use renewable sources, these factors have affected energy prices and put the German Government in doubt about the continuity of the energy transition program.

Based on the global IEA scenario, which takes into consideration the current and planned policies adopted by different countries, the emission trajectory is not in compliance with the Paris Agreement. This treaty was signed in 2015 and stipulated GHG emission reduction targets for signatory countries. It is necessary enabling a sharp drop in the emission curve from 2020 onwards in order to meet the mitigation goals and to reverse the increase observed in the previous two years. This process would require reducing GHG emissions by 52%, from the current level until 2040[11].

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[8] Ibid, p. 290

[9] CHAVES, Ikaro. O Brasil e a Transição Energética Mundial. Ilumina, Agosto, 2019. Available at http://www.ilumina.org.br/o-brasil-e-a-transicao-energetica-mundial/

[10] ENERGIEWENDE. A Transição energética Alemã: A "Energiewende" ou a transformação do abastecimento energético alemão. Ministério Federal das Relações Externas. 2015. Available at http://www.energiewende-global.com/pt/?topic=erneuerbare-energien

[11] IEA. World Energy Outlook 2020. November. IEA. Paris : IEA Publications, 2021, p. 360.

3. Energy transition in Brazil

As previously mentioned, nowadays, Brazil has clean energy matrix in comparison to matrices in other countries, with emphasis on electric power generated from its water potential. Most recently, factors such as incentive policies, low-interest financing and competitive prices - enabled by auctions held to generate electric power - have boosted the growth of the wind and solar energy sectors, despite the persistent regulatory barriers to these new sources, mainly in the free market.

According to the 2020 National Energy Balance (BEN - Balanço Energético Nacional) published by the Energy Research Company (EPE - Empresa de Pesquisa Energética), 46.1% of domestic energy supply in the country currently consists of renewable sources such as water, biomass, firewood and charcoal, among others. Natural gas has increased its share among the remaining 53.9% in recent years. Industries, as well as cargo and passenger transportation, account for 63% of all national energy consumption. For the second consecutive year, consumption in the transport sector in the country has exceeded that of industries[12]. Thus, we understand that natural gas has room to grow even more and it can, in fact, become an important transition fossil fuel over the next thirty years. This process will make it possible reducing the use of coal and other fossil fuels in the country[13], in the aforementioned sectors.

Investments in the Brazilian energy sector, including oil, natural gas and electricity, are estimated at approximately two billion dollars, in the coming years. Installed wind energy capacity has increased by 21% in 2018, whereas installed solar energy capacity has increased by more than 115%[14]. Increased confidence of investors and energy companies was also observed due to the favorable scenario of greater renewable energy insertion in the national matrix.

The Climate Scope survey carried out in 2018, which analyzed the scenario of countries experiencing energy transition process, has ranked Brazil in fourth place among developing countries and acknowledged its ability to attract investments to the clean energy market. From 2010 to 2017, US $ 57 billion dollars were invested in new financial assets for clean energy plants in the country. Investors were attracted by favorable market and energy conditions, which corresponded to the largest capital invested in all Latin America, in the aforementioned period[15].

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[12] EPE (Empresa de Pesquisa Energética). Balanço Energético Nacional 202, Maio, Rio de Janeiro, 2021, p.32. Available at https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-479/topico-521/Relato%CC%81rio%20Si%CC%81ntese%20BEN%202020-ab%202019_Final.pdf

[13] FERNANDEZ, Eloi. ALMEIDA, Edmar. O gás natural e a transição energética, Fevereiro, Valor Econômico. Available at https://www.abegas.org.br/arquivos/75040

[14] ABSOLAR. Capacidade instalada de energia solar vai crescer 115% em 2018, diz associação. Folha de São Paulo, 2018. Available at em http://www.absolar.org.br/noticia/noticias-externas/capacidade- instalada-de-energia-solar-vai-crescer-115-em-2018-diz-associacao.html.

[15] ZOGHBI, Eduarda. ***Como a energia eólica e solar pode ajudar a impulsionar a transição de energia limpa no Brasil.*** Hablemos de Sostenibilidad y Cambio Climático. IDB. Outubro, 2019. Available at https://blogs.iadb.org/sostenibilidad/pt-br/como-a-energia-eolica-e-solar-pode-ajudar-a- impulsionar-a-transicao-

The current Brazilian energy sector dynamics in the use of sustainable energy, energy deriving from renewable sources and from other low carbon sources, in association with the supply of, and demand for, greater energy efficiency, have resulted in low GHG emissions[16]. Despite the increased use of renewable sources, the demand for energy and the emission of environmental-harmful gases continue to increase.

The electricity sector, which is currently based on large-scale hydropower generation, has been facing challenges such as the increasing demand for this energy source type, due to decreased relative storage capacity in the system. This process leads to increasing use of natural gas in thermal plants, which, although cleaner, is a non-renewable source. The demand for transport fuels has been expanding due to improved living standards and to long-term policies that tend to boost the use of road transportation.

Overall, transportation and increased demand for oil, in this and other sectors, are the main drivers of increased GHG emissions in Brazil. According to ANP, oil volume produced in 2021 has increased by 7.78%, whereas natural gas production increased by 9.46%, in comparison to that of 2020[17]. With respect to Pre-salt fields, oil and natural gas production has increased by 21.56% and 23.27%, respectively, in the same comparison period[18].

For a long time, it was assumed that hydroelectric plants would supply the basic demand for electricity in the country. However, difficulties in regulating the level of water reservoirs in hydroelectric sources have led to increased dependence on thermoelectric power generation,[19] which can be done through diesel, oil, coal, nuclear and natural gas. Each of these sources has its own specificities, greater or lesser environmental impact, and greater or lesser influence on the final energy price.

Given the need of using more thermal energy, it is possible saying that diesel-powered thermoelectric power plants (TPPs) present high variable cost and high GHG emissions. On the other hand, the ones powered by coal have low cost, but present remarkably high GHG emission level. Fuel oil-powered thermoelectric plants have high variable cost and high GHG emissions, despite presenting low VCU (variable cost per unit). Nuclear plants, on the other hand, present slow activation and significant environmental restrictions.

Finally, natural gas-powered thermoelectric plants depend on access infrastructure and on project type (taking into account the implementation cost

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de-energia-limpa-no-brasil/

[16] FAPESP. *Um futuro com energia sustentável: iluminando o caminho / Fundação de Amparo à Pesquisa do Estado de São Paulo* ; tradução, Maria Cristina Vidal Borba, Neide Ferreira Gaspar. – [São Paulo] : FAPESP ; [Amsterdam] : InterAcademy Council ; [Rio de Janeiro] : Academia Brasileira de Ciências, 2010. Available at http://www.fapesp.br/publicacoes/energia.pdf

[17] CORREA, Douglas. *Produção de petróleo bate recorde e ultrapassa 1 bilhão de barris.* Agência Brasil. Rio de Janeiro, 2020. Available at https://agenciabrasil.ebc.com.br/economia/noticia/2020-01/ producao-de-petroleo-bate-recorde-e-ultrapassa-1-bilhao-de-barris

[18] CORREA, Douglas. *Produção de petróleo bate recorde e ultrapassa 1 bilhão de barris.* Agência Brasil. Rio de Janeiro, 2020. Available at https://agenciabrasil.ebc.com.br/economia/noticia/2020-01/ producao-de-petroleo-bate-recorde-e-ultrapassa-1-bilhao-de-barris

[19] GALVAO, Jucilene; BERMANN, Célio. Crise hídrica e energia: conflitos no uso múltiplo das águas. Estud. av., São Paulo , v. 29, n. 84, p. 43-68, Aug. 2015. Available at https://www.scielo.br/scielo. php?pid=S0103-40142015000200043&script=sci_arttext

and the CVU). Their great advantages lie on dispatch versatility and on lower environmental impact. These factors highlight the tradeoff faced by decision makers at the time to define the most efficient energy policy, with the lowest cost and environmental impact[20].

Yet in the scope of thermal energy generation, cogeneration can be an alternative to increase energy efficiency based on the use of thermal and mechanical energy generated through the already installed technology. It can happen through gas combustion or through heat resulting from exhaust gases, which is widely used in industries with great potential for cogeneration such as chemical, pig iron, paper and cellulose, and aluminum industries.

4. Global LNG market expansion

Liquefied Natural Gas (LNG) introduction in the Asian market was intensified in the late 1950s. Japan and Korea remained the largest LNG consumers after the liberalization policies applied by their leaders. At the same time, China started importing more LNG and making purchase and sale contracts with other countries more flexible, a factor that boosted LNG supply in the market.

According to estimates by **BP Energy Outlook 2021**, renewable energy sources and natural gas will account for 85% of the primary energy increase in an energy transition scenario led by these sources by 2040. The same report has pointed out that LNG will account for more than 15% of total LNG demand by 2040, as well as that the United States and Qatar will account for 40% of LNG exports within twenty years[21].

In the long run, it is possible mentioning three trends shaping the LNG market, namely: greater supply flexibility, increased participation in energy transition, and greater and more diversified demand.

The recent drop in LNG price in the Asian market (a region that has some of the world's largest LNG suppliers) to less than $ 2- $ 3 / mmBtu (in comparison to $ 14 / mmBtu six years ago) is partly explained by the mismatch between supply and demand during the recent crisis (pandemic).

In addition, increased supply by sellers did not follow the demand retraction resulting from the expectation of uncertainty in the crisis scenario. However, long-term-contract buyers were able to inform sellers about the early drop in such a demand. Therefore, surplus cargo could be offered in the short-term spot market (four-year contracts or less), a fact that emphasized the flexibility of the LNG market with respect to the rapid repositioning of players on the supply side, which evidenced its dynamism[22].

In this scenario of global LNG supply expansion, there is pressure to

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[20] LAWSON, André. PEREIRA, Guilherme. *Termelétricas e seu papel na matriz energética brasileira*. FGV: Caderno Opinião, Fevereiro. 2017. p. 6. Available at http://bibliotecadigital.fgv.br/dspace/bitstream/handle/10438/20398/Coluna%20Opiniao%20Fevereiro%20-%20Termeletricas%20-%20Andre%20e%20Guilherme.pdf?sequence=1&isAllowed=y

[21] BP. *BP Energy Outlook 2021*. Press Releases.Brasil, Fevereiro. 2020. Available at https://www.bp.com/pt_br/brazil/home/noticias/press-releases/bp-energy-outlook-2021.html

[22] PRADE, Yanna Clara. A evolução dos contratos no mercado internacional de GNL. Grupo de Economia da Energia. Blog Infopetro, Abril, 2018. Available at https://infopetro.wordpress. com/2018/04/18/a-evolucao-dos-contratos-no-mercado-internacional-de-gnl/

reduce gas price to consumers. This new approach encourages new importers to enter the LNG market and the likelihood of having local industries reducing the level of CO_2 emissions. In addition, the growing dependence of the transport sector on diesel justifies the need of using alternative energy sources, since diesel price is strongly influenced by uncertainties and variations in the international oil price.

5. LNG in Brazil and regulatory barriers

The likelihood of generating energy through gas-powered thermal plants stands out in the global expansion of LNG supply. Despite the high costs with building pipelines, LNG transportation through the so-called "virtual pipelines" shows the potential to use natural gas in the growing energy transition process, as the driver capable of positively changing the world's energy matrices. However, when it comes to the current production in Brazil, there are uncertainties about the high cost of extracting gas from the Pre-salt layer, in addition to the high reinjection level in the wells and to the high CO level in the gas[23].

With respect to the regulatory sphere, the Gas Law (Law N. 11.909 / 2009) has opened room for third parties to use regasification terminals to compensate for the period when they are not used. However, some logistical, operational and movement barriers have hampered the use of these terminals by third parties. One of the ways to boost LNG would lie on using commercial gas swap; however, Brazil still lacks regulation and fiscal framework capable of adapting the commercial swap operation to market reality, which would help reducing consumers 'cost in case of double taxation[24].

Commercial swap would help optimizing gas transport flows in the financial sphere, given the detachment between the physical and the contractually negotiated part; besides, it would enable more than one buyer to use the gas. The swap would make the LNG market more competitive and increase its liquidity in trading. Finally, lack of secondary market hampers surplus gas reusing, which consequently forces large consumers to purchase cargo beyond their need[25].

Secondary markets operate with sufficient volumes to support variations in gas supply, which would bring more security to agents operating in the primary Market.

Therefore, the development of secondary markets in the energy transition scenario can take place by using gas-powered thermal plants as base generation.

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[23] ANP. *Estudo sobre o aproveitamento do gás natural do Pré-Sal*. Estudos. Março, 2020. p.10. Available at http://www.anp.gov.br/arquivos/estudos/aproveitamento-gn-pre-sal.pdf

[24] BOTÃO, Rodrigo. *O cenário de GNL no Brasil e no mundo e os entraves regulatórios nacionais*. In: Hirdan Katarina de Medeiros Costa. (Org.). A regulação do gás natural no Brasil. 1ed. Rio de Janeiro: Lumen Juris, 2019.

[25] MME. *Propostas para o Mercado Brasileiro de Gás Natural*. Comitê de Promoção da Concorrência no Mercado de Gás Natural do Brasil. Nota Técnica, Novo Mercado de Gás. Junho, 2019. P. 114. Available at http://www.mme.gov.br/documents/36112/491930/2.+Relat%C3%B3rio+Comit%C 3%AA+de+Promo%C3%A7%C3%A3o+da+Concorr%C3%AAncia+vfinal+10jun19.pdf/2379cc7f- f6b7-8ba0-72db-1278e7d252ca

However, certain features inherent to the gas market hinder the development of secondary markets. Among them, one finds price competitiveness at international level, high cost with transport infrastructure and energy supply in places located not so close to thermoelectric plants. Electric power generation based on the dispatch model, which aims at reducing the seasonality of hydropower generation depending on favorable climatic conditions, also takes into consideration the increased use of new renewable sources (which present intermittency just like hydroelectric generation) in the national energy matrix and requires greater flexibility in electric power generation systems. Thus, balance between supply and demand can take place in the long-run in order to guarantee greater supply security to consumers[26].

This scenario opens room for gas-powered thermoelectric plants presenting greater efficiency and lower GHG emission levels, since the ideal power generation park must be able to operate in an independent way and to quickly reach the expected power generation levels.

Finally, the energy transition process has highlighted the need of reducing national dependence on water sources for energy generation purposes. In addition, the expansion of natural gas supply by the Federal Government gave rise to the initiative called *Gás Para Crescer* (Gas to Grow) and to the program called *Novo Mercado do Gás* (New Gas Market), whose goal is to suggest more efficient, competitive and transparent measures to be taken in the natural gas sector, based on changes in the regulatory scope. It must be done to attract new competing companies, to force gas price reduction and, consequently, to reduce the price of energy to be used by final consumers.

6. Final considerations

Brazil plays a key role in the energy transition process, since it is an example of clean matrix comprising 46% of renewable sources. However, the country still faces a hard time reducing its dependence on energy generated by hydroelectric plants. Challenges such as greater investments in technology, long-term balance between energy supply and demand, as well as joint and balanced use of intermittent sources, such as wind and solar sources, are on the table.

The country has already reached its NDC with regard to the total rate of renewable sources in its energy matrix. In addition, there is the potential and expectation of greater natural gas participation in the Brazilian matrix, which can replace the most emitting fossil sources and, at the same time, provide backup for the intensive use of intermittent renewables. Moreover, it can also increase fossil rates in the matrix if this gas is not necessarily used to replace the most emitting fossil sources.

Thus, there is clear need of modernizing the regulatory framework of the gas and energy sector in order to attract private investors and innovative business models. These models overall present better results in legally favorable environments capable of developing energy generation projects based on clean

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[26] BOTÃO, Rodrigo. ***O cenário de GNL no Brasil e no mundo e os entraves regulatórios nacionais***. In: Hirdan Katarina de Medeiros Costa. (Org.). A regulação do gás natural no Brasil. 1ed. Rio de Janeiro: Lumen Juris, 2019.

sources feasible. Long-term strategies must focus on attracting capital, as well as on avoiding risk contracts capable of increasing GHG emissions, since these factors can bring financial risks to investors during the energy transition process to less polluting matrices.

Based on regulatory changes focused on increasing competition in the energy sector, Brazil can take advantage of its potential to use renewable energy and to avoid climate risks deriving from fossil fuels - not only to comply with international agreements, such as the Paris Agreement, but also to leverage the business environment and attract more foreign investments.

Gas-powered thermoelectric power generation, as well as solar and wind power generation, are gradually entering the national energy matrix. Assumingly, the country will not face many difficulties in maintaining a cleaner and more renewable electrical matrix in the coming years, based on the commercial perspective.

It is important taking into consideration the need of increasing the country's electric power generation capacity, as well as to increase its energy storage capacity. The complexity of electrical systems lies on the monitoring and balance necessary between supply and demand. In this scenario, the advantage of making thermal power generation based on natural gas (including LNG) more flexible can provide greater security to the supply system, prevent its collapse in the long-run, as well as contribute to the use of a cleaner matrix and to speed up the energy transition process.

References

ABSOLAR. *Capacidade instalada de energia solar vai crescer 115% em 2018, diz associação.* Folha de São Paulo, 2018. Available at http://www.absolar.org.br/noticia/noticias-externas/capacidade-instalada-de-energia-solar-vai-crescer-115-em-2018-diz-associacao.html.

ANP. *Produção de petróleo sobe 7,78% no Brasil em 2019 e ultrapassa pela primeira vez a marca de 1 bilhão de barris no ano.* Notícias. Janeiro, 2020. Available at <http://www.anp.gov.br/noticias/5596-producao-de-petroleo- sobe-7-78-no-brasil-em-2019-e-ultrapassa-pela-primeira-vez-a-marca-de-1- bilhao-de-barris-no-ano>

ANP. *Estudo sobre o aproveitamento do gás natural do Pré-Sal.* Estudos. Março, 2020. Available at http://www.anp.gov.br/arquivos/estudos/aproveitamento- gn-pre-sal.pdf

BOTÃO, Rodrigo. *O cenário de GNL no Brasil e no mundo e os entraves regulatórios nacionais.* In: Hirdan Katarina de Medeiros Costa. (Org.). A regulação do gás natural no Brasil. 1ed. Rio de Janeiro: Lumen Juris, 2019.

BP. *BP Energy Outlook 2021.* Press Releases. Brasil, Fevereiro. 2020. Available at https://www.bp.com/pt_br/brazil/home/noticias/press-releases/bp-energy-outlook-2021.html

CHAVES, Ikaro. *O Brasil e a Transição Energética Mundial.* Ilumina, Agosto, 2019. Available at < http://www.ilumina.org.br/o-brasil-e-a-transicao-energetica-mundial/>.

CORREA, Douglas. *Em relação ao pré-sal, o aumento da produção de petróleo e gás natural, foi respectivamente de 21,56% e 23,27% no mesmo período de comparação.* Agência Brasil. Rio de Janeiro, 2020. Available at <https://agenciabrasil.ebc.com.br/economia/noticia/2020-01/producao-de-petroleo-bate-recorde-e-ultrapassa-1-bilhao-de-barris>

IEA. *World Energy Outlook 2020* November, IEA, Paris: IEA Publications. 2020. Available at https://www.iea.org/reports/world-energy-outlook-2021.

ENERGIEWENDE. A Transição energética Alemã: A "Energiewende" ou a transformação do abastecimento energético alemão. Ministério Federal das Relações Externas. 2015. Available at http://www.energiewende-global.com/ pt/?topic=erneuerbare-energien

EPE. Informe: Terminais de Regaseificação de GNL nos Portos Brasileiros Panorama dos Principais Projetos e Estudos, 2018. Available at http://gesel.ie.ufrj.br/app/webroot/files/IFES/BV/epe54.pdf

EPE (Empresa de Pesquisa Energética). *Balanço Energético Nacional 2020,* Maio, Rio de Janeiro, 2020. Available at https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2020

FERNANDEZ, Eloi. ALMEIDA, Edmar. MAÇAIRA, Paula, PEDROSA, Oswaldo. *O gás natural e a transição energética,* Fevereiro, Valor Econômico. Available at < https://www.abegas.org.br/arquivos/75040>

GALVAO, Jucilene; BERMANN, Célio. Crise hídrica e energia: conflitos no uso múltiplo das águas. Estud. av., São Paulo , v. 29, n. 84, p. 43-68, Agosto, 2015. Available at https://www.scielo.br/scielo.php?script=sci_arttext&pi d=S0103-40142015000200043

LAWSON, André. PEREIRA, Guilherme. *Termelétricas e seu papel na matriz energética brasileira.* FGV: Caderno Opinião, Fevereiro. 2017. p. 6. Available at http://bibliotecadigital.fgv.br/dspace/bitstream/handle/10438/20398/Coluna%20Opiniao%20Fevereiro%20-%20Termeletricas%20-%20Andre%20 e%20Guilherme.pdf?sequence=1&isAllowed=y

MINTZ, M. S&P Global. What is Energy Transition? 2020. Available at https://www.spglobal.com/en/research-insights/articles/what-is-energy-transition

MME. *Propostas para o Mercado Brasileiro de Gás Natural.* Comitê de Promoção da Concorrência no Mercado de Gás Natural do Brasil. Nota Técnica, Novo Mercado de Gás. Junho, 2019. P. 114. Available at http://www.mme.gov.br/documents/36112/491930/2.+Relat%C3%B3rio+Comit%C3%AA+de+Promo%C3%A7%C3%A3o+da+Concorr%C3%AAncia+vfinal+10jun19.pdf/2379cc7f- f6b7-8ba0-72db-1278e7d252ca

PRADE, Yanna Clara. A evolução dos contratos no mercado internacional de GNL. Grupo de Economia da Energia. Blog Infopetro, Abril, 2018. Available at https://infopetro.wordpress.com/2018/04/18/a-evolucao-dos-contratos-no- mercado-internacional-de-gnl/

SPGLOBAL. *What is Energy Transition?*. ESG Global, Research Insights, February, 2020. Available at <https://www.spglobal.com/en/research-insights/articles/what-is-energy-transition>

WILSON, Adam. *The 2020 US Renewable Energy Outlook,* December, 2019. Available at <https://www.spglobal.com/marketintelligence/en/news-insights/research/the-2020-us-renewable-energy-outlook>

ZOGHBI, Eduarda. *Como a energia eólica e solar pode ajudar a impulsionar a transição de energia limpa no Brasil.* Hablemos de Sostenibilidad y Cambio Climático. IDB. Outubro, 2019. Available at <https://blogs.iadb.org/sostenibilidad/pt-br/como-a-energia-eolica-e-solar-pode-ajudar-a-impulsionar-a-transicao-de-energia-limpa-no-brasil/>

Markets for flexible power

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Introduction

Balancing power supply and demand is becoming ever more challenging in the Brazilian power system (and in many other power systems) due to the increasing share of power generation derived from sources that cannot modulate production. Much of the power expansion is derived from wind and solar generation, whose production is dictated by their primary energy resource availability, which not only is uncontrollable, but adds additional volatility to net load. Thermopower plant operation also is restricted by operational limitations, such as ramp-up rates or minimum on and off periods, and due to inflexible fuel sourcing (i.e. fuel contracts with take-or-pay clauses). Even, hydroelectric plants face many operational restrictions due to hydro restrictions (imposition of maximum and minimum reservoir storage levels, and maximum and minimum discharge rates). Together these factors make flexible generation increasingly scarce.

In a context where system expansion is no longer coordinated by vertically integrated power utilities, market mechanisms must be redesigned to ensure the supply of the needed attributes to meet system needs.

Metodology

The procurement of power flexibility is difficult because it is an ancillary attribute of power systems. The provision of the flexibility service depends on short-term operational decisions but are constrained by long-term investment decisions.

Thus, there are two ways to promote flexibility:

- long-term contracting with the objective of promoting new power plants with the required attributes to provide flexibility; and
- short-term and recurrent contracting of ancillary service to remunerate power plants based on the flexibility services rendered.

The two approaches present some of the same trade-offs that are present in the discussions regarding 'capacity markets' versus 'energy-only markets'. The long-term contracting provided by capacity markets seeks to directly address the 'missing money' problem that arises from the difficulty to attract investment in power capacity to meet sporadic demand needs. On the other hand, the energy-only markets have the advantage of paying out only to power plants that effectively provide the services and avoiding the need to establish monitoring and penalization mechanisms to deal with contracted capacity that does not perform.

However, flexible power supply also brings some unique challenges due the nature of technologies that may be employed to meet the power system's needs (including demand response). Market mechanisms should be technology neutral, seeking to promote widespread competition from all technological alternatives that are able to meet the system's needs.

The issue is addressed by a review of the literature and by means of a two-stage game, where market players:

- make their invest decisions in the first stage; and
- make their operational decisions in the second stage.

The model seeks to evaluate long-term and short-term contracting considering potential problems of adverse selection and moral hazard, considering uncertainty regarding future demand and technological innovation.

Expected results

This theoretical exploration is expected to shed light on the trade-offs associated to the various market mechanism alternatives and help identify mechanism design features that are important to avoid pitfalls.

Conclusions

The best market solutions likely employs both long-term and short-term contracting, each aimed at meeting particular concerns. The literature review of different approaches together with theoretical model will provide helpful guidelines for policymakers.

References

Boscán, L. and R. Poudineh (2016). Flexibility-Enabling Contracts in Electricity Markets (OIES Paper EL 21). Oxford: The Oxford Institute for Energy Studies.

Hsieh, E. and R. Anderson (2017). Grid flexibility: The quiet revolution. *The Electricity Journal* 30(2): 1-8.

Khoshjahan, M. *et al.* (2021). Enhancing electricity market flexibility by deploying ancillary services for ramping product procurement. *Electric Power Systems Research*: 106878.

Mays, J. (2021). Missing incentives for flexibility in wholesale electricity markets. *Energy Policy* 149.

Nicholson, E. (2019). Procuring Flexibility in Wholesale Electricity Markets. *Current Sustainable Renewable Energy Reports* 6: 100-106.

Anaya, K. and M. Politt (2021). How to Procure Flexibility Services within the Electricity Distribution System: Lessons from an International Review of Innovation Projects. *Energies* 14: 4475.

Xu, Z and S. Po (2019). The electricity market design for decentralized flexibility sources (OIS Paper EL 36). Oxford: The Oxford Institute for Energy Studies.

Do tax incentives increase solar energy adoption? Evidence from Brazil

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Overview

It is a global consensus that renewable energy has been a critical factor for sustainable development in recent years. Hence, some governments have created incentives to promote its adoption. The internalization of negative externalities from burning fossil fuels and the limited support for market-based policies (e.g., carbon tax) justify these specific incentives. Besides subsidies to reduce upfront investment costs and feed-in tariffs, policymakers usually rely on self-consumption policies, particularly for small-scale solar photovoltaic (PV) systems (Borenstein, 2012).

In this work, we will investigate the impact of economic incentives on residential solar PV adoption using a novel individual administrative data from the Brazilian Electricity Regulatory Agency (ANEEL). From 2015 to 2018, state governments implemented tax reductions on electricity consumption for distributed generation (DG) systems owners - including small-scale solar PV. The state policies aimed to increase the share of renewable sources in the energy matrix and boost economic activity through green employment generation. We will explore the staggered implementation across states and use the recent advances in this literature to understand how the policy stimulated the adoption of solar PVs in Brazil.

Brazil has great potential for exploring solar energy. The greatest solar irradiation occurs in the semi-arid climate area of the northeastern region and the lowest in the southern. However, in the least sunny place in the country, it is possible to generate more solar electricity than in the sunniest place in Germany (Martins et al., 2017). In this sense, Brazil reached the 16^{th} position in total solar PV capacity and the 12^{th} in the yearly new capacity in 2019. The country's solar PV capacity, including centralized and decentralized generation, increased from 0.08 gigawatts (GW) in 2015 to 7.9 GW in 2020. Small-scale distributed solar systems, such as rooftop panels, account for 59% of the total solar PV capacity in 2020 (EPE, 2021).

The evidence of tax incentives for renewable energy is largely based on policies applied in developed countries. To the extent of our knowledge, this study will be the first to assess the effect between taxes and the adoption of solar photovoltaic systems in a developing country context. Empirical studies applied to Brazil are particularly relevant. It is a large country with more than 210 million people, it has spatial and social heterogeneity, and the Brazilian households face potential credit constraints for investment in new technologies.

Methods

Our study explores the Brazilian Electricity Regulatory Agency (ANEEL) administrative dataset of small-scale distributed generation (DG) systems. It provides information at the owner level of all DG systems up to 5,000 kW in Brazil, including grid connection date, location, generation type, capacity size, sector, and energy source. We aggregated the data at the municipal level by quarter, and then we merged with all Brazilian municipalities to build a balanced panel. Our final database is a panel with 5,570 units and 20 periods.

Using the per capita installation rate and average capacity size as the outcome, we exploit the staggered roll-out of the tax incentive. We will use this timing variation as our identification strategy. The discrete events time adoption suggests a staggered difference-in-differences (DiD) approach to estimate counterfactual outcomes after one has adjusted for common shocks and time-invariant differences. We select *never-treated*, *not-yet treated group* and *early-treated* municipalities as control group. This estimation framework assumes that the outcome change immediately with the change in treatment status.

However, sudden changes can spread their effects over time. Such dynamics should become apparent in the event study approach.

In our estimations, municipalities are treated at different points in time. So, the estimated coefficients may not represent a weighted average of the treatment effects correctly. When treatment effects are heterogeneous, these comparisons may lead to coefficients having the opposite sign due to negative weightings (Roth et al., 2022; Goodman-Bacon, 2021). As robustness checking, we will apply the strategy proposed by Callaway and Sant'Anna (2020). The estimator isolates the comparisons between treated and control groups and then aggregates them using specific weights to estimate the global effect.

Results

The estimations suggest that the average effects decrease with tighter controls. Our preferred specification shows an increase of 0.34 installations per 100,000 residents. The event study approach indicates a greater significant impact four quarters after (one year later) the tax incentive implementation of around 1.5 installations. Regarding the capacity size of solar PV, our preferred specification shows an increase of 0.7 kW per unit after the incentive. If we consider an average capacity size of 350 W (0,35 kW) per solar panel, these result suggests that the tax incentive increases two panels in the system.

The heterogeneity analysis suggests that as we exclude larger municipalities the average effect increases. The results are consistent with the literature finds that most installations occur in lower population areas, such as suburban or rural areas. The results are consistent with the different staggered DiD approaches proposed recently.

We use the parameter estimated to predict the number of installations under the tax incentives. We then compare the predicted result with the cumulative installations from 2015 to 2018. Over the period, 64,189 residential solar PV systems up to 1,000 kW were installed in the country. The estimated average effect of the program (0.34 units per 100,000 people) corresponds to 4,976 installations under the tax incentives. In this context, the policy contributed to 7.75% of all installations over the period.

Conclusion

This article exploits a novel Brazilian administrative dataset of distributed generation to evaluate the effect of a tax incentive for solar PV installation. We use the staggered policy adoption by states from 2015 to 2018 to estimate the causal impact on the number of residential installations. Our results indicate that the state tax incentives account for 8% of residential solar PV installations and increase two out of ten panels of an average solar PV system. We also find that municipalities with higher solar irradiation and lower population present a greater average effect. These findings suggest that regional tax design may help governments meet their climate goals.

References

Severin Borenstein. The private and public economics of renewable electricity generation. *Journal of Economic Perspectives*, 26(1):67–92, 2012.

Brantly Callaway and Pedro HC Sant'Anna. Difference-in-differences with multiple time periods. *Journal of Econometrics*, 2020.

EPE. Balanço energético nacional (BEN): Ano base 2015. Technical report, Empresa de Pesquisa Energética, 2021.

Andrew Goodman-Bacon. Difference-in-differences with variation in treatment timing. *Journal of Econometrics*, 2021.

Fernando Ramos Martins, Enio Bueno Pereira, André Rodrigues Gonçalves, Rodrigo Santos Costa, Francisco José Lopes de Lima, Ricardo Rüther, Samuel de Lima Abreu, Gerson Máximo Tiepolo, Silvia Vitorino Pereira, and Jefferson Gonçalves de Souza. Atlas brasileiro de energia solar 2. Technical report, Inpe, 2017.

Jonathan Roth, Pedro HC Sant'Anna, Alyssa Bilinski, and John Poe. What's trending in difference-in-differences? a synthesis of the recent econometrics literature. *arXiv preprint arXiv:2201.01194*, 2022.


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ELECTRICITY PRICING STRUCTURE AND TAX COORDINATION ACROSS SUB NATIONAL REGULATORY JURISDICTIONS

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electricity rate design
energy taxes
price and tax coordination

Introduction

Electricity pricing and taxation is undergoing a fast transformation in line with the substantial structural changes embedded in the energy transition. This required shift puts a lot of pressure for reform of the status quo of electricity pricing, particularly in emerging economies or subcontinents like LAC, where the “pricing code” is still conceived in the old paradigm, too much biased towards volumetric components without time varying differentiation and showing sub-optimal pricing such as an overuse of increasing block pricing. This paper looks to end user residential segments because we see them as an area where gaps are larger and gains can be substantial. We start separating end user electricity tariffs, charges and taxes, to suggest a need to address a coordination between pricing and taxation across several different regulatory jurisdictions that form part of an interconnected electricity system but have quite different tariff structures and (provincial, municipal) taxes and charges. Differences in “tariff formats” across jurisdictions mean different fixed charges and rate levels, different non-linear block pricing schemes and different charges and taxes that have an excess bias towards volumetric pricing and depart from what would be in principle considered as an efficient two-part scheme where a uniform variable component seeks matching marginal pricing with social marginal costs and fixed charges are oriented to cover fixed or common costs and policy costs (subsidies, renewables support, etc)(e.g. Borenstein and Bushnell, 2021; Lopez Arriaga et al, 2017).

Methodology

We assume two coordination issues for the purposes of our reform simulation. The first is between pricing and tax policy, where the first one specializes in determining levels and structures of cost-reflective rates consistent with a regulation of service costs, while taxes are mainly responsible for managing the distributional impacts of pricing structures rebalancing and raising funds for infrastructure financing that include common network costs (Navajas, 2018, 2022). The second coordination is among different regulatory jurisdictions, where a common two part tariff format is adopted although leading to different (across jurisdictions, but uniform within jurisdictions) fixed charges, marginal prices, charges and taxes. We define the status quo of our reform exercise in practice using the case of Argentina. We use National Household Expenditure Survey (ENGH) microdata, which allow using a distribution of electricity consumption for the distribution areas. Our estimates of quantities allow to report the distribution of fixed charges, marginal prices, charges and taxes across tariff blocks (of an increasing block tariff for instance) and across household per capita income or consumption deciles. We consider three reform exercises (A,B,C) aimed at evaluating the impacts of a coordination of tariff “formats” across jurisdictions. In reform A we simulate a revenue neutral (for utilities) change in the tariff structure towards a two-part tariff format. In reform B we further assume that fixed charges must be raised to cover 20% of utilities revenues. Finally, reform C additionally assumes a coordination of taxes where the tax burden cannot be higher than 25% of total expenditures of households, which is the status quo average; that is, the reform does not study the impact of lower taxes on aggregate. The three reforms are revenue neutral for utilities, reforms A and B are also (almost) revenue neutral for subnational governments while reform C implies a redistribution of tax revenues. The three reforms must imply compensations and charges to maintain the initial status quo across households and subnational governments. We study the size and nature of these compensations and charges as they inform about the requirements for a sustainable reform.

Main Findings

We find that the consequences of reform A (basically to converge to uniform two part tariff formats) has relatively minor effects on the status quo and requires manageable transfers across households. Instead reform B makes the size of transfers across households relatively large and conditional on the magnitude of the rebalancing towards fixed charges. Finally, Reform C requires an important redistribution from those jurisdictions benefiting from the cap on taxation to those with higher taxes in the status quo. We calibrate the size of the compensations and charges to households in terms of household expenditures.

Conclusion

In many LAC countries electricity pricing is distorted towards excess volumetric bias and taxation is not only burdensome but it contributes to this distortion. This status quo requires a reform towards an efficient two part tariff with a rebalancing to fixed charges and a simplification of taxes. As pricing must respect a similar format structure from an heterogeneous status quo (albeit not same end user prices due to differences in social marginal costs and other structural differences) this involves a coordination of pricing and tax formats across jurisdictions. A reform of pricing and tax structures, with revenue neutrality for utilities, involves charges and compensations across households and jurisdictions if one wants to respect the status quo insofar as incomes and tax revenues are concerned. It implies a coordination between pricing and taxation because the size of redistributions cannot be performed by utilities but by fiscal authorities. This opens the door for a reform of subsidies towards lump sum formats and away from schemes and cross subsidies that distort pricing.

Main References

Borenstein S. and J. Bushnell (2021), “Issues, Questions and a Research Agenda for the Role of Pricing in Residential Electrification”, Working Paper 21/35, Resources for the Future.

Burger S., C. Knittel, I. Pérez-Arriaga, I. Schneider and F. vom Scheidt (2020) “The Efficiency and Distributional Effects of Alternative Residential Electricity Rate Designs”, Energy Journal, 41, pp.199-239

Hancevic P., H. Nuñez and J. Rosellon, (2022). ”Electricity Tariff Rebalancing in Emerging Countries: The Efficiency-equity Tradeoff and Its Impact on Photovoltaic Distributed Generation”, The Energy Journal, Vol. 43, No. 4.

McRae F and F. Wollak (2021), “Retail Price in Colombia to Support the Efficient Deployment of Distributed Generation and Storage and Electric Vehicles”, Journal of Environmental Economics and Management, 110, pp. 1-23.

Mejdalani A., D. Lopez, K. Antonio, A. Gomez, M. Hallack, M. Tolmasquin and L. Camara (2022), “Assessing Tariff Design in Latin America”, mimeo, IDB.

Navajas F. (2018), “Impuestos y cargos específicos en las tarifas de los servicios de infraestructura”, Nota Técnica 1473, Banco Interamericano de Desarrollo, Agosto.

Navajas F. (2022), “Electricity rate structure design in LAC; Where do we stand?”, mimeo, IDB project on electricity tariff performance and design in LAC.

Pérez-Arriaga I., J.D. Jenkins and C. Batlle (2017), “A regulatory framework for an evolving electricity sector: Highlights of the MIT utility of the future study”, Economics of Energy and Environmental Policy, 6, pp.71-92.

Urbiztondo S., D. Barril and F. Navajas (2020), “Regulation of Public Utilities of the Future in Latin America & the Caribbean: the Argentine electricity sector”, Technical Note #1814, IDB Washington.

Wolak F. (2008) “Public utility pricing and finance”, The New Palgrave Dictionary of Economics, London: Macmillan

Economics of Cross-Border Electricity Trade in Latin America in the Long Term

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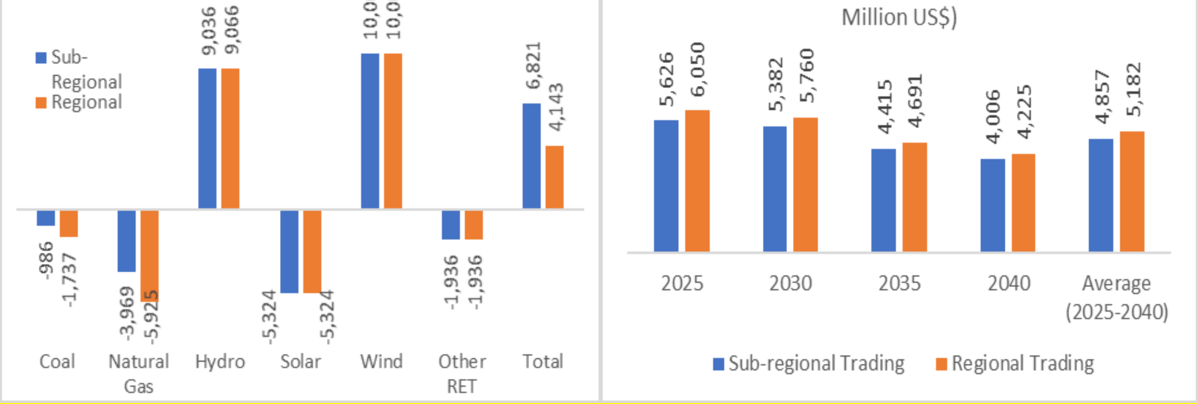
Overview: Regional or cross-border electricity trade entails several economic and environmental benefits, including optimal use of electricity generation resources across the borders; hourly cross-border electricity trade utilizing differing load curves between the countries; sharing peak load and reserve margins, enhancing the system reliability; facilitating clean energy trade to reduce emissions of greenhouse gases (GHGs) and local air pollutants and finally reducing the cost of electricity supply. The total benefits of the regional electricity trade could be much larger than the costs of realizing it (e.g., Rogers and Rowse, 1989; Bowen et al., 1999; Yu, 2003; Gnansounou et al., 2007; ESMAP, 2010; Timilsina and Toman, 2016; Timilsina and Curiel, 2020). Limited regional electricity trade has been exercised in Latin America (LAC region), multilaterally in Central America (SIEPAC), and multilaterally or bilaterally in other parts, such as Brazil-Uruguay-Argentina (Del Campo, 2017). However, the volume of cross-border electricity trade in the region accounts for less than 5% of the total regional generation. Several LAC countries have excess capacities; their load profiles differ significantly, indicating cross-border electricity trade opportunities even without adding new capacities for electricity generation. Timilsina et al. (2021) estimate that the LAC region would gain US$1.5 billion and US$2 billion annually under the sub-regional and regional level electricity trade, respectively, in the short run by utilizing the existing generation capacities (e.g., day-ahead, intra-day, and balancing services). The current study extends Timilsina et al. (2021) and estimates the long-term benefits of the regional electricity trade until 2040.

Methodology: The study first highlights cross-border trading opportunities in the region by showing (i) differences in hourly and seasonal load curves across the countries; (ii) electricity price differences between the countries; (iii) excess capacities in different countries that can be utilized; (iv) differing fuel mixes indicating the potential clean energy trade and (v) difference in average as well as marginal costs across the countries. It then uses the World Bank's electricity planning model (EPM) to simulate hourly electricity generation and trading potential at the sub-regional and regional levels. We developed three scenarios – Baseline, Sub-Regional trade, and Regional trade. Under the baseline scenario, each country dispatches its power plants following the merit-order rule and meets its demand in 2020. It also accounts for existing cross-border electricity trading facilities. The Sub-regional trade scenario assumes unconstraint cross-border electricity between the countries within three sub-regions: Andean sub-region (Bolivia, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela), Central sub-region (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua and Panama) and Mercosur sub-region (Argentina, Brazil, Chile, Paraguay and Uruguay). The regional trade scenario considers unconstraint electricity trade across all countries in the LAC region.

Results: The study finds that the existing volume of electricity trade (baseline scenario) in LAC is approximately 4% of the regional generation. The electricity trade volume would increase, on average, by 10 and 13 times under the sub-regional and regional scenarios, respectively. The electricity trade would cause avoidance of total installed capacity by 6.8 GW by 2040 under the sub-regional scenario; however, it drops to 4.1 GW under the regional trading scenario (Fig. 1a). Overall, the region will gain, on average, US$4.9 and US$5.2 billion (2020 price using a 6% discount rate) annually during the 2025-2040 period, under the sub-regional and regional trading scenario, respectively (Fig. 1b). These gains are much higher than the short-term gains estimated by Timilsina et al. (2021), which were US$1.5 billion under the sub-regional trading scenario and almost US$2 billion under the regional trading scenario. Of the total electricity supply cost savings, 72% comes through the reduction in fuel costs, 24% comes from the reduction in capital costs, and the remaining 4% comes from the reduction in O&M costs. If the cost of electricity not supplied or unserved is also accounted for, the benefits from the trade would be much higher depending on the value assigned to the unserved energy. Under the sub-regional trading scenario, Andean and Mercosur sub-regions gain almost equally, about 39% each, of the total gains. Under the regional trading scenario, the share of the Mercosur sub-region drops, whereas the shares of the other two regions increase.

Figure 1. Impacts of regional trade on the power sector in LAC



(a) Avoidance of total installed capacity

(b) Savings in electricity supply costs

Conclusions: This study estimates the potential savings on electricity supply costs if 20 Latin American countries facilitate unrestricted trade of electricity between the borders over the 20 years between 2019 and 2040. The study shows that the volume of cross-border electricity trade would increase by 10 and 13 times from the current level under the sub-regional and regional trading scenarios, respectively. The region would gain US$4.9 billion (2020 price) annually under the sub-regional trading scenario and US$5.2 billion under the regional trading scenario by reducing electricity supply costs. More than 70% of the cost savings come through the reductions in fuel costs. Latin American countries should enhance regional cooperation and facilitate unrestricted cross-border electricity trade by building transmission interconnections and introducing necessary laws and regulations.

References

Bowen, B.H., F.T. Sparrow and Z. Yu (1999). Modeling electricity trade policy for the twelve nations of the southern African power pool (SAPP). Utility Policy 8 (3), 183–197.

Del Campo, Francisco José Martínez-Conde (2017). Electric Integration and Development of a Renewable Electric Grid in Latin America, University of Chile. Santiago. Chile.

Energy Sector Management Assistance Program (ESMAP) (2010). Regional Electricity Trade: Lessons from Global Case Studies and a Literature Review. World Bank, Washington, DC.

Gnansounou, E., H. Bayem, D. Bednyagin and J. Dong (2007). Strategies for regional integration of electricity supply in West Africa. Energy Policy 35, 4142–4153.

Rogers, J.S., J.G. Rowse (1989). Canadian interregional electricity trade: analysing the gains from system integration during 1990–2020. Energy Econ. 11 (2), 105–118.

Timilsina, Govinda R. and Ilka Fabiana Deluque Curiel (2020). "Power System Implications of Subsidy Removal, Regional Electricity Trade, and Carbon Constraints in MENA Economies". World Bank Policy Research Working Paper, WPS 9297. World Bank Washington, DC.

Timilsina, Govinda R., Ilka Fabiana Deluque Curiel and Deb Chattopadhyay (2021). "How Much Does Latin America Gain from Enhanced Cross-Border Electricity Trade in the Short Run?" World Bank Policy Research Working Paper, WPS 9692. World Bank Washington, DC.

Timilsina, Govinda R. and Mike Toman (2016). Potential Gains from Expanding Regional Electricity Trade in South Asia. Energy Economics, Vol. 60, pp. 6-14, 2016

Yu, X. (2003). Regional cooperation and energy development in the Greater Mekong subregion. Energy Policy 31 (12), 1221–1234.

SISTEMA DE MEDICIÓN ENERGÉTICA CON ARQUITECTURA IOT EN MOTORES MONOFÁSICOS INDUSTRIALES

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RESUMEN

Este articulo tiene como finalidad analizar diversas metodologías aplicadas en la industria para aumentar la eficiencia energética en los procesos, particularmente para usos con bombas de agua y compresores de aire, equipos de los cuales se realizó medición de parámetros eléctricos mediante la implementación de un sistema AMI con el fin de analizar la información disponible y establecer un sistema de gestión de energía que permita aumentar la eficiencia energética en PyMES Colombianas, encontrando los tiempos muertos de los equipos y los picos de arranque de los motores usados.

Palabras clave: Eficiencia energética, motores, sistemas de gestión de energía, AMI.

INTRODUCCIÓN

La eficiencia energética está relacionada con el desempeño físico de usos finales específicos o servicios energéticos tales como iluminación, calefacción, refrigeración y máquinas y mecanismos accionados por motor. Es posible obtener mayor eficiencia energética en los procesos si se logra reemplazar, actualizar o simplemente realizando mantenimiento de los equipos existentes de tal forma que se puedan optimizar los procesos y reducir la cantidad de energía utilizada en el sistema que se esté analizando.

Por lo general la eficiencia energética relaciona una cantidad de salida por unidad de entrada de energía (por ejemplo, lúmenes por vatio o millas por galón). Ya que la energía es uno de los factores de producción (otros son los materiales, la mano de obra y el capital), las mejoras en la eficiencia energética llevan a obtener una mayor productividad energética y eficiencia económica; además si la amenaza del cambio climático global y situaciones en las que la falta de soberanía energética afecta los precios, el uso y disponibilidad de electricidad cómo actualmente sucede con muchos países de la unión Europea frente a Rusia, se puede impulsar un movimiento en el que se unan esfuerzos buscando reducir las emisiones de carbono asociadas a las actividades productivas principalmente, por lo tanto maximizar la eficiencia energética será un objetivo primordial y requerirá que en un plazo cada vez menor se modifiquen las formas de proporcionar y pagar los servicios energéticos (Poudineh, R., & Jamasb, T., 2014).

METODOLOGIA

Para el desarrollo del sistema de medición se utilizó 2 medidores de energía SPM91, un Módulo Zigbee FourthFaith F8914 y una Raspberry pi 3, el primer medidor de energía se comunica por medio de Modbus RS-485 a la Raspberry por medio de un convertidor Modbus RS-485 a USB, por medio de Python se denominan las mediciones de los registros de voltaje, corriente y potencia del medidor. El segundo medidor es comunicado por medio del dispositivo ZigBee a través de Modbus RS-485 y este se comunica a su vez con un receptor ZigBee que está conectado a la Raspberry por medio del mismo convertidor Modbus RS-485 a USB mencionado anteriormente. Una vez leída la información, los datos son organizados en un JSON para ser enviados vía MQTT a una plataforma en la nube que actúa como agregador, la función del agregador es analizar el consumo de energía de las cargas.

RESULTADOS

Se desarrollo un programa basado en Python con el cual se puedan recibir los datos obtenidos de los medidores inteligentes y se puedan procesar para hacer un análisis del consumo energético de los equipos de uso final, en los que se están tomando datos con el fin de dar sugerencias de eficiencia energética.

Se obtienen las gráficas con la energía consumida por días del compresor, en la gráfica se puede observar los promedios y consumos anómalos del compresor durante días específicos dentro del proceso industrial, además de observar los días de mayor consumo de energía. Se puede observar que el viernes y sábado es más probable tener un consumo energético menor, esto se debe a que la producción en la planta disminuye. Los martes, miércoles y jueves son los de mayor consumo energético llegando a 22 kWh, un análisis similar se obtiene de la bomba de agua teniendo picos de consumo de energía de 35 kWh.

Con la medición de la bomba de agua se pudo obtener intervalos de tiempo en los que el equipo se deja prendido sin que la línea de producción se encuentre activa, a partir de la revisión de los consumos anómalos de energía y la productividad de la empresa en el intervalo de tiempo estudiado.

CONCLUSIONES

El sistema de medición permite obtener los consumos energéticos del compresor y de la bomba de agua, haciendo uso del avance en las tecnologías de medición y comunicación, estos consumos energéticos pueden ser usados para evaluar la eficiencia energética de los dispositivos ya bien sea por los tiempos de uso o los picos de arranque de los motores permitiendo a los encargados del proceso productivo verificar si el consumo de energía está siendo útil o por el contrario se realiza un gasto de energía innecesario como es el caso de la bomba de agua, que en ocasiones se deja encendida sin estar activa la línea de producción.

A partir de estas mediciones se pueden explorar más aplicaciones de eficiencia energética para estas cargas industriales, debido a que los datos son enviados a un sistema en la nube los operarios y administradores pueden observar los históricos para determinar si el consumo energético de los dispositivos está siendo aprovechado o por el contrario es un consumo de energía innecesario, esto también puede ser de utilidad para generar un proceso automatizado que sea encendido solo cuando se encuentre activa la línea de producción.

La flexibilidad de la comunicación modbus permite integrar el sistema de medición con otros dispositivos de comunicación inalámbrica como ZigBee, esto favorece la implementación de estos sistemas en casos como el de la bomba de agua que se encuentra a 25 metros del compresor ahorrando en términos de cableado y facilitando la instalación de los dispositivos, centralizando la información del medidor cableado y el comunicado por el protocolo ZigBee en la Raspberry para ser enviada al sistema en la nube.

REFERENCIAS

Poudineh, R., & Jamasb, T. (2014). Distributed generation, storage, demand response and energy efficiency as alternatives to grid capacity enhancement. Energy Policy, 67, 222–231. https://doi.org/10.1016/j.enpol.2013.11.073

Waide, P., & Brunner, C. U. (2011). Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. Internationale Energy Agency, na(na), 132.

Mohagheghi, S., & Raji, N. (2015). Dynamic demand response: A solution for improved energy efficiency for industrial customers. IEEE Industry Applications Magazine, 21(2), 54–62. https://doi.org/10.1109/MIAS.2014.2345799

Amaxilatis, D., Akrivopoulos, O., Mylonas, G., & Chatzigiannakis, I. (2017). An IoT-based solution for monitoring a fleet of educational buildings focusing on energy efficiency. Sensors (Switzerland), 17(10), 1–15. https://doi.org/10.3390/s17102296

PEACEFUL USES OF NUCLEAR ENERGY IN LESS INDUSTRIALIZED COUNTRIES: CHALLENGES, OPPORTUNITIES, AND ACCEPTANCE

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Abstract

While less industrialized countries may associate nuclear energy with weapons or with the adverse events that have taken place since the late 1970’s, the peaceful uses have greatly benefited society and the opportunity for nuclear energy playing a substantially expanded role in generating clean and abundant electricity is well recognized. For example, in the U.S., where nuclear power accounts for 19% of electricity, even though US public attitudes towards nuclear remain uncertain, a January 2022 Pew Research Center survey found that 35% of U.S. adults say the federal government should encourage the production of nuclear power, 26% say it should discourage it, and 37% say it should neither promote nor prevent it.

In addition to producing clean electricity, the peaceful uses of nuclear energy has significantly improved human life in health, agriculture, food preservation, industry, and the understanding of our world and universe. Nuclear technology is used in the diagnosis and treatment of cancer and other diseases, radiography cameras, blood irradiators, and radio sterilization of biological tissues for the treatment of various conditions; it helps the development of scientific knowledge on the understanding and searches for a solution on environmental issues, like climate change and tracing of ecological impacts; in augmenting agricultural productivity and the elimination of food diseases, like reducing the threat of fruit flies in Latin America; and in for various industrial applications like radiography, flow measurement and leak detection in industry and mining, in dredging operations in ports, and space exploration, among many others. Not to mention the critical impact of nuclear energy programs on a solid workforce and the technological development of the countries that scale their capabilities.

For energy, nuclear has the opportunity to expand the supply of clean electricity generation. To achieve the deep decarbonization required to keep the average rise in global temperatures below 1.5°C, combating climate change without an increased role of nuclear power generation would be much more complicated. The IEA state that achieving the pace of CO_2 emissions reductions in line with the Paris Agreement is already a considerable challenge, as shown in the Sustainable Development Scenario. It requires significant increases in efficiency and renewable investment and an increase in nuclear power. Also, the World Nuclear Association notices that nuclear power plants, throughout their life cycle, produce about the same amount of carbon dioxide-equivalent emissions per unit of electricity as wind and one-third of the emissions per unit of electricity compared to solar. Further, with the technological and

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financial attributes of small modular reactors (SMR), more countries and regions can gain the advantages available with nuclear energy.

In this work, we unveil the opportunities and challenges within less industrialized countries to develop a plan and their capabilities to take advantage of peaceful uses of nuclear energy and power generation.

Some of the critical issues/questions we address in this work are:

- How should governments interact with civil society in analyzing and evaluating the peaceful uses of nuclear energy? How should the benefits and risks of peaceful uses of nuclear energy be communicated to civil society? What role has the scientific community here?
- What steps should countries take to build capacities to become ready to decide on building critical infrastructure for the peaceful uses of nuclear energy?
- How can IAEA and other industrialized countries support capacity building in less industrialized countries to be ready for a yes or no decision regarding nuclear energy?
- How important are the institutional framework and strong and independent regulatory and supervisory authorities in the nuclear industry for an atomic program's success and safe development?
- In many countries, institutions are weak, which can seriously threaten the success and safety of any nuclear energy program. How can governments and the international community protect from this risk by exposing the world industry to higher downside risk?
- How should we address the lack of human capital, scientists, and experts in the field?
- Is nuclear power a realistic and cost-effective solution for less industrialized countries, given significant upfront investment costs and construction periods? Is an SMRs turn-on key a solution for less industrialized countries?
- Advantages and disadvantages of installing a turn-key SMR v/s large scale custom reactor, technology development and capacity building.
- When building nuclear power infrastructure, upfront investments are significant compared to other power generation sources, such as solar or wind, which can develop. How can less developed countries secure access to finance, and what are its essential requirements?
- What are the critical characteristics of technology when deciding on the different alternatives of nuclear technologies available in the market and future SMRs?
- Should nuclear power generation be evaluated as a standalone project, only looking at a long-term reliable supply of cheap energy?
- Chernobyl, Three Mile Island, and Fukushima nuclear accidents marked a stopping point in many countries on their decision to implement a peaceful use of atomic energy program. How can we assure that safety standards, in a broad sense, have been enhanced to preclude future situations like the ones there? Should the safety standards depend on organization structure development and modernized reactor design?

References

- CCHEN (2020), “Energía Nuclear de Potencia: Revisión de temáticas relevantes para una discusión,” Comisión Chilena de Energía Nuclear – CCHEN-.
- IAEA (2015), "Milestones in the Development of a National Infrastructure for Nuclear Power," IAEA Nuclear Energy Series No. NG-G-3.1 (Rev. 1).

- IAEA (2021), "Nuclear Technology Review 2021," IAEA GC(65)/INF/2.
- IEA (2022), “Nuclear Power and Secure Energy Transitions: From Today’s Challenges to Tomorrow’s Clean Energy Systems”
- Nivalde de Castro, Mauricio Moszkowicz and Lucca Zamboni (2022), “Perspectivas da Energia Nuclear no Setor Elétrico Brasileiro,” GESEL Grupo de Estudos do Sectro Eléctrico, UFRJ.
- Nuclear Energy Institute (2016), "Comments of the Nuclear Energy Institute on Staff's Responsive Proposal for Preserving Zero-Emissions Attributes, Proceeding on Motion of the Commission to Implement a Large-Scale Renewable Program and Clean Energy Standard, Case No. 15-E-0302," State of New York Public Service Commission.
- Pew Research Center (2022), "Americans Largely Favor U.S. Taking Steps to Become Carbon Neutral by 2050", by Alec Tyson, Cary Funk and Brian Kennedy, March 2022.
- Teresa Benson- Wiltschegg (1993), "Applying nuclear techniques for environmental protection: A global research network," IAEA BULLETIN, 2/1993.

Paper outline:

Abstract

Introduction

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Chapter 2: Peaceful uses of Nuclear Energy

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Chapter 4: Conclusions

References

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Jeffrey Binder has had over a thirty-year career in applied energy technology as both an engineering & scientific contributor and high impact leader. His experiences include nuclear reactor technology, renewable energy, advanced/critical materials, and manufacturing technology. He has had multiple leadership roles including Associate Laboratory Director for applied energy at Oak Ridge and Argonne National Laboratories, and the Founding Director of the University of Illinois Applied Research Institute. Dr. Binder has significant international experience in promoting nuclear and renewable energy technology. He has proposed, built, and led multiple technology development initiatives in areas from the nuclear reactor safety, fuel cycle, radioisotope production, advanced/critical materials, advanced energy systems, and manufacturing technology. Dr. Binder was a significant leader for the United States in supporting and solving nuclear safety and security issues following the Three Mile Island accident, the dissolution of the Soviet Union and following the Chornobyl accident, and the Fukushima accident in Japan.

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His experience also includes nearly seven years as Deputy Director for Operations at the Princeton Plasma Physics Lab, and 18 years at Argonne National Laboratory, where he held several positions, including Deputy Associate Director for Energy Sciences and Engineering, and Deputy Director/Chief Operations Officer. He has served as head of the U.S. Delegation on the ITER Council, on the New Jersey Department of Environmental Protections' Oyster Creek Oversight Panel, and on the D.O.E. Laboratory Operations Board. Earlier in his career, he spent four years in the U.S. Navy as a submarine officer, and he worked at Babcock & Wilcox manufacturing nuclear fuel for research reactors.

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Estado actual del transporte automotor carretero de cero y bajas emisiones en Colombia, un acercamiento desde la política pública

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Introducción

El dinamismo en los centros poblados ha llevado al aumento de la demanda de energía y con esto al aumento de las emisiones, el Panel Intergubernamental de Cambio Climático IPCC en su último informe ofrece nuevas estimaciones sobre las probabilidades de sobrepasar el nivel de calentamiento global de 1,5 ºC en las próximas décadas, así mismo expresa que a menos de que las emisiones de gases de efecto invernadero se reduzcan de manera rápida y a gran escala, limitar el calentamiento a cerca de 1,5 ºC o incluso a 2 ºC será un objetivo prácticamente inalcanzable; para lograr esos objetivos se requerirá de acciones inmediatas y profundas transformaciones (IPCC, 2021). La Agencia Internacional de energía ha definido al sector transporte como uno de los más relevantes en el ejercicio de descarbonización, considerando que a nivel mundial el sector del transporte emitió más de 7 Gt de CO2 en 2020 y casi 8,5 Gt en 2019, la disminución en el valor del año 2020 fue provocada por la pandemia de COVID 19 (International Energy Agency, 2021).

Colombia es un país con una matriz energética diversa, de acuerdo con el Balance de Energía Colombiano, el consumo final de energía del país para el año 2018 fue de 1.308 PJ, ocupando el primer lugar de participación el sector transporte con un 40% (UPME - Unidad de Planeación Minero-Energética, 2018). El modo carretero tiene la mayor participación en el total de la flota con (88%) contando pasajeros y carga, el siguiente modo con mayor participación es el aéreo (10%). Con respecto a la participación de los energéticos en el sector transporte, la gasolina tuvo una participación del 45%, el ACPM 40%, el Jet fuel 10 %, el GN 4%, el fuel oil 0,30% y la electricidad 0,07% (UPME - Unidad de Planeación Minero-Energética, 2018).

Considerando que, a futuro se tendrá un mayor uso de vehículos dado que el crecimiento urbano se mantiene constante, especialmente en los países en desarrollo, esto permite suponer que el uso de energía y los niveles asociados de emisiones de gases efecto invernadero aumenten de manera proporcional (Martinez, 2015). Adicionalmente los costos de los combustibles fósiles están en continuo aumento, dada la creciente demanda con relación a una oferta limitada (UPME - Unidad de Planeación Minero-Energética, 2018). Es por esto que a nivel mundial se tiene como acción relevante la transición hacia tecnologías de cero y baja emisión que permitan descarbonizar el transporte y garantizar la movilidad para la población (International Energy Agency, 2020a, 2020b, 2021).

Todos los factores anteriormente expresados han sido considerados a nivel nacional, y se han generado una serie de acciones de política pública como lo establecido en la Política de Crecimiento Verde que tiene como meta para el año 2030 tener 600.000 vehículos eléctricos (Departamento Nacional de Planeación, 2018a), la Política para el Mejoramiento de la Calidad el Aire que tiene por objetivo aumentar la incorporación de vehículos eléctricos y dedicados a GN en los sistemas de transporte público (Departamento Nacional de Planeación, 2018b) y la Ley 1964 que tiene por objeto promover el uso de vehículos eléctricos y cero emisiones, contribuyendo así a la reducción de emisiones contaminantes (Congreso de la República de Colombia, 2019), entre otras acciones de política pública que han permitido el despliegue de tecnologías de cero y baja emisión y que a su vez han posicionado a Colombia como líder a nivel de Latinoamérica.

Metodología

Se pretende realizar una revisión de literatura que permita reconocer algunas políticas públicas implementadas en la región. Así mismo, realizar una revisión rigurosa del estado actual de Colombia que permita identificar las políticas públicas actualmente implementadas y esto como ha influenciado en la penetración de tecnologías de cero y baja emisión en la flota nacional. A partir de la revisión regional y nacional poder identificar potenciales avances y lecciones aprendidas.

Para el ejercicio de levantamiento de información se considerarán artículos en revistas indexadas, estudios, planes, programas, proyectos diseñados e implementados tanto en otras naciones de la región como en Colombia y los datos e información de entidades públicas, organizaciones internaciones y nacionales y demás actores relevantes.

Resultados esperados

Se espera obtener un diagnóstico específico del estado actual del transporte automotor carretero de cero y bajas emisiones en Colombia, considerando la serie de tiempo de flota de cero y bajas emisiones que transita en el país, los incentivos tributarios y no tributarios implementados y demás acciones de política implementadas. Adicionalmente se espera construir un comparativo entre Colombia y otros países de la región en cuanto al avance de la penetración de los vehículos de cero y bajas emisiones, y de las políticas implementadas.

Conclusiones

El consumo eficiente de la energía es un pilar importante en el proceso de desarrollo de cualquiera de los niveles de la sociedad, pues garantiza la permanencia y disponibilidad, considerando en la disponibilidad la calidad, cantidad y acceso a los recursos energéticos. Dado que el sector transporte es responsable de una porción importante del consumo de energía y de las emisiones, es pertinente buscar una transición energética que permita satisfacer las necesidades actuales y garantizar la seguridad energética para los años siguientes. En Colombia, se han implementado una serie de acciones de política pública, las cuales son de alta importancia para este ejercicio, pero podrían ser insuficientes para alcanzar los objetivos trazados.

Referencias

Congreso de la República de Colombia. (2019). Ley 1964 de 2019. *Diario Oficial 50976*, 1–57. Retrieved from https://www.suin-juriscol.gov.co/viewDocument.asp?id=30036543%0Ahttps://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=94590

Departamento Nacional de Planeación. (2018a). Política de Crecimiento Verde - CONPES 3934, 44. Retrieved from https://colaboracion.dnp.gov.co/CDT/Conpes/Económicos/3934.pdf

Departamento Nacional de Planeación. (2018b). Política para el mejoramiento de la calidad del aire - CONPES 3943. *Dnp*, 1–79.

International Energy Agency. (2020a). Global EV Outlook 2020. *Global EV Outlook 2020: Technology Report*, 39–85.

International Energy Agency. (2020b). Sustainable Recovery: World Energy Outlook Special Report. *World Energy Outlook*, 185. Retrieved from https://www.iea.org/reports/sustainable-recovery%0Ahttps://webstore.iea.org/download/direct/4022?fileName=Energy_Technology_Perspectives_2020_-_Special_Report_on_Clean_Energy_Innovation.pdf%0Ahttps://www.oecd-ilibrary.org/energy/sustainable-recovery_3f36f

International Energy Agency. (2021). Net Zero by 2050 A Roadmap for the, 222. Retrieved from www.iea.org/t&c/no need for

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen,. *Cambridge University Press*, (In Press), 3949. Retrieved from https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

Martinez, P. (2015). Energy and sustainable development in cities : A case study of Bogotá. https://doi.org/10.1016/j.energy.2015.02.003

UPME - Unidad de Planeación Minero-Energética. (2018). *Plan Indicativo de Abastecimiento de combustibles líquidos*.

Análisis de pobreza energética en poblaciones afrodescendientes considerando una transición energética justa.

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Introducción.

Actualmente, en Europa, los indicadores de pobreza energética indican la dificultad de una familia para pagar los servicios públicos energéticos. Por eso, definen que la pobreza energética es “la situación que sufren los hogares que son incapaces de pagar los servicios mínimos de energía que satisfagan sus necesidades domésticas básicas o que se ven obligados a destinar una parte excesiva de sus ingresos a pagar las facturas energéticas de sus viviendas” (Ecodes, 2021). En Colombia, mientras continúa la transición energética, existen más de 1 millón de ciudadanos sin acceso de calidad a la electricidad o que no están conectadas a la red eléctrica nacional, éstas se identifican como Zonas No Interconectadas (ZNI). Al mismo tiempo y considerando esto como una causa, el nivel de calidad de vida es mínimo y el índice de necesidades básicas insatisfechas (NBI) es alto, lo que agrava la situación de minorías étnicas como afrodescendientes e indígenas, que son los principales pobladores en estas regiones. Por ello este artículo, presenta el análisis de una población identificada como pobre energéticamente, se define y aplica a una población del consejo comunitario afrodescendiente del pacifico colombiano. Para una transición justa, los resultados de una investigación multidimensional revelan una pobre medición de indicadores que no consideran las múltiples dimensiones de la comunidad. Además, se identifica el enorme potencial energético para el desarrollo de proyectos energéticos sostenibles que permitan impulsar emprendimientos de economía local social.

Metodología

En este artículo, las discusiones están centradas en una propuesta interdisciplinaria que correlaciona el diseño resultado del dialogo de saberes con la comunidad, la consideración de implementación de sistemas energéticos sostenibles (ambiental, económica y técnicamente), particularmente usando energía solar fotovoltaica y los discursos, las nociones y la mirada crítica planteada desde la triada entre la pobreza energética, la ciudadanía de la energía y los procesos de apropiación social de la tecnología. Parte de las revisiones críticas sobre los modelos de medición e indicadores, la incidencia e impacto de la pobreza energética en las comunidades, la construcción y desarrollo de procesos de apropiación social de la tecnología y la pertinencia discursiva y pragmática de una concepción de la ciudadanía de la energía. Se concreta en preguntas tales como: primero: ¿Qué se concibe como pobreza energética?, segundo: ¿Cómo se mide la pobreza energética? Y tercero, concluyendo con las reflexiones sobre: ¿Cuáles son las concepciones de los procesos de apropiación social de las tecnologías y la ciudadanía de la energía?

Caso de estudio: Comunidad Afrodescendiente del Consejo Comunitario de Bahía Málaga, en Buenaventura, Colombia. En este artículo, se considera el pacífico colombiano como la zona de estudio, que pertenece o está identificada como una zona no interconectada – ZNI, a la red o sistema de distribución de electricidad. El grupo de investigación realiza la selección de la comunidad, considerando la cercanía (menores costos en traslados), accesibilidad a la comunidad, organización bajo un Consejo Comunitario y finalmente el interés de la misma en trabajar por la universalización de las energías y participar de una transición energética utilizando los recursos energéticos renovables locales. Para ello, se realiza un diagnóstico multidimensional, que permite identificar múltiples aspectos para un más acertado y completo diseño de la solución energética. Los principales aspectos analizados y descritos a continuación son: el social, ambiental, político, económico y técnico.

Resultados

Una detallada Evaluación de Indicadores Globales de Pobreza Energética que permitieron definir un indicador apropiado para medir e implementar en las ZNI con poblaciones afrodescendientes del pacífico colombiano. Además, resultados estadísticos de un completo diagnóstico multidimensional de poblaciones del pacífico, que permiten un desarrollo más acertado de proyectos energéticos sostenibles en una transición energética justa. Por ello, se define y mejora el índice de pobreza multidimensional, con diseño multicriterio para estas poblaciones. Los habitantes de Bahía Málaga, son multidimensionalmente pobres.

Conclusiones

La pobreza energética, es definitivamente un indicador multidimensional.

En nuestra investigación, la metodología que el DANE, tiene, a cada indicador le da un peso que, en el agua, está dentro del indicador vivienda y servicios públicos, solo recibe una importancia del 4% del indicador.

Los habitantes de Bahía Málaga, son multidimensionalmente pobres porque el 41.67% de sus habitantes tiene la educación básica primaria incompleta y solo un 16.67% bachillerato completo

- **Referencias**

Boardman, B. (1991). Fuel poverty is different. Policy Studies, 12(4), 30-41. https://doi.org/10.1080/01442879108423600

Ecodes. Ecología y desarrollo sostenible. (2021). Pobreza energética. https://archivo.ecodes.org/web/pobreza-energetica/que-es-la-pobreza-energetica

Lopez, Yuri. Gaviria, Fabian. (2018). Metodología y evaluación de recursos energéticos renovables: implementación de microrredes aisladas. Universidad Distrital Francisco José de Caldas. Visión electrónica. 12. 10.14483/22484728.14260.

LA IMPORTANCIA DE LA PARTICIPACIÓN DE LA DEMANDA EN LA TRANSFORMACIÓN TECNOLÓGICA DE LOS MERCADOS ELÉCTRICOS

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Introducción

El incremento de la participación de las fuentes renovables en la generación de energía eléctrica, sumado a la aparición de nuevos modelos de negocio, son indicadores de que los mercados eléctricos se encuentran atravesando una etapa de transformación tecnológica [1]–[3]. En este mismo sentido, se observa que diferentes gobiernos propenden por favorecer dicha transformación, ya que a través de la suscripción de acuerdos internacionales como el Acuerdo de París - COP21 [4] se manifiesta el interés y compromiso por buscar y favorecer mecanismos de generación de energía más amigables con el medio ambiente.

En medio del proceso de transformación tecnológica se ha observado cómo la demanda ha tenido un papel destacable. Por ejemplo, gracias a la disminución de los precios de tecnologías renovables se ha incrementado la generación con fuentes como la solar, no sólo a gran escala, sino también a nivel de micro y auto generación [5]–[7]; y han aparecido formas de generación no centralizada sino distribuida, modificando algunos paradigmas en la generación eléctrica tradicional [3], [8], [9]. Por otro lado, algunos autores han mostrado cómo algunas políticas que buscan favorecer determinados cambios en los mercados eléctricos a partir de la modificación del comportamiento de la demanda (incentivos en precios, subsidios, tarifas horarias, entre otros) logran impactar los mercados eléctricos de forma importante, haciendo incluso peligrar su estabilidad [10]–[12].

Ante estos acontecimientos, y considerando que múltiples políticas actuales de los gobiernos están orientadas a modificar los comportamientos de la demanda; resulta pertinente preguntarse de qué manera la participación de la demanda puede favorecer la transición tecnológica de los mercados de electricidad. El presente trabajo se acerca a estas cuestiones a partir de una visión sistémica del problema, utilizando la metodología de simulación con dinámica de sistemas para el caso de estudio del mercado eléctrico colombiano.

Metodología

Para dar respuesta a la pregunta planteada se toma en consideración la metodología de simulación, ya que ésta permite comprender las dinámicas de sistemas complejos, además de favorecer el efecto de intervenciones de estrategias y políticas, así como la predicción de estados futuros [13].

La metodología de simulación seleccionada es la dinámica de sistemas puesto que ésta permite plasmar relaciones de realimentación entre las variables, incluyendo efectos de complejidad, causalidad y no linealidad; presentes en las dinámicas de los mercados eléctricos, y en las decisiones de los consumidores [14], [15].

En cuanto al análisis de los impactos de la participación de la demanda los mercados eléctricos, se utilizaron indicadores sobre efectos en curva de carga y emisiones contaminantes al medio ambiente; pues ayudan a cuantificar la contribución técnica y ambiental de la participación de la demanda en los mercados de electricidad.

Resultados

Este trabajo identifica identifica la contribución de los usuarios de electricidad a la transición tecnológica de energía en el mercado eléctrico colombiano como caso de aplicación, utilizando la simulación con dinámica de sistemas como herramienta metodológica.

Se encuentra que, dentro de las diferentes alternativas de participación de la demanda, la generación distribuida es la alternativa que produce los mayores ahorros para los usuarios, aún cuando se implementan baterías para el almacenamiento, y que además es una alternativa de participación que contribuye a las mayores disminuciones de emisiones de CO2 a la atmósfera. Sin embargo, se encuentra también que ésta alternativa es la que genera los mayores retos de operación técnica del mercado, a menos que se lo suusarios la utilicen con baterías de respaldo.

Finalmente se encuentra que el uso de políticas por parte del regulador puede favorecer la participación de la demanda, y modular los efectos de las diferentes alternativas de participación en el desempeño técnico y ambiental del sistema.

Conclusiones

Las principales conclusiones de este trabajo consisten en resaltar la participación activa de la demanda como una herramienta del regulador para favorecer la transición tecnológica de los mercados eléctricos. A través de indicadores ambientales y técnicos se concluye que los usuarios activos pueden ayudar a una transición energética favorable para el sistema, y además, se evidencia que el apoyo regulatorio es importante para que los efectos sean más rápidos y beneficiosos para el mercado en conjunto.

Referencias

[1] OCDE/IEA, “World energy outlook 2016: resumen ejecutivo,” Paris, 2016. doi: http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf.

[2] REN 21, *Renewables 2017: global status report*. 2017.

[3] C. Rochlin, “Distributed renewable resources and the utility business model,” *Electr. J.*, vol. 29, no. 1, pp. 7–12, 2016, doi: 10.1016/j.tej.2015.12.001.

[4] UNFCCC, “Paris Agreement,” 2015. doi: FCCC/CP/2015/L.9/Rev.1.

[5] J. A. Hayward and P. W. Graham, “A global and local endogenous experience curve model for projecting future uptake and cost of electricity generation technologies,” *Energy Econ.*, vol. 40, pp. 537–548, Nov. 2013, doi: 10.1016/j.eneco.2013.08.010.

[6] OECD/IEA, “Next generation wind and solar power from cost to value,” 2016. doi: 10.1787/9789264258969-en.

[7] IEA, “Medium-Term Renewable Energy Market Report 2016. Executive Summary,” 2016. doi: 10.1007/s13280-010-0059-7.

[8] R. Khalilpour and A. Vassallo, “Leaving the grid: An ambition or a real choice?,” *Energy Policy*, vol. 82, pp. 207–221, Jul. 2015, doi: 10.1016/j.enpol.2015.03.005.

[9] M. F. Akorede, H. Hizam, and E. Pouresmaeil, “Distributed energy resources and benefits to the environment,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 724–734, Feb. 2010, doi: 10.1016/j.rser.2009.10.025.

[10] L. M. Cardenas, C. J. Franco, and I. Dyner, “Assessing emissions–mitigation energy policy under integrated supply and demand analysis: the Colombian case,” *J. Clean. Prod.*, vol. 112, pp. 3759–3773, Jan. 2016, doi: 10.1016/j.jclepro.2015.08.089.

[11] M. Jimenez, C. J. Franco, and I. Dyner, “Diffusion of renewable energy technologies: The need for policy in Colombia,” *Energy*, vol. 111, pp. 818–829, 2016, doi: http://doi.org/10.1016/j.energy.2016.06.051.

[12] L. Cardenas, M. Zapata, C. J. Franco, and I. Dyner, “Assessing the combined effect of the diffusion of solar rooftop generation, energy conservation and efficient appliances in households,” *J. Clean. Prod.*, vol. 162, pp. 491–503, Sep. 2017, doi: 10.1016/j.jclepro.2017.06.068.

[13] N. Gilbert and K. G. Troitzsch, *Simulation for the Social Scientist*, Second. Mc Graw-Hill Education, 2005.

[14] J. D. Sterman, *Systems Thinking and Modeling for a Complex World*, no. December 1999. 2000.

[15] I. Dyner, C. J. Franco, and L. M. Cardenas, “Energy Policy Modeling in the 21st Century,” no. 65, 2013, doi: 10.1007/978-1-4614-8606-0.

Policy Brief: *Mercado eléctrico 100% renovable al año 2030 en Colombia*

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***Abstract*—El presente articulo presentará la propuesta de política pública producto del modelamiento de dinámica de sistemas, realizado por la Universidad Jorge Tadeo Lozano y la UTberlin para establecer y asegurar un mercado eléctrico 100% renovable en Colombia para el año 2030, basado en la generación de las diversas Fuentes de Energía Renovable. A través de este documento se presentará un contexto internacional y nacional acerca de los compromisos de Colombia para apoyar la descarbonización del sector energético nacional y la desaceleración del cambio climático en el mundo. Se presentarán los objetivos generales y específicos, así como la prospección para el cumplimiento de la hoja de ruta 100 % en Colombia al año 2030, describiendo los actores principales y los proyectos específicos para alcanzar esta meta.**

***Index Terms*—Política pública, energía renovable, descarbonización, mercado eléctrico ,Universidad Jorge Tadeo Lozano, UTBerlín, 2030.**

I. INTRODUCCIÓN

EN el marco del Acuerdo de Paris y de los Objetivos de Desarrollo Sostenible-ODS, en es especial el objetivo 7, energía asequible y no contaminante, investigadores de la Universidad Jorge Tadeo Lozano y la Universidad Técnica de Berlín, presentan la propuesta de Política Pública para el mercado eléctrico 100 % renovable al año 2030 en Colombia, con un horizonte de tiempo de 8 años. La Política Pública de Energía 100 % renovable al año 2030 en Colombia, busca atender el total de la demanda del sistema eléctrico interconectado nacional a través de fuentes limpias, y excluyendo aquellas fósiles como gas y carbón, a través de una estrategia costo-eficiente para el pueblo colombiano. Esto, con el propósito de apoyar la descarbonización del sector energético nacional y, liderando una campaña mundial que busca contribuir con la desaceleración del cambio climático, puesto que muchas de las medidas tomadas en los diversos sectores de la gran mayoría de los países están siendo insuficientes, deficientes e ineficaces. Después de abordar una metodología que integra escenarios y simulaciones, que incorpora el establecimiento y análisis de los predeterminados e incertidumbres, un grupo de técnicos, especialistas y expertos en energía a nivel nacional desarrolla el siguiente objetivo para contribuir a la solución del problema anteriormente mencionado: Colombia.

II. METODOLOGÍA - PROPUESTA DE POLÍTICA PÚBLICA

Establecer y asegurar un mercado eléctrico 100% renovable en Colombia para el año 2030, basado en la generación de las diversas Fuentes de Energía Renovable.

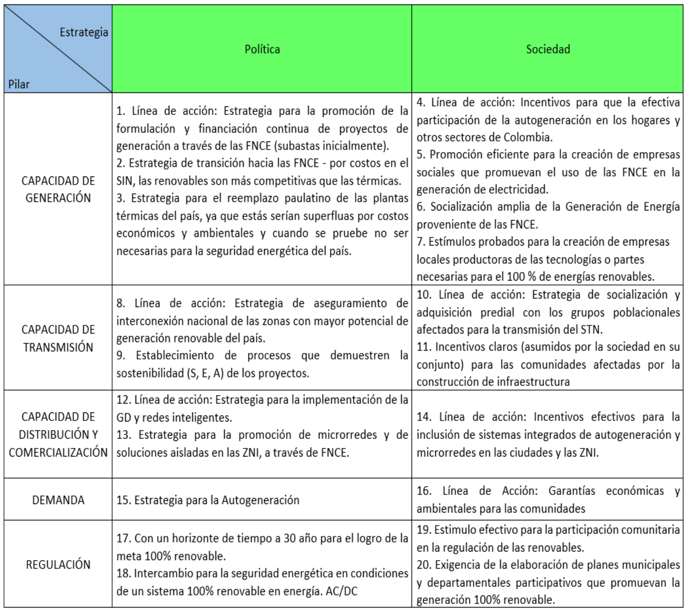
A. Objetivos específicos

- ”Más oferta en la generación de renovables” – Asegurar que tanto los incrementos de la demanda como el reemplazo de la generación eléctrica convencional de origen fósil se de a través del uso de las fuentes renovables.
- “Mayor intercambio directo” – Desarrollar los proyectos necesarios de la red interconectada nacional para conectar las regiones norte y centro de Colombia que promuevan el intercambio energético generado por las fuentes renovables.
- “Mayor generación distribuida” – Asegurar la difusión de paneles solares en techos de viviendas, edificios y bodegas, o en lugares vecinos, para abastecer total o parcialmente las correspondientes necesidades eléctricas, garantizando la facilidad de venta de excedentes.
- “Comercialización renovada” – Actualizar las capacidades de distribución y comercialización que promuevan y aseguren la utilización de las FNCE en el mercado eléctrico nacional.
- “Demanda consciente y renacida” – Establecer el plan programático de necesidades de la sociedad colombiana en el marco de la implementación de las FNCE y el 100% renovables al año 2030.
- “Regulando el presente y el futuro” – Generar el marco normativo para priorizar el uso de las fuentes renovables de energía.

En aras de dar cumplimiento a estos objetivos, el Ministerio de Minas y Energías de Colombia, la UPME, los 32 Departamentos de Colombia, así como las ciudades Capitales, Bogotá D.C. las Corporaciones Autónomas Regionales del País y la Academia hacen parte del Plan de Acción de la Política Pública de Energía 100 % renovable al año 2030 en Colombia, el cual comprende veinte líneas de acción (20) y veintinueve (29) proyectos dispuestos en la vigencia de la política. El cumplimiento de esta política pública requiere de una inversión que no corresponde definir en este Policy Brief)

III. RESULTADOS ESPERADOS

En el caso de la propuesta de política pública aquí descrita, esta se desarrollará a través de las acciones de los actores de valor político y de la sociedad, los cuales juntando esfuerzos y cooperando podrán llevar a cabo la transición de la capacidad de generación renovable, promoviendo proyectos de transmisión para el intercambio entre las regiones norte y centro, y estableciendo leyes y normativas que permitan que las empresas privadas y la población se beneficien de la electricidad renovable, ya sea por medio de la autogeneración o a través de grandes empresas generadoras de electricidad. Otro de los factores que promoverá e impulsará las FNCE, son los precios de estas tecnologías, los cuales llevarán a la paulatina inutilización de las plantas térmicas basadas en carbón para el año 2025 y en gas para el año 2026. Otro de los hitos relevantes, es el protagonismo de las fuentes solar y eólica, las cuales proveerán aproximadamente el 36% de la generación eléctrica (GE) del país al año 2030. Ahora bien, esta política se complementará con el incremento significativo de la fuente Solar Dw (Techos Solares) la cual al año 2030 alcanzará 24360 MWh. Finalmente se destaca que la matriz energética de Colombia se soportaría en las hidroeléctricas previamente construidas, las cuales se complementarán con las FNCE planteadas anteriormente. Las estrategias para el aumento de la generación se presentan a continuación:



Estrategia Pilar	Política	Sociedad
CAPACIDAD DE GENERACIÓN	1. Línea de acción: Estrategia para la promoción de la formulación y financiación continua de proyectos de generación a través de las FNCE (subastas inicialmente). 2. Estrategia de transición hacia las FNCE - por costos en el SIN, las renovables son más competitivas que las térmicas. 3. Estrategia para el reemplazo paulatino de las plantas térmicas del país, ya que estás serían superfluas por costos económicos y ambientales y cuando se pruebe no ser necesarias para la seguridad energética del país.	4. Línea de acción: Incentivos para que la efectiva participación de la autogeneración en los hogares y otros sectores de Colombia. 5. Promoción eficiente para la creación de empresas sociales que promuevan el uso de las FNCE en la generación de electricidad. 6. Socialización amplia de la Generación de Energía proveniente de las FNCE. 7. Estímulos probados para la creación de empresas locales productoras de las tecnologías o partes necesarias para el 100 % de energías renovables.
CAPACIDAD DE TRANSMISIÓN	8. Línea de acción: Estrategia de aseguramiento de interconexión nacional de las zonas con mayor potencial de generación renovable del país. 9. Establecimiento de procesos que demuestren la sostenibilidad (S, E, A) de los proyectos.	10. Línea de acción: Estrategia de socialización y adquisición predial con los grupos poblacionales afectados para la transmisión del STN. 11. Incentivos claros (asumidos por la sociedad en su conjunto) para las comunidades afectadas por la construcción de infraestructura
CAPACIDAD DE DISTRIBUCIÓN Y COMERCIALIZACIÓN	12. Línea de acción: Estrategia para la implementación de la GD y redes inteligentes. 13. Estrategia para la promoción de microrredes y de soluciones aisladas en las ZNI, a través de FNCE.	14. Línea de acción: Incentivos efectivos para la inclusión de sistemas integrados de autogeneración y microrredes en las ciudades y las ZNI.
DEMANDA	15. Estrategia para la Autogeneración	16. Línea de Acción: Garantías económicas y ambientales para las comunidades
REGULACIÓN	17. Con un horizonte de tiempo a 30 año para el logro de la meta 100% renovable. 18. Intercambio para la seguridad energética en condiciones de un sistema 100% renovable en energía. AC/DC	19. Estimulo efectivo para la participación comunitaria en la regulación de las renovables. 20. Exigencia de la elaboración de planes municipales y departamentales participativos que promuevan la generación 100% renovable.

Fig. 1: Hoja de ruta 100% renovables

IV. CONCLUSIONES

1) A través del instrumento de política pública se fomentará la generación de electricidad 100 % renovable en Colombia, ya que por medio de esta se lograrán integrar a los actores sociales, políticos y privados, los cuales a través de un plan acción y una hoja de ruta impulsaran el objetivo 100 % renovables al año 2023.
2) A través del modelamiento de dinámica de sistemas se lograron diferentes escenarios para la generación de electricidad 100 % renovable, en los cuales la sociedad y el sector público o el ejecutivo son los principales responsables de que se logré de aquí al año 2030 o en su defecto se traslade en el tiempo.
3) Esta propuesta de política pública servirá de base para que los tomadores de decisiones en el país, tengan opciones para incluirlas en los planes nacionales de desarrollo, planes de departamentales de desarrollo y en los planes de ordenamiento territorial.
4) Es posible llegar a un escenario 100 % renovables en Colombia, si se centran los esfuerzos en generación y distribución de energía eléctrica, especialmente en el intercambio energético entre la región central y la costa norte de Colombia.

REFERENCES

[1] UPME. (2021). Plan Energético Nacional 2020-2050: “La transformación energética que habilita el desarrollo sostenible.” UPME.

[2] UPME. (2022, August). Informe Dinámico de Registro de Proyectos de Generación de Energía Eléctrica. Sistema de Información Eléctrico Colombiano.

[3] SIEL, SIMEC, Sistema de información eléctrico colombiano, Disponible: http://www.siel.gov.co/Inicio/Generaci%C3%B3n/Inscripci%C3%B3ndeproyectosdeGeneraci%C3%B3n/tabid/113/Default.aspx

[4] Dyner Rezonzew et.al. (2022). Hoja de ruta electricidad 100% renovable en Colombia a 2030. Editorial Jorge Tadeo Lozano

[5] IRENA. (2021). Renewable Power Generation Costs in 2020. International Renewable Energy Agency.

POTENCIAL DE INSERCIÓN DE VEHÍCULOS DE CELDAS DE COMBUSTIBLE EN EL PARQUE AUTOMOTOR COLOMBIANO

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INTRODUCCIÓN

En 2020 el sector transporte fue el responsable del 20% de las emisiones globales de gases de efecto invernadero (GEI) (IEA, 2021). Adicionalmente, desde el 2000 las emisiones aportadas por este sector se han incrementado en un 28%, principalmente por el aumento del parque automotor de vehículos de transporte terrestre, por lo que descarbonizar este sector se ha vuelto una prioridad en todo el mundo (IEA, 2021).

En Colombia, de acuerdo con el Inventario Nacional y Departamental de Gases Efecto Invernadero del año 2014, de las 236,97 Mt CO2-eq totales emitidas del país, el 11,14 % son atribuidas transporte terrestre (UNDP, 2018). Por esta razón, dentro del portafolio de las 32 medidas de mitigación de GEI de la NDC, 7 van dirigidas específicamente al transporte terrestre (Gobierno de Colombia, 2020). De estas 7 medidas, la más ambiciosa es la de movilidad eléctrica, ya que la meta para 2030 consiste en la inserción de 600.000 vehículos eléctricos al parque automotor, para la mitigación de 4,04 Mt CO2-eq (Gobierno de Colombia, 2020). Para lograr esta meta, actualmente existen dos tecnologías totalmente eléctricas, también llamadas cero emisiones: (i) los vehículos de batería eléctrica (BEV por sus siglas en inglés) y (ii) los vehículos de celdas de combustibles (FCEV por sus siglas en inglés).

Este estudio presenta un análisis de los posibles escenarios de despliegue de tecnologías FCEV en el sector de transporte terrestre en Colombia, para contribuir con la reducción de emisión de GEI durante el periodo 2020-2050. Los escenarios contemplaron los siguientes factores: tecnologías disponibles y su prospectiva, autonomía de los vehículos, eficiencia, costos, competitividad con otras tecnologías, y el potencial de adopción tecnológica en Colombia.

METODOLOGÍA

Para evaluar el potencial de adopción de vehículos cero emisiones, se compararon las tecnologías FCEV, BEV y de combustión interna (ICEV por sus siglas en inglés), calculando el Costo Total de Propiedad (TCO por sus siglas en inglés) entre 2020 y 2050 para las siguientes categorías de vehículos: automóviles, taxis, buses, camiones y tractocamiones, con tecnologías FCEV, BEV y ICEV durante toda su vida útil. El TCO de cada vehículo se obtuvo considerando los siguientes tres componentes: (i) el costo del vehículo antes de impuesto, (ii) el IVA, y (iii) el costo del combustible, incluyendo el impuesto al carbono establecido por el decreto 926 de 2017 (MINAMBIENTE, 2017), el NDC (Gobierno de Colombia 2020). El IVA para los FCEV y BEV se tomó del 5 % (Minambiente 2019) de acuerdo con lo aplicado actualmente en Colombia, sin tener en cuenta el límite de cupos, y para los ICEV del 19 %.

La vida útil es un factor clave que lo afecta directamente el costo del vehículo, por lo que se considera que las mejoras tecnológicas de los FCEV proyectadas en diferentes estudios aumentaran su vida útil, y por lo tanto su competitividad, para el planteamiento del escenario . Adicionalmente, se tiene en cuenta la implementación de políticas que incentiven la adopción de tecnologías cero emisiones, como regulaciones, subvenciones, incentivos tributarios, subastas de contratación entre otras.

Como resultado del análisis comparativo, se determina para qué tipologías de vehículos y en qué año los FCEV presentan un menor TCO en comparación con los BEV y los ICEV. Adicionalmente, se establece un porcentaje de inserción de estos vehículos, para lo que se tomaron en cuenta: la tendencia actual de crecimiento que tienen los BEV, las políticas que Colombia tiene para la adopción de tecnologías cero emisiones en el transporte público y las metas internacionales establecidas para descarbonizar el sector transporte.

RESULTADOS ESPERADOS

En el caso de los vehículos de transporte liviano (automóviles y taxis), la tecnología FCEV no demuestra ser competitiva respecto a BEV. En los automóviles, se espera que los BEV lleguen a ser más económicos que los ICEV, a diferencia de los taxis, donde a pesar de la reducción de costos, el ICEV será más económico en 2050 si no se mejora la vida útil de las baterías. Tanto para los BEV como para los FCEV el factor determinante son los kilómetros recorridos, donde en promedio los taxis recorren 53.000 kilómetros más que los automóviles (UPME, 2020).

Por otro lado, en el caso de vehículos de transporte pesado (buses, tractocamiones y camiones), los FCEV tendrían un menor TCO que los BEV y los ICEV. En los buses, siempre que la vida útil aumente, podrían ser más competitivos que los BEV e incluso que los ICEV. Para el caso de los tractocamiones, la tecnología disponible de FCEV alcanzaría la paridad de costos con los BEV sin necesidad de aumentar su vida útil. Sin embargo, para que los tractocamiones FCEV logren menor TCO que los ICEV se requieren aumentar su vida útil. Finalmente, los FCEV son la mejor alternativa para camiones en la actualidad, debido a que no es necesario aumentar la vida del vehículo para que el TCO sea menor que el de los BEV y los ICEV.

A partir de lo anterior, se planeta el escenario del porcentaje de compra de camiones FCEV durante el periodo 2020-2050 como se muestra en la Figura 1. De igual manera se planteará este escenario para buses y tractocamiones donde también se espera encontrar que los FCEV sean la tecnología adecuada para la descarbonización del sector en estas tipologías.

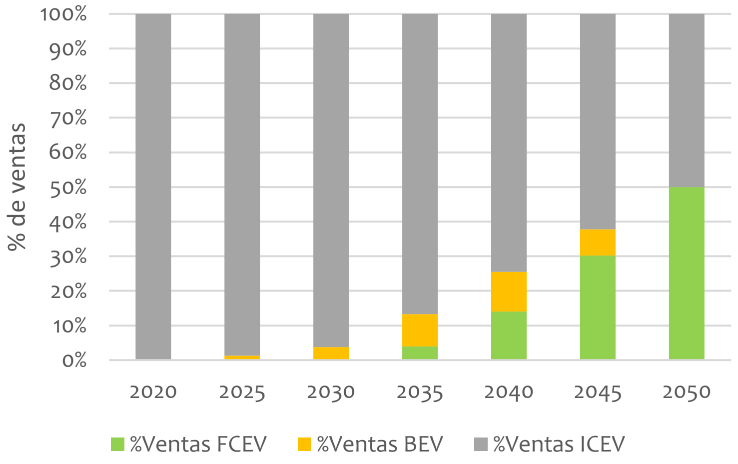

Figura 1. Escenario distribución de ventas de camiones de: combustión interna (ICEV), batería eléctrica (BEV) y de celdas de combustible (FCEV), en el periodo 2020 a 2050.

CONCLUSIONES

Se concluye que los vehículos FCEV en el estado tecnológico actual solo son viables en Colombia para los camiones. Para lograr la viabilidad y despliegue en buses y tractocamiones se requiere minimizar este impacto económico por medio del desarrollo tecnológico que permita aumentar la vida útil de los vehículos, reducir su costo hasta el punto en el que sea viable su remplazo, o una combinación de ambos.

REFERENCIAS

Gobierno de Colombia. (2020). *ACTUALIZACIÓN NDC COLOMBIA-2020 Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC)*.

IEA. (2021). *Tracking Transport 2021*. https://www.iea.org/reports/tracking-transport-2021

MINAMBIENTE. (2017). *Principales preguntas frente al impuesto nacional al carbono y la solicitud de no causación por carbono neutralidad (Decreto 926 de 2016)*.

UNDP, G. de C. (2018). *Segundo Reporte Bienal de Actualización de Colombia ante la CMNUCC*. https://unfccc.int/sites/default/files/resource/47096251_Colombia-BUR2-1-2BUR%20COLOMBIA%20SPANISH.pdf

UPME. (2020). *Plan Energético Nacional*. Plan energético nacional

SESIÓN DE POSTER

El 22 de noviembre se realizó la exposición de poster en el cual se contó con la participación de 6 expositores:

1. Efecto de la energía en el proceso de potabilización del agua en zonas no interconectadas.
   Autores: Catalina Maya Iregui, Maria Ríos Puerta, Alexandra Pantoja Quiscualtud y Laura Cárdenas Ardila

2. Evaluación de las opciones de almacenamiento térmico de energía aplicables en zonas no interconectadas de la región caribe colombiana.
   Autores: Genny Carolina Pinzon, John Harvey Gonzalez y Claudia Caro Ruiz.

3. Hidrógeno verde en Colombia: Contexto y perspectivas.
   Autores: Carmenza Osorio Gutiérrez, Laura Milena Cardenas Ardila y Juan Sebastián Jaén Posada.

4. Developers' perspective on barriers affecting distributed solar PV generations in Chile.
   Autores: Shahriyar Nnasirov, Paula Gonzales, Claudio A. Agostini, Carlos Silva y Jose Opazo

5. Assessment of Energy System Decarbonization for Colombia Using an Optimization Modelling Approach.
   Autor: Fernando Plazas

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Efecto de la energía en el proceso de potabilización del agua en Zonas No Interconectadas

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Introducción

En Colombia alrededor de dos millones de personas aún viven sin electricidad, puesto que se encuentran en lugares geográficamente aislados, donde no es viable la interconexión a la red eléctrica nacional, estos son más conocidos como Zonas No Interconectadas (ZNI) [1]. En algunos municipios de este país existen altos índices de necesidades básicas insatisfechas, específicamente en el acceso a servicios de energía, agua potable, educación, salud y vivienda digna [2], impactando directamente en el nivel de vida de la población.

Entre las ZNI en Colombia se encuentra el municipio de Murindó, ubicado en el Urabá antioqueño, fronterizo con el departamento del Chocó. Este se ha caracterizado por estar en un permanente aislamiento y tener poca presencia del Estado, lo cual lo ha llevado a estar en situaciones precarias en cuanto al acceso al servicio de agua y energía.

En este sentido, en lugares alejados de fuentes confiables de agua potable, por ejemplo, aquellos que no cuentan con redes de acueducto, la energía solar es una opción para apoyar el proceso de la potabilización del agua [3]. Lo anterior es el caso del municipio de Murindó, el cual carece de un sistema de acueducto para abastecer a la comunidad de agua potable [4], por tal razón la energía solar es una opción dadas las condiciones actuales del municipio frente a la radiación solar y las ventajas que se destacan de este recurso por su naturaleza inagotable, renovable y su utilización libre de polución [5].

Teniendo en cuenta la importancia del acceso al agua potable para mejorar la calidad de vida de la población, específicamente del municipio de Murindó, este trabajo pretende analizar cuál es el impacto del uso de la energía en la potabilización del agua en dicha región.

Metodología

Con el fin de analizar el efecto que podría tener la energía como alternativa para aportar en la problemática de la potabilización del agua en el municipio de Murindó, se implementa la dinámica de sistemas, ya que es un campo que posibilita la comprensión de la estructura y la dinámica de los sistemas complejos en los que estamos integrados [6]. En este sentido, se realiza una caracterización y análisis causal del proceso de potabilización del agua en el municipio, con el fin de identificar las variables y las relaciones causales existentes. Finalmente, se elabora un modelo de simulación para analizar el impacto que tiene la energía solar como solución energética para apoyar el proceso de potabilización del agua para una ZNI de Colombia.

Resultados esperados

La caracterización del proceso refleja que, en Murindó, el tratamiento que se le realiza al agua difiere en gran medida del proceso convencional que debe recibir este recurso, ya que solo se realiza captación, desinfección y almacenamiento mediante métodos muy caseros y con los recursos que la población tiene a su alcance. El análisis del proceso potabilización hace visible que el Municipio carece de una red de alcantarillado o de planta de tratamiento de agua, por lo tanto, las soluciones energéticas que se evalúen deben permitir una integración descentralizada. Por otro lado, con el diagrama causal se establecen como variables importantes el porcentaje de agua para consumo por hogar, las precipitaciones y el consumo eléctrico de la planta portátil potabilizadora de agua. En cuanto al modelo de simulación construido se busca conocer las características que debe tener en cuenta el municipio de Murindó para la solución de la energía en el proceso de potabilización del agua, en términos de cantidades, comportamiento en el tiempo e impacto en la calidad del agua y en la comunidad.

Conclusiones

El uso de la energía solar puede ser una opción viable para mejorar el proceso de potabilización actual del municipio de Murindó, lo cual se pretende medir por medio de un modelo de dinámica de sistemas ya que ha encontrado dentro las simulaciones una fuerte dependencia del municipio frente al ciclo del agua, puesto que si tienen el recurso hídrico existe más proliferación de enfermedades, sin embargo, cuando no hay suficiente agua tienen periodos de sequía que afectan la vida cotidiana de los habitantes de una región que tiene altos índices de pobreza.

Referencias

[1] E. Garcés, C. J. Franco, J. Tomei, and I. Dyner, “Alternativas de gestión para el suministro eléctrico sostenible en zonas no interconectadas - ZNI,” *Encuentros 2021 comunidades, Univ. y Territ.*, 2021.

[2] J. C. Feres and X. Mancero, “El método de las necesidades básicas insatisfechas (NBI) y sus aplicaciones en América Latina,” 2001. .

[3] J. E. Castrillón Forero and D. A. Hincapié Zuluaga, “Potabilizar agua con energía solar, una alternativa para las comunidades más alejadas de los centros urbanos,” *trilogía Cienc. Tecnol. Soc.*, vol. 4, no. 6, p. 121, 2012, doi: 10.22430/21457778.76.

[4] Alcaldía Municipal de Murindó, “Plan de desarrollo Murindó 2016-2019.”

[5] M. C. C. Máquez and L. V. R. Rodriguez, “Diseño Y Evaluación Financiera De Un Sistema De Tratamiento De Agua a Partir Del Uso De Energía Solar En El Carmen de Bolívar,” pp. 1–105, 2018.

[6] J. D. Sterman, “System Dynamics: systems thinking and modeling for a complex world,” *J. Franklin Inst.*, 2002, doi: 10.1016/s0016-0032(99)90164-3.

Evaluación de las opciones de almacenamiento térmico de energía aplicables en zonas no interconectadas de la región caribe colombiana

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Introducción:

La región Caribe colombiana conformada por 7 departamentos cuenta en la mayoría de estos con Zonas No Interconectadas (ZNI) en sectores rurales apartados de las capitales, por lo que sus habitantes carecen del servicio de electricidad y si lo llegan a tener este no está disponible las 24 horas del día. El plan del Gobierno Nacional es poder garantizar que estas familias cuenten con suministro de energía para mejorar la calidad de vida ya que el común denominador en estos sectores es la extrema pobreza [1].

En estos lugares no conectados a la red nacional la solución se ha enfocado en el uso de plantas generadoras alimentadas por combustibles fósiles que suplen electricidad por unas pocas horas al día. Actualmente se está introduciendo un tipo de generación más limpio a través de las fuentes de energía no convencionales como la solar y la eólica, pero estas no están disponibles todo el tiempo, por lo que se hace necesario el uso de sistemas que permitan tomar la energía mientras el recurso solar o eólico está disponible y almacenarla garantizando el aprovechamiento de esta cuando los usuarios la requieran. El almacenamiento de energía no está tan desarrollado a nivel mundial para el uso a pequeña escala y el que existe es muy costoso y con un tiempo de vida útil corto, por lo que a través de este trabajo lo que se busca es evaluar los sistemas de Almacenamiento Térmico de Energía (TES) como una opción para garantizar el suministro continuo de energía a los hogares de las ZNI del Caribe colombiano. Actualmente los sistemas TES están más enfocados al calentamiento o refrigeración y sólo una pequeña parte de esta tecnología se está encaminando al almacenamiento de energía para luego ser entregada como electricidad. Los sistemas TES se dividen dos tipos térmicos y químicos, los primeros pueden ser por calor sensible o por calor latente, los cuales usan materiales sólidos, líquidos, gaseosos o combinación entre estos para acumular el calor [2]. El identificar un tipo de sistema TES que se adapte a las condiciones geográficas y energéticas de las ZNI del Caribe colombiano sería un paso importante para contribuir con la mejora de las condiciones de vida de los habitantes de estas zonas ya que contarían con energía eléctrica que ayuda a impulsar y potencializar las actividades económicas de la región.

Metodología:

Teniendo en cuenta que la mayor participación de nuevos proyectos en energías renovables no convencionales parte de los sistemas solares fotovoltaicos, la primera parte del trabajo de este artículo se enfocará en resaltar los niveles de radiación que se presentan en la región caribe, los cuales pueden oscilar entre los 4.5 a 5.5 kW-h/ día. [3]

Definido el nivel de radiación solar para el caso de estudio, se procura hacer la estimación de las horas que el sistema TES deberá dar respaldo total o parcial de energía. Adicionalmente, se deberá estimar un perfil de carga por carga usuario de estos sectores.

Con el siguiente trabajo se revisarán los diferentes tipos de tecnología para el almacenamiento de energía térmica (TES) y su efectiva aplicación para proyectos a menor escala (menores a 10 kW), principalmente para autoconsumo; los cuales provienen de la autogeneración en las ZNI.

Para realizar esta evaluación se analizarán diferentes parámetros [2]: la capacidad de energía almacenada, la potencia, la eficiencia, el periodo de almacenamiento, el tiempo de carga y descarga; y unos de los factores con mayor importancia, el costo.

Resultados esperados: Principales hallazgos

Con esta evaluación metodológica de los diferentes TES, se espera identificar la solución con mayor viabilidad para la implementación de sistemas de almacenamiento de energía proveniente de fuente no convencionales.

Conclusiones:

Los principales aportes en este documento se fundamentan en:

- Determinar la radiación solar y perfil de carga de los usuarios producto del caso de estudio
- Identificar sistema de almacenamiento térmico de energía y sus parámetros técnicos óptimos a ser implementado en la zona de estudio.
- Contribuir a la identificación de sistemas alternativos de bajo costo que permitan suplir la demanda energética para este tipo de comunidades.

REFERENCIAS

[1] Ministerio de Minas y Energía, *Gobierno Nacional aumenta los subsidios en las Zonas No Interconectadas del país*, 2022.

[2] Ioan Sarbu and Calin Sebarchievici, *A Comprehensive Review of Thermal Energy Storage*, Sustainability, 2018.

[3] IDEAM, *Atlas irradiación Global Horizontal*. Consultado en la web: http://atlas.ideam.gov.co/visorAtlasRadiacion.html
Fecha de consulta: 28/08/2022

Hidrógeno verde en Colombia: Contexto y perspectivas

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Introducción

La demanda global de hidrógeno verde viene aumentando significativamente, debido principalmente a los potenciales nuevos usos del hidrógeno. En el sector del transporte, el hidrógeno verde surge como una alternativa para sustituir a los combustibles fósiles proporcionando ventajas relevantes en cuanto a autonomía y tiempos de repostaje comparado con los vehículos eléctricos de batería (Minenergía, 2021). Igualmente, para la reducción de la huella de CO_2 en procesos industriales (Minenergía, 2021). Este trabajo presenta las perspectivas que se tienen para el desarrollo del hidrógeno verde en Colombia, brindando posibles caminos de acción para su desarrollo en el país.

Metodología

En la construcción del contexto del hidrógeno verde en Colombia, se realiza una revisión de literatura sobre las condiciones y recursos disponibles en el país, y las expectativas de desarrollo internacionales, con el propósito de evaluar la introducción del hidrógeno verde como vector energético para la generación de energía renovable en Colombia.

Resultados esperados

Colombia tiene ventajas significativas en cuanto a la producción de hidrógeno de clasificación verde. Dentro de las ventajas, esta su privilegiada ubicación geográfica y recursos naturales, dado que, la generación hidroeléctrica en gran parte del territorio nacional llega a suponer el 70% de la generación eléctrica del país. Conjuntamente, se cuenta con el gran potencial eólico del norte del país y un atractivo potencial solar en gran parte del territorio (Minenergía, 2021).

Además, dentro del marco regulatorio colombiano, con el objetivo de incentivar el desarrollo de proyectos competitivos de hidrógeno y facilitar la búsqueda de acuerdos internacionales que atraigan la inversión y las capacidades tecnológicas necesarias, la Ley 2099 de Transición Energética de 10 de Julio de 2021 fija un marco fiscal ventajoso para la inversión en fuentes no convencionales de energía (ANLA,2021).

Asimismo, la Ley 1715 de 2014 aplica para el hidrógeno verde ya que está considerado dentro de las Fuentes No Convencionales de Energía Renovable (FNCER), lo que implica la exención de pago de derechos arancelarios, la exclusión del IVA, la depreciación acelerada y la deducción del impuesto de la renta del 50% de la inversión durante un periodo de 30 años (UPME, 2014).

También, Colombia cuenta con una red de gaseoductos de transporte de gas natural de más de 7500 km de longitud y una red de distribución que abastece una demanda nacional de 911 MPCD (millones de pies cúbicos promedios por día) (CREG, 2019). Esta red, se estima, podría ser reacondicionada si fuera necesario para el transporte y distribución de hidrógeno en los tramos que conectarían los centros de producción y demanda (Minenergía, 2021).

Finalmente, se prevé que utilizando modelos de electrólisis basados en 10 MW de capacidad para la producción de hidrógeno se obtiene que, para su uso en cada una de las aplicaciones potenciales en el país, es posible obtener hasta un 3,1% de reducción de emisiones de CO_2, con respecto a la meta de descarbonización de 2,3 $MtCO_2$/año para alcanzar la neutralidad de carbono para el año 2050 (Muñoz, Fernández & Mendoza, Beleño & Consuegra, Díaz, 2022).

Conclusiones

Existen en esta primera aproximación, indicaciones positivas de la viabilidad del aprovechamiento en un futuro cercano de H_2 producido en Colombia, considerando especialmente los suficientes recursos hidroeléctricos con que cuenta el país, que contribuirían a un desarrollo sostenible dentro de una economía de hidrógeno globalizada (Carvajal, Hernán & Babativa, Jhon & Alonso, Julio, 2010).

Referencias

ANLA. (2021). Transición energética, dinamización del mercado energético y reactivación económica del país. Retrieved October 15, 2021, from https://www.anla.gov.co/eureka/normatividad/leyes/1681-ley-2099-del-10-de-julio-de-2021-transicion-energetica-dinamizacion-del-mercado-energetico-y-reactivacion-economica-del-pais|

Carvajal, Hernán & Babativa, Jhon & Alonso, Julio. (2010). Estudio sobre producción de H2 con hidroelectricidad para una economía de hidrógeno en Colombia. Ingeniería y Competitividad, 12(1),31-42.ISSN: 0123-3033, from https://www-redalyc-org.udea.lookproxy.com/articulo.oa?id=291323517003

CREG. (2019). Proceso de selección del gestor del mercado de gas.Retrieved October 15, 2021, from https://www.creg.gov.co/sectores-que-regulamos/gas-natural/proceso-de-seleccion-del-gestor-del-mercado-de-gas

Minenergia. (2021). Colombia's hydrogen roadmap. Retrieved October 15, 2021, from https://www.minenergia.gov.co/enlaces-ruta-hidrógeno

Muñoz, Fernández & Mendoza, Beleño & Consuegra, Díaz. (2022). Análisis del potencial del uso de hidrógeno verde para reducción de emisiones de carbono en Colombia. Revista Fuentes, El reventón energético, 20(1), 57–72. https://doi.org/10.18273/revfue.v20n1-2022006

UPME. (2014). Integración de las energías renovables no convencionales al sistema energético nacional. Retrieved October 15, 2021, from https://www.upme.gov.co/Normatividad/Nacional/2014/LEY_1715_2014.pdf

Developers' perspective on barriers affecting distributed solar PV generations in Chile

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Overview

Over the last few years, the role of Non-Conventional Renewable Energies (NCRE) in the Chilean matrix has increased significanttly. The participation of NCRE in the total installed energy capacity grew from only 5% in 2014 to 30% in August 2021 (Energía Abierta, 2021). Solar PV technology is the most developed technology, corresponding to 16% of the energy matrix. However, most of this capacity comes from large-scale projects (utility scale). Despite the large resource potential of distributed solar PV generation in the country and all their benefits -emission reductions, cost reductions in electricity supply, decrease in electrical losses, improvement in service quality, and lessening transmission congestions- to date, the progress of these technologies in the country has been low. On reason for this is that distributed solar PV is currently in a development stage and facing several important obstacles.

In this context, we examine the key barriers that influence the implementation of distributed photovoltaic projects in Chile from the perspective of project developers, which is relevant as they are directly involved in the implementation of distributed generation projects. Identifying the main barriers allows to then propose policy recommendations to policy makers and other market players to encourage the deployment of distributed photovoltaic solar generation in Chile.

Methods

The methodology utilized in the paper consists of three complementary methods. First, we designed and implemented a questionnaire survey (comprising quantitative and qualitative data collection). Second, we conducted a series of semi-structured interviews (qualitative data collection only) with the project developers in Chile. Third, we analyzed the data to obtain robuts conclusions. These methods allow us not only to gather detailed and systematic information about the different barriers preventing a higher penetration of distributed solar PV generation in Chile, but also understanding better the exising limitations and analyzing them in a systematic a consistent way.

The questionnaire was designed and developed for conducting an online survey of project developers and obtain their opinions concerning the barriers affecting the distributed solar PV generation in Chile. For this purpose, a selection of potential barriers and relevant market actors were selected first. Then, a preliminary list of barriers was tested in a small pilot study to establish the extent to which the barriers found in the literature were also relevant and applicable in Chile. This was followed by the implementation of a questionnaire survey. Finally, the data collection from the online survey was complemented afterwards by face-to-face interviews from a random sample of selected developers from the survey respondents. The purpose of these interviews was to provide important insights and better understading of the investors' opinions and experiences over the barriers they have faced in the marketplace. In the last phase, the study uses a well-known methodology, based on the Technique of Order of Preference for Similarity with the Ideal Solution (TOPSIS) to identify and prioritize in a systematic and robust way the main critical barriers for the implementation of distributed photovoltaic projects.

Results

The results show that the most important barriers affecting and limiting the implementation of distribuated solar PV projects in Chile are "the structure of the network, its capacity and regulation for expansion" , "the long administrative process and the costs of connection to the network", "uncertainty due to stabilized price policy and other regulatory requirements" and "financial structuring and financing costs". Several of these barriers can be overcome with public policies that are not difficult to designed and implement as they mainly depend on directly government intervention, while others required a change in regulations that need Congress approval and then required a longer time.

Conclusions

The greater expansion of photovoltaic distributed generation in Chile can play a key role in the achievement of main energy objectives of the country established by the National Energy Policy plan, which contemplates fully decarbonizing its energy matrix and reaching 80% of electricity generation from renewable energy sources by 2050. In addition, This is why identifying the barriers that this segment currently faces is key to encouraging its further development.

References

Reindl, K. and Palm, J. (2021) Installing PV: Barriers and enablers experienced by non-residential property owners. *Renewable and Sustainable Energy Reviews.* 141, 110829. https://doi.org/10.1016/j.rser.2021.110829

Roberts M.B., Bruce, A. and MacGill, I. (2019). Opportunities and Barriers for Photovoltaics on Multi-Unit Residential Buildings: Reviewing the Australian Experience. *Renewable and Sustainable Energy Reviews.* 104, 95-110. https://doi.org/10.1016/j.rser.2018.12.013

Osorio-Aravena J.C., de la Casa, J., Tofflinger, J.A. and Muñoz-Cerón, E. (2021) Identifying barriers and opportunities in the deployment of the residential photovoltaic prosumer segment in Chile. *Sustainable Cities and Society.* 69, 102824. https://doi.org/10.1016/j.scs.2021.102824

Nasirov S., Silva, C. and Agostini, C.A. (2015) Investors'Perspectives on Barriers to the Deployment of Renewable Energy igur in Chile. Energies. 8(5), 3794-3814. https://doi.org/10.3390/en8053794

Assessment of Energy System Decarbonization for Colombia Using an Optimization Modelling Approach

Introduction

The threat of climate change has promoted the implementation of the Paris agreement aimed at holding global warming below 2 °C regarding pre-industrial levels and pursuing efforts to limit it below 1.5 °C (United Nations Framework Convention on Climate Change, 2015). Colombia is part of the agreement, and its National Determined Contribution (NDC) establishes a reduction of 169.44 MtonCO$_2$eq by 2030 and the tentative goal of carbon neutrality by 2050 (Gobierno de Colombia, 2020). The energy sector accounts for 31% of greenhouse gas emissions in Colombia (IDEAM et al., 2021), and it will require progressive decarbonization to fulfill the environmental targets.

The energy planning and the policy design to guarantee a secure energy transition can be supported by energy system optimization models (Kueppers et al., 2021). Previous works have explored the Colombian energy system using simulation models (Arango-Aramburo et al., 2020; Pupo-Roncallo et al., 2019; UPME, 2020) and integrated assessment models (Bataille et al., 2020; Calderón et al., 2014; Gonzalez-Salazar et al., 2016). Nevertheless, no prior study has explored the decarbonization pathways required to accomplish the NDC and a future approximation to carbon neutrality using an optimization model; thus, this is the gap to be addressed.

Methodology

The assessment of the energy mix is carried out by an energy system optimization model. The model is based on mixed-integer linear programming (MILP), gathering elements from popular frameworks such as OSEMOSYS (Howells et al., 2011) and MARKAL (Fishbonet & Abilocks, 1981). It represents the energy chain, including primary energy sources (domestic production and imports), processing technologies (refineries, treatment gas plants, power generation, biofuels production, hydrogen production), and end-use technologies for four sectors (transport, industry, residential, and others). The basic structure of the model is:

$$\begin{gathered}
\textbf{Min}\ \ \boldsymbol{Total\ Discounted\ Cost} \\
= \sum_{\boldsymbol{y=1}}^{\boldsymbol{years}} (\mathbf{1} + \boldsymbol{Discount\ Rate})^{(\boldsymbol{y_0-y})} * \Big(\sum_{\boldsymbol{k=1}}^{\boldsymbol{tech}} (\boldsymbol{Capital\ Investment} + \boldsymbol{Operating\ Cost} + \boldsymbol{Emissions\ Tax}\,)\\
\boldsymbol{s.t.}\\
\boldsymbol{a})\ \boldsymbol{balance\ of\ final\ energy\ supply\ and\ demand};\\
\boldsymbol{b})\ \boldsymbol{available\ renewable\ energy\ resources};\\
\boldsymbol{c})\ \boldsymbol{energy\ system\ constraints\ such\ maximum\ annual\ investment\ or\ maximum\ technology\ activity}\\
\boldsymbol{d})\ \boldsymbol{environmental\ constraints\ e.g.\ CO2\ emissions}\\
(\mathbf{1})
\end{gathered}$$

Results

The optimized total system cost for the baseline scenario is 414 billion dollars, and for the decarbonization scenario is 524 billion dollars. The capital investment for supply and demand technologies is huge, ranging between 175 and 251 billion dollars (around 3% of the 2020 national GPD per year). The energy transformation lies in the electrification of end-uses services, essentially in the residential and transport sectors, and hydrogen-powered equipment in the industrial sector. Natural gas is also relevant for the baseline scenario in the hard-to-abate sectors. The participation of electricity and hydrogen reaches 94% in the decarbonization scenario, as shown in Figure 1.

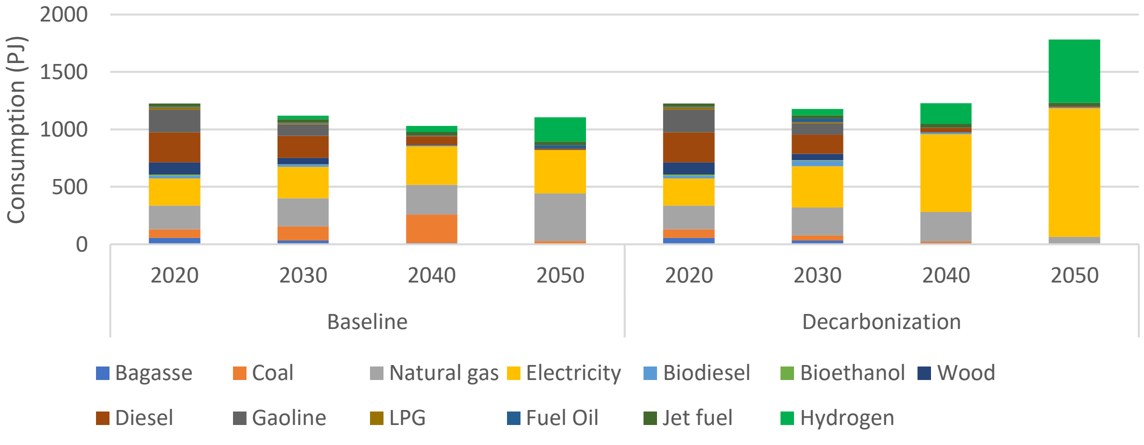

Figure 1. Final energy mix in the scenarios.

The increased use of electricity improves the energy efficiency of all the sectors going from 36% to 65%. It also reduces the carbon intensity moving from 66.7 TJ/MtonCO2 to 4.6 TJ/MtonCO2 (decarbonization scenario). The power generation shows a baseload of hydro (both dam and run of river) and increasing shares of photovoltaic (PV) utilities with and without battery systems, wind onshore facilities, and geothermal plants. The renewable installed capacity grows from 15% to 34% in the baseline scenario and to 62% in the decarbonization scenario, as illustrated in Figure 2.

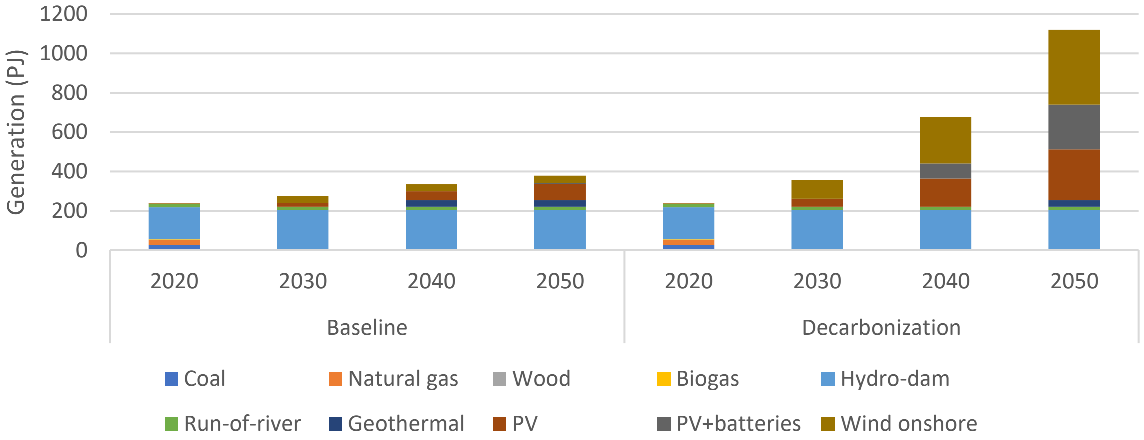

Figure 2. Power generation mix in the scenarios.

Conclusions

The study explored the optimal Colombian energy mix through a MILP model under two different scenarios. The model results provide four key insights: (1) Any decarbonization pathway will require unprecedented investments ranging between 175 and 251 billion dollars; (2) Electricity and hydrogen are the main energy carriers in the energy transition achieving mix shares of 94%, while natural gas is required to support the decarbonization of hard-to-abate sectors; (3) New technologies play a crucial role to increase energy efficiency highlighting solar photovoltaic energy, onshore wind energy, geothermal energy, batteries, electrolyzers, electric vehicles, and hydrogen-powered equipment; and (4) The carbon intensity in the energy sector could be reduced from 66.7 TJ/MtCO2 to 4.6 TJ/MtCO2 with a strong decarbonization strategy.

References

Arango-Aramburo, S., Veysey, J., Martínez-Jaramillo, J. E., Díez-Echavarría, L., Calderón, S. L., & Loboguerrero, A. M. (2020). Assessing the impacts of nationally appropriate mitigation actions through energy system simulation: a Colombian case. *Energy Efficiency*, *13*(1), 17–32. https://doi.org/10.1007/s12053-019-09826-7

Bataille, C., Waisman, H., Briand, Y., Svensson, J., Vogt-Schilb, A., Jaramillo, M., Delgado, R., Arguello, R., Clarke, L., Wild, T., Lallana, F., Bravo, G., Nadal, G., le Treut, G., Godinez, G., Quiros-Tortos, J., Pereira, E., Howells, M., Buira, D., … Imperio, M. (2020). Net-zero deep decarbonization pathways in Latin America: Challenges and opportunities. *Energy Strategy Reviews*, *30*. https://doi.org/10.1016/j.esr.2020.100510

Calderón, S., Alvarez, A. C., Loboguerrero, A. M., Arango, S., Calvin, K., Kober, T., Daenzer, K., & Fisher-Vanden, K. (2014). Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets. *Energy Economics*, *56*, 575–586. https://doi.org/10.1016/j.eneco.2015.05.010

Fishbonet, L. G., & Abilocks, H. (1981). MARKAL, A LINEAR-PROGRAMMING MODEL FOR ENERGY SYSTEMS ANALYSIS: TECHNICAL DESCRIPTION OF THE BNL VERSION. *International Journal of Energy Research*, *5*, 353–375. https://doi.org/doi.org/10.1002/er.4440050406

Gobierno de Colombia. (2020). *ACTUALIZACIÓN NDC COLOMBIA-2020 Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC)*. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Colombia First/NDC actualizada de Colombia.pdf

Gonzalez-Salazar, M. A., Venturini, M., Poganietz, W. R., Finkenrath, M., Kirsten, T., Acevedo, H., & Spina, P. R. (2016). A general modeling framework to evaluate energy, economy, land-use and GHG emissions nexus for bioenergy exploitation. *Applied Energy*, *178*, 223–249. https://doi.org/10.1016/j.apenergy.2016.06.039

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., Decarolis, J., Bazillian, M., & Roehrl, A. (2011). OSeMOSYS : The Open Source Energy Modeling System An introduction to its ethos , structure and development. *Energy Policy*, *39*(10), 5850–5870. https://doi.org/10.1016/j.enpol.2011.06.033

IDEAM, Fundación Natura, PNUD, MADS, DNP, CANCILLERÍA. (2021). *Tercer Informe Bienal de Actualización de Colombia a la Convención Marco de las Naciones Unidas para el Cambio Climático (CMNUCC).*

Kueppers, M., Paredes Pineda, S. N., Metzger, M., Huber, M., Paulus, S., Heger, H. J., & Niessen, S. (2021). Decarbonization pathways of worldwide energy systems – Definition and modeling of archetypes. *Applied Energy*, *285*. https://doi.org/10.1016/j.apenergy.2021.116438

Pupo-Roncallo, O., Campillo, J., Ingham, D., Hughes, K., & Pourkashanian, M. (2019). Large scale integration of renewable energy sources (RES) in the future Colombian energy system. *Energy*, *186*, 115805. https://doi.org/10.1016/j.energy.2019.07.135

United Nations Framework Convention on Climate Change. (2015). *Paris Agreement*.

UPME. (2020). *Plan Energético Nacional 2020-2050*. https://www1.upme.gov.co/DemandaEnergetica/PEN_2020_2050/Plan_Energetico_Nacional_2020_2050.pdf

A percepção dos proprietários de veículos automotores sobre a utilização do hidrogênio como combustível alternativo na cidade de São Paulo.

INTRODUÇÃO

A descarbonização do sistema energético global é fundamental para que o aumento da temperatura média da Terra não ultrapasse os 2ºC, objetivo central do Acordo de Paris. Os veículos com célula combustível a hidrogênio podem ser opções adequadas para lidar com os desafios de redução dos gases de efeito estufa emitidos pelos veículos tradicionais a combustão.

Sendo assim, a pesquisa em questão tem como objetivo obter respostas quanto a viabilidade técnica e econômica da incorporação do hidrogênio como fonte alternativa de abastecimento energético para as demandas atuais e futuras, bem como, do posicionamento dos proprietários de veículos automotores em relação ao tema.

Palavras-chave: combustíveis alternativos; hidrogênio; preferência declarada; conjoint analysis.

METODOLOGIA

Metodologia: A metodologia utilizada para o referido estudo é a de revisão bibliográfica e aplicação de pesquisa piloto por meio de questionário de preferência declarada. Para a aplicação dos questionários, serão elaboradas perguntas que possibilitem avaliar a percepção dos proprietários de veículos automotores quanto a adoção ou não desta modalidade energética em substituição aos combustíveis já utilizados.

RESULTADOS ESPERADOS

Esperamos que os dados obtidos na conclusão das atividades, aqui propostas, possam estimular novas pesquisas relacionadas à aceitabilidade dos veículos movidos a hidrogênio. Bem como, disponibilizar informações relevantes que possam servir de base aos tomadores de decisão e demais stakeholders envolvidos nessa temática.

CONCLUSÕES

A pesquisa social que investiga a aceitação e percepção pública da tecnologia do hidrogênio tem recebido atenção significativa nas últimas décadas. Este trabalho mostra que o incremento no número de artigos científicos direcionados à percepção dos principais interessados é um sinalizador de que a comunidade de pesquisa acadêmica, está comprometida em estabelecer uma economia do hidrogênio para tal vetor energético e entende a importância da sua aceitação social.

REFERÊNCIAS

BRANDLI, L. L.; HEINECK, L. F. M. **As abordagens dos modelos de preferência declarada e revelada no processo de escolha habitacional.** Ambiente Construído, Porto Alegre, v. 5, n. 2, p. 61-75, abr./jun. 2005.

CHOI, H.; KOOB, Y. **Do I have to buy it now? A vehicle replacement model considering strategic consumer behavior** Transportation Research Part D: Transport and Environment Volume 73, August 2019, Pages 318-337

IPCC, 2021: **Resumo para formuladores de políticas. Dentro:Mudanças Climáticas 2021: A Base da Ciência Física. Contribuição do Grupo de Trabalho I para o Sexto Relatório de Avaliação do Painel Intergovernamental sobre Mudanças Climáticas**.

KHAN, U.; YAMAMOTO, T.; SATOC, H. **An insight into potential early adopters of hydrogen fuel-cell vehicles in Japan** International Journal of Hydrogen Energy Volume 46, Issue 18, 11 March 2021, Pages 10589-10607

KOWALSKA, A. *et al*. **Consumer preferences towards alternative fuel vehicles. Results from the conjoint analysis Renewable and Sustainable** Energy Reviews Volume 155, March 2022, 111776

LIMA, R. V.; BRITO, T. L. F.; MOUETTE, D. **Veículos movidos a hidrogênio: O que pensam os proprietários de veículos automotores a respeito dessa alternativa energética como substituto para os combustíveis de origem fóssil?**. IN: Energy Virtual Experience (EVEx). Lisboa. 2021.

MARTIN, A. **Users in the design of Hydrogen Energy Systems: A systematic review International** Journal of Hydrogen Energy Volume 45, Issue 21, 17 April 2020.

MURUGAN, A. *et al.* (2019) **Measurement challenges for hydrogen vehicles International Journal of Hydrogen Energy** Volume 44, Issue 35, 19 July 2019.

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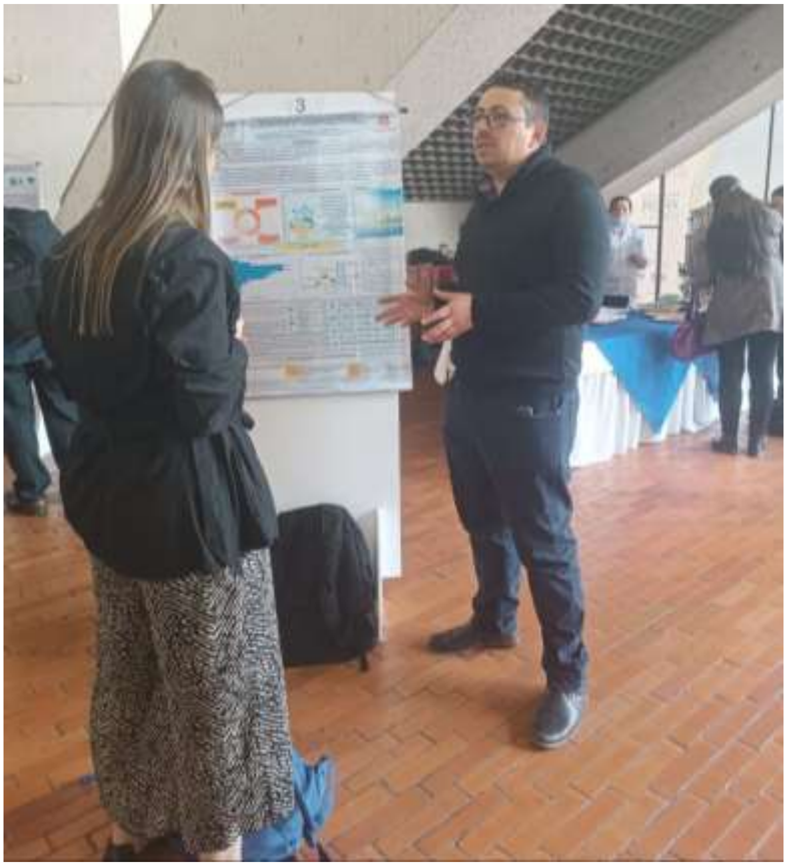

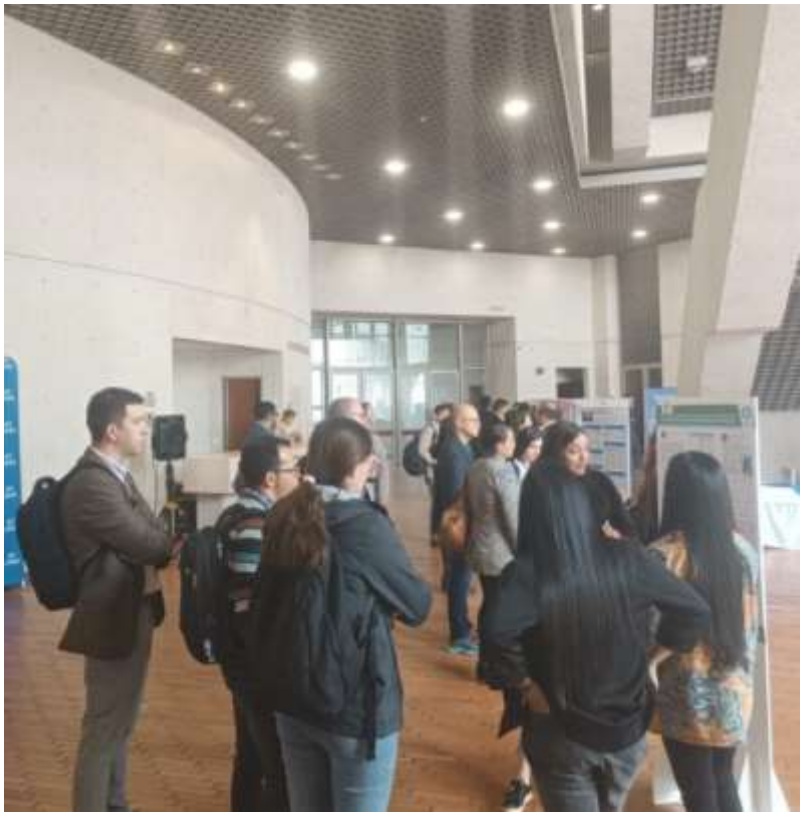


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