PLEXOS for modeling hydrothermal systems with strong presence of renewable and pumped storage plants.

Energy Exemplar

12th August 2019

Rio de Janeiro, Brazil

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1. Energy Exemplar

1. Energy Exemplar: History

Global organization founded in 1999 with headquarters in Adelaide, Australia.

More than 100 employees across eight locations in North America, South America, Europe and Australia.

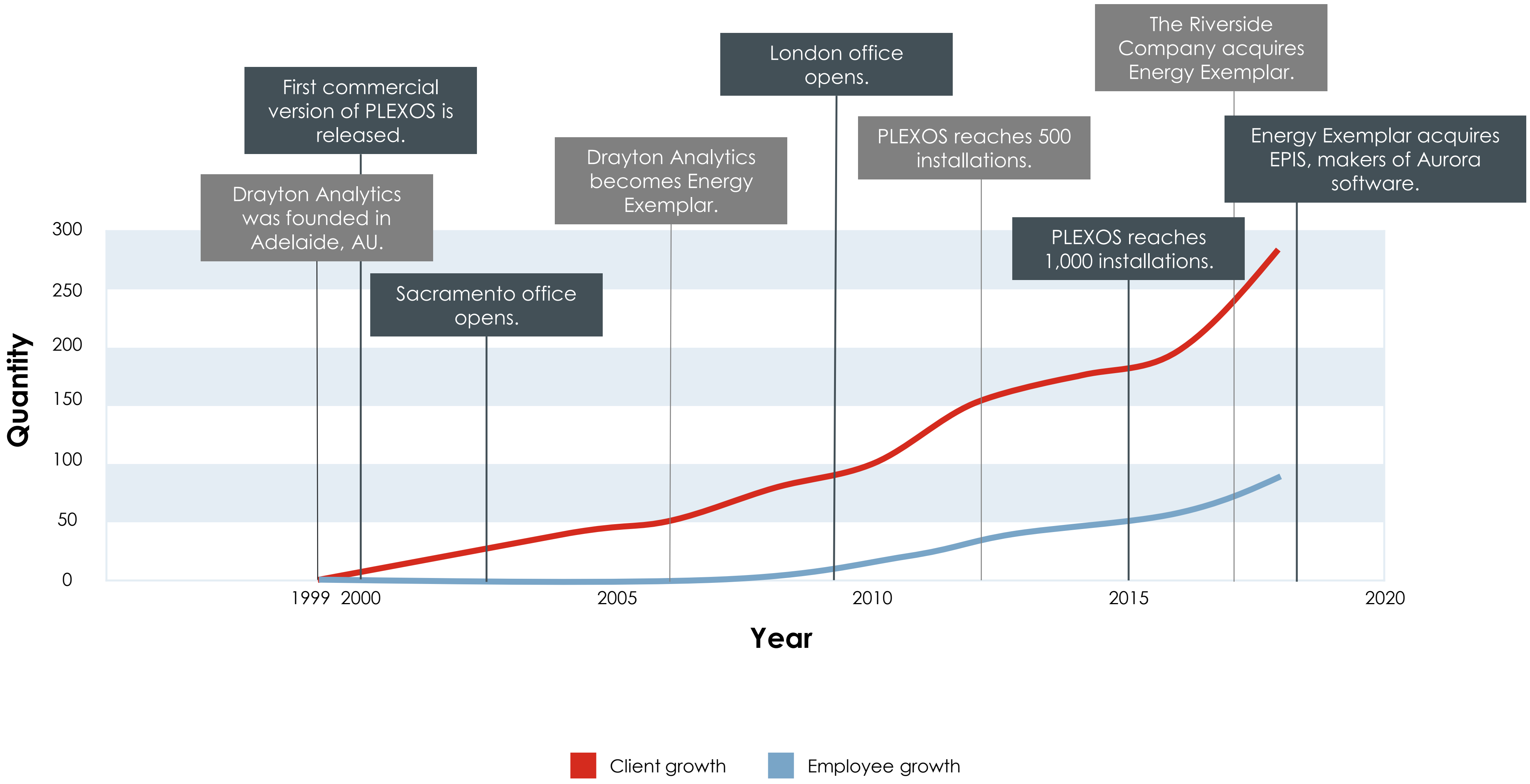
Serving 1,500 users in 52 countries at more than 300 sites.

In 2017, the Riverside Company became the majority stakeholder with a focus on growing the business into new markets.

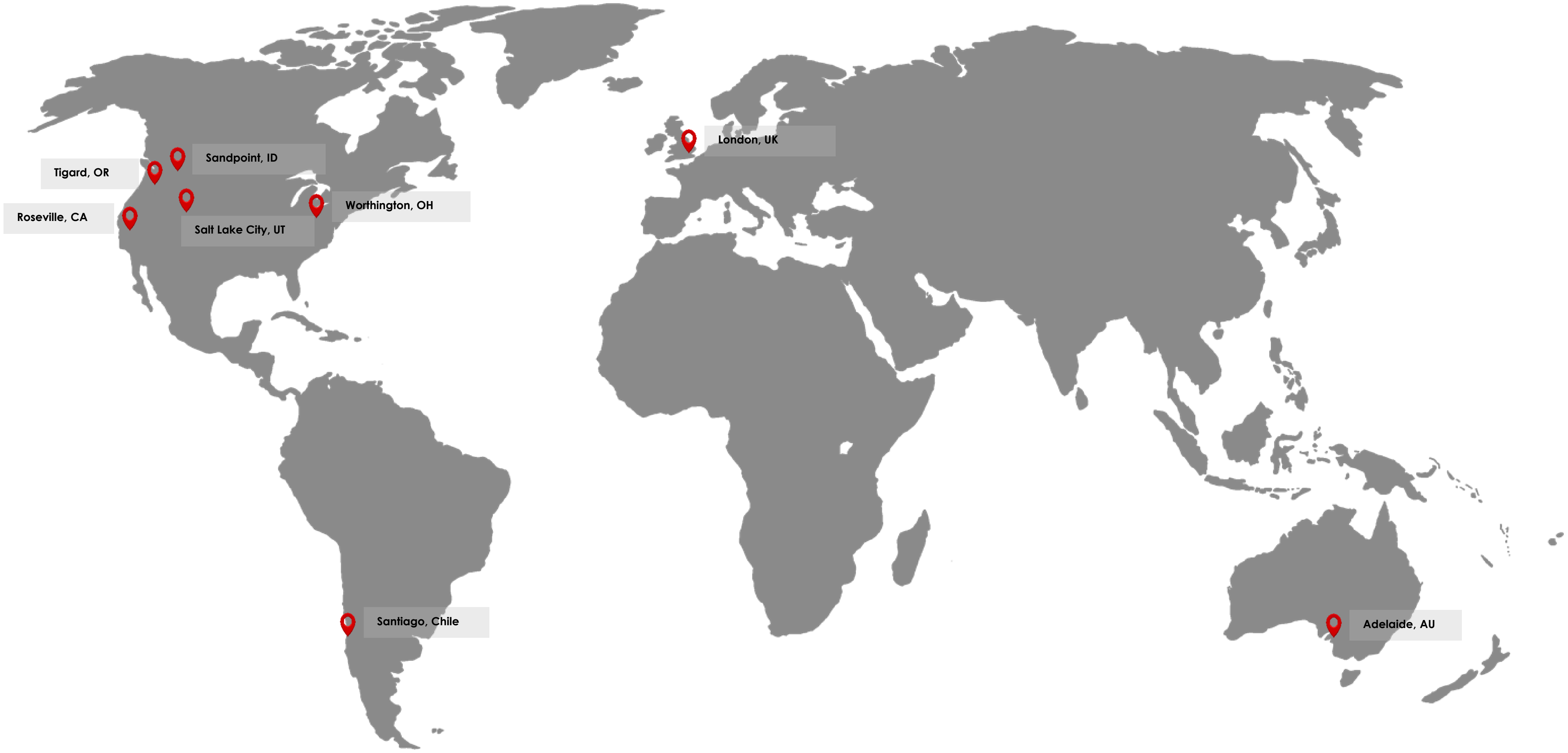
Acquired EPIS in 2018, developers of a leading electricity forecasting and analysis tool with clients in North America and Europe.

Proven power market simulation tool that is a leader in modelling flexibility, efficiency, simulation alternatives and advanced analysis.

1. Energy Exemplar: Growth

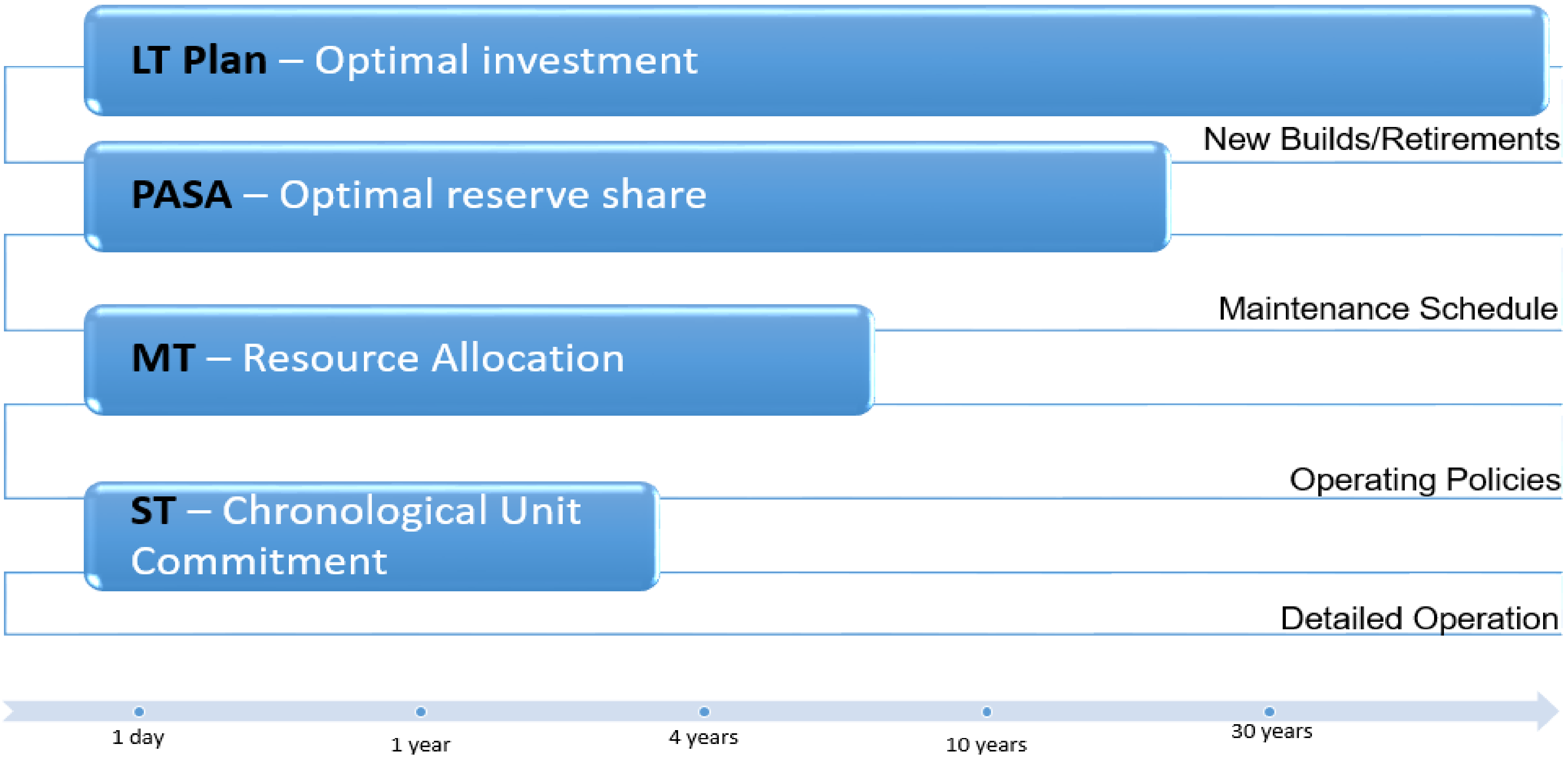


1. Energy Exemplar: Offices



2. PLEXOS
a) Introduction

2 a) PLEXOS. Introduction



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2 a) PLEXOS Introduction. Components

PLEXOS System

PLEXOS GUI

input interface

in.xml

Power system description
Analysis specification
Execution launch

.csv

output interface

solution.zip

Solution review and export

log

PLEXOS Engine

Data read
Power system logic application
Formulation and solution of sequence of MP problems
Solution interpretation

Solver

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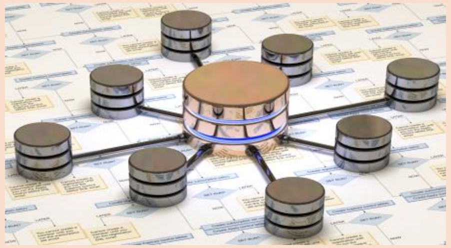
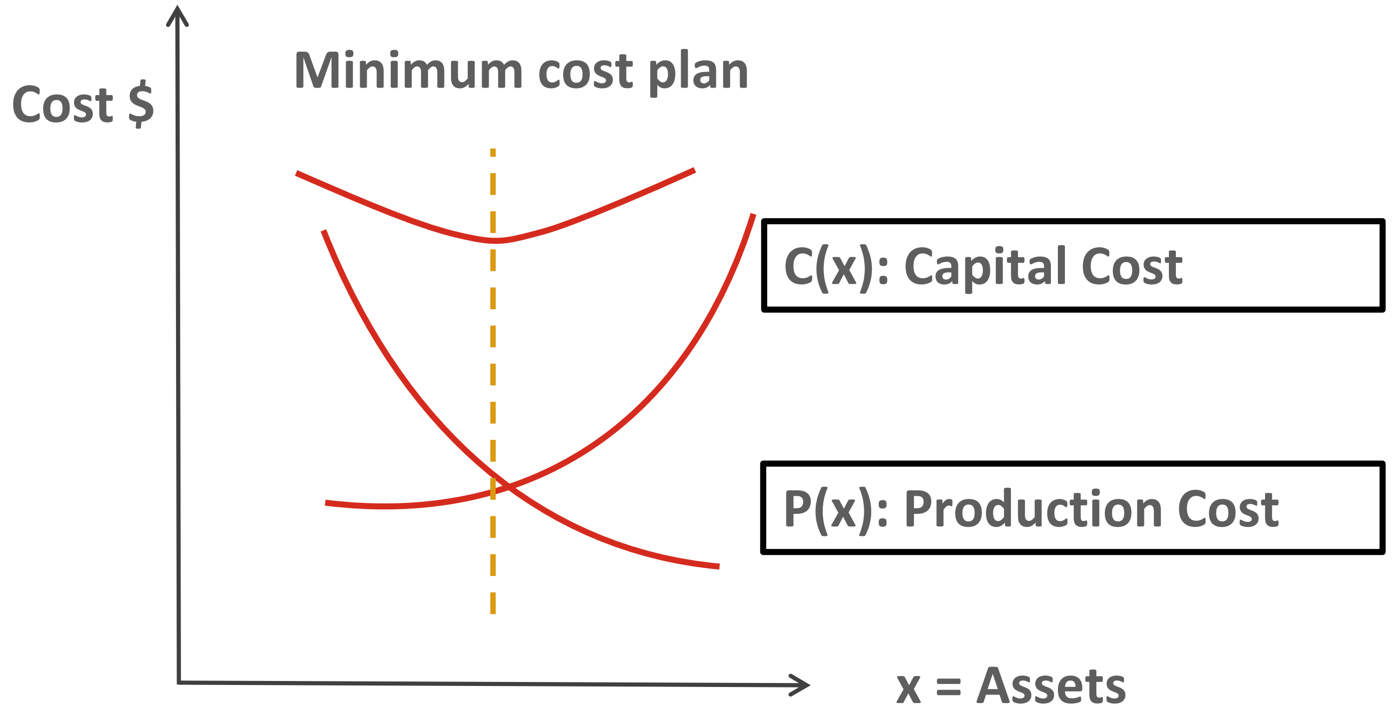
2 a) PLEXOS Introduction. Differentiation vectors

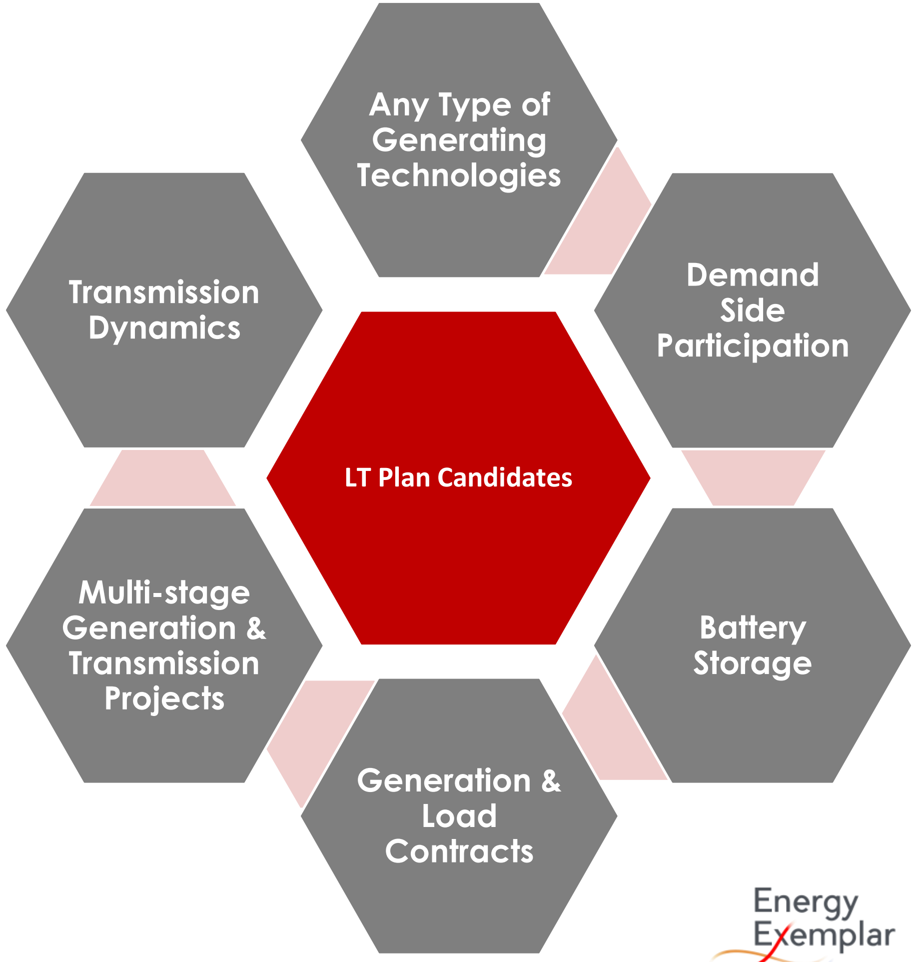
Differentiator	Description
Transparent	• PLEXOS is not a black box: User can print mathematical formulation to a file 
Customizable	• Generic constraint and decision variable class: User can write any constraint and decision variables to the problem 
Integrated	• Long, Medium and short term integrated: Unique database and graphical user interface integrating 3 phases. 

2. PLEXOS
b) Long Term

2 b) PLEXOS: Long Term

Finds the optimal combination of generation and transmission new builds and retirements





MIP Objective: Minimise NPV of capital & production

C(x) + P(x) = Total Cost

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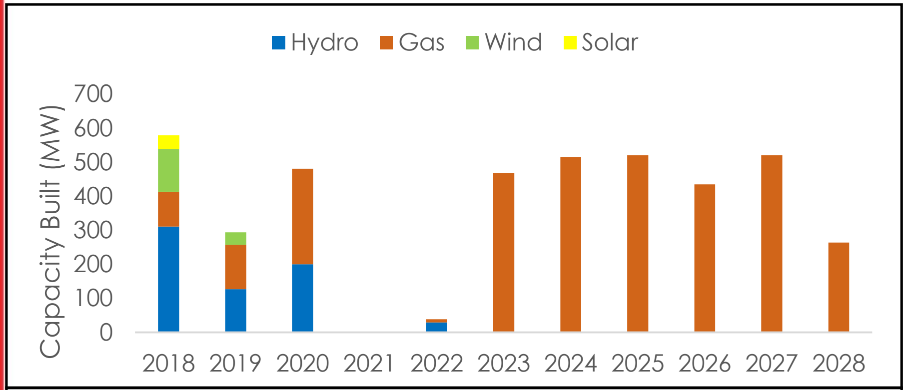
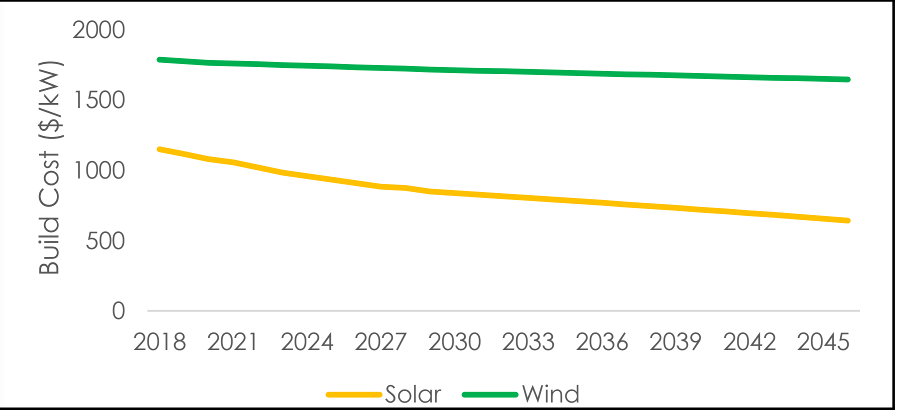
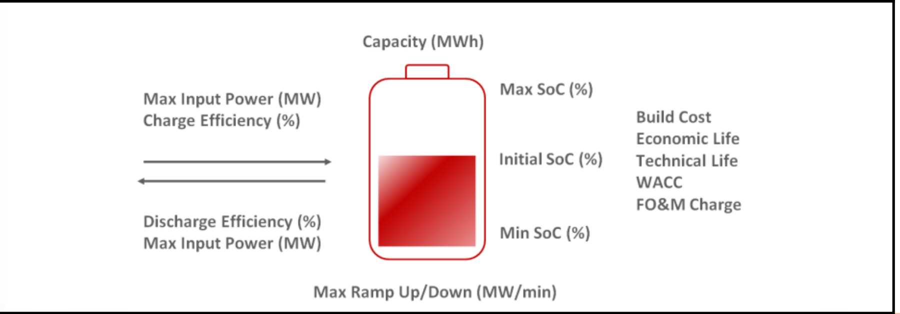
2 b) PLEXOS: Long Term







- It produces a generation/transmission expansion plan answering what, when and where.
- The simulator can read build costs decreasing in time to represent non-mature technologies such as wind and solar.
- The simulator can model batteries and analyse for example when a pack solar + battery or wind + battery is beneficial for the system.

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2. PLEXOS
c) Medium Term

2 c) PLEXOS: Medium Term

MT Schedule addresses a key challenge in power system modelling:

Optimize medium to long term decisions in a computationally efficient manner.

This means:

- Managing hydro storages
- Fuel supply
- Emission constraints
- But there are many other constraints and commercial considerations that need to be addressed over timescales longer than a day or week.

These constraints create such a challenge because we must optimize decision spanning weeks, months and years and simultaneously optimize decision in the short –term (hourly or lower) level

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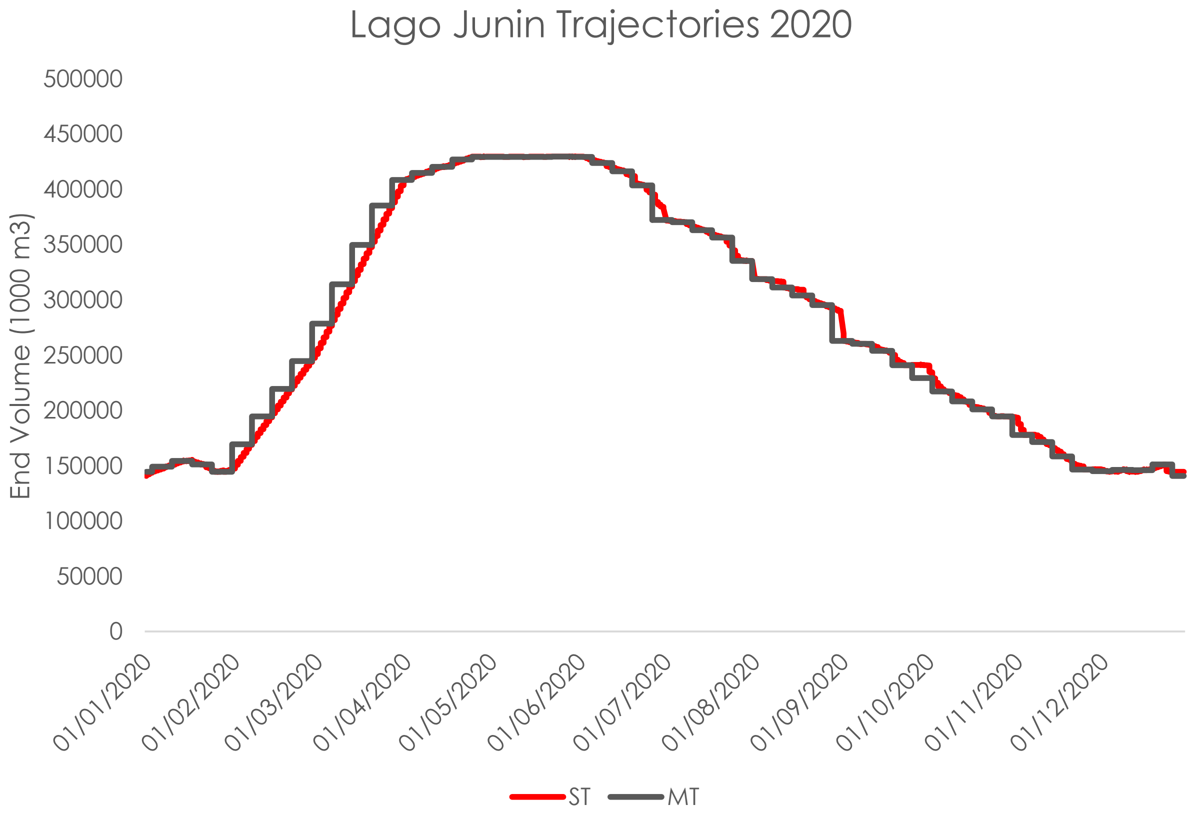
2 c) PLEXOS: Medium Term



MT solves this problem by:

- Reducing the number of simulated periods by combining together dispatch intervals in the horizon into 'blocks'
- Optimizing decisions over this reduced chronology; then
- *Decomposing* medium-term constraints and objectives into a set of equivalent short-term constraints and objectives.

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2. PLEXOS
d) Short Term

2 d) PLEXOS: Short Term

ST Schedule is mixed-integer programming (MIP) based chronological optimization.

It can emulate the dispatch and pricing of real market-clearing engines providing a wealth of additional functionality to deal with:

- Unit commitment.
- Constraint modelling.
- Financial/portfolio optimization; and
- Monte Carlo simulation.

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2 d) PLEXOS: Short Term

Over 300 Unit Commitment Properties

- Minimum stable generation
- Heat Rate: Polynomial or Step function
- Min up and down times
- Ramping constraints
- Start costs variable by cooling state
- Start up & Shut down profiles
- Rough running zones

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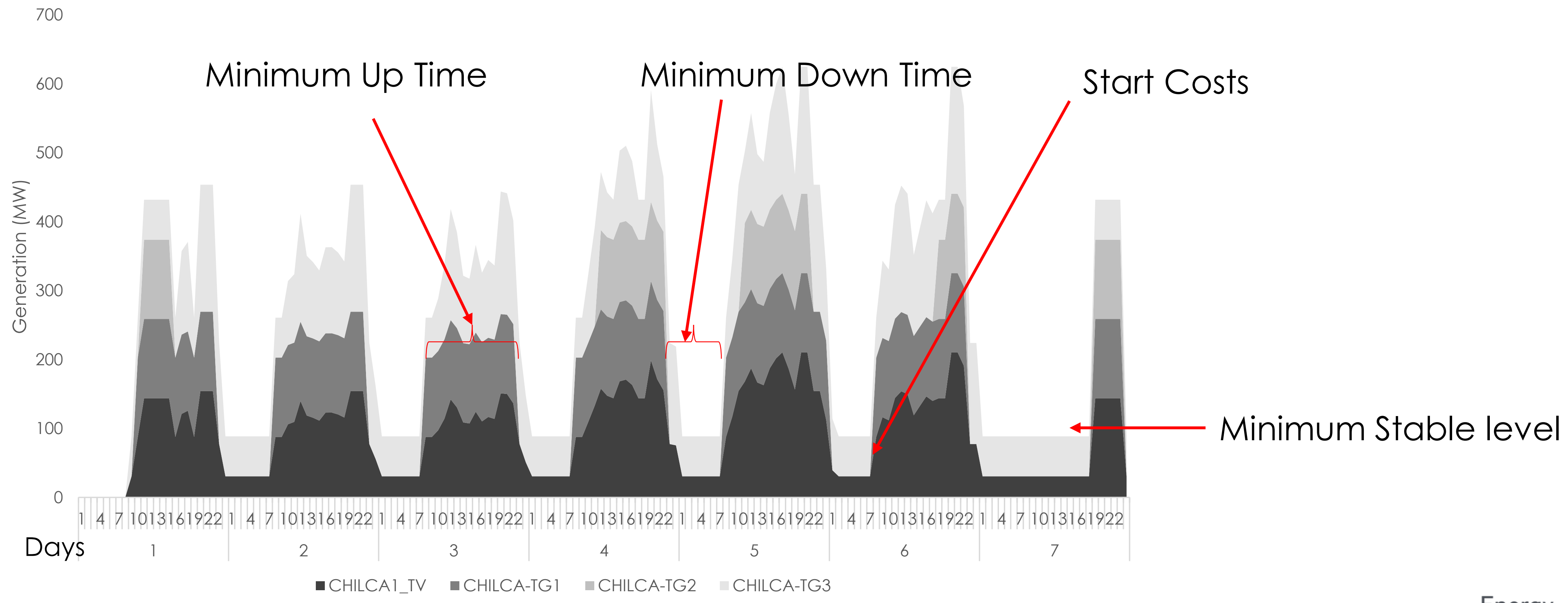
2 d) PLEXOS: Short Term

ST Schedule output illustrating unit commitment constraints

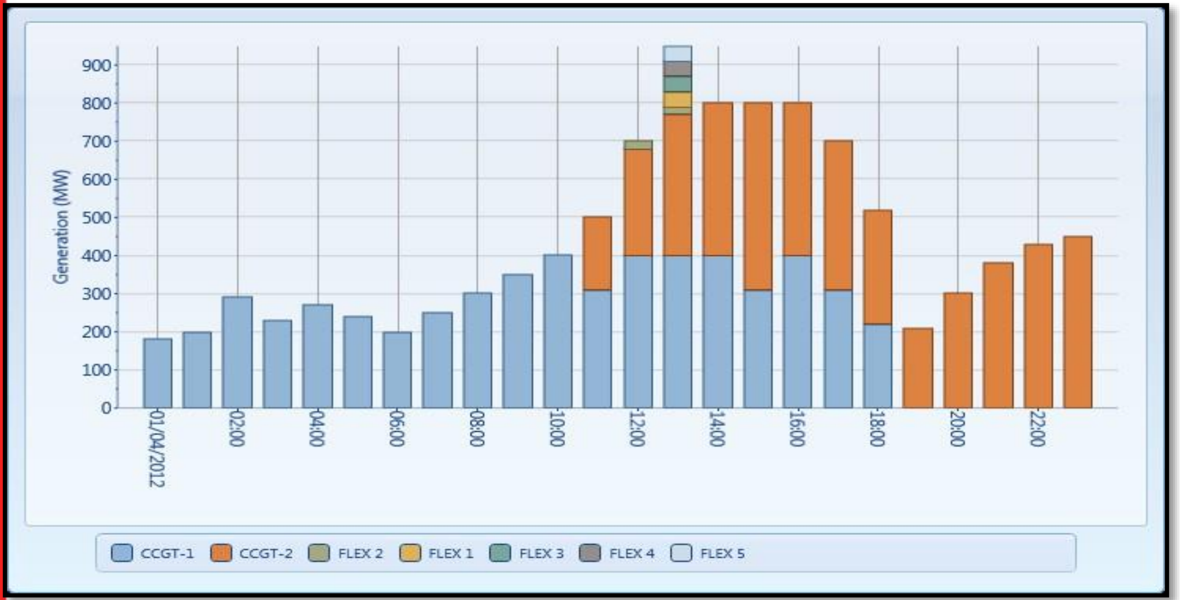


3. PLEXOS Case Studies:
a) Sub Hourly Modelling

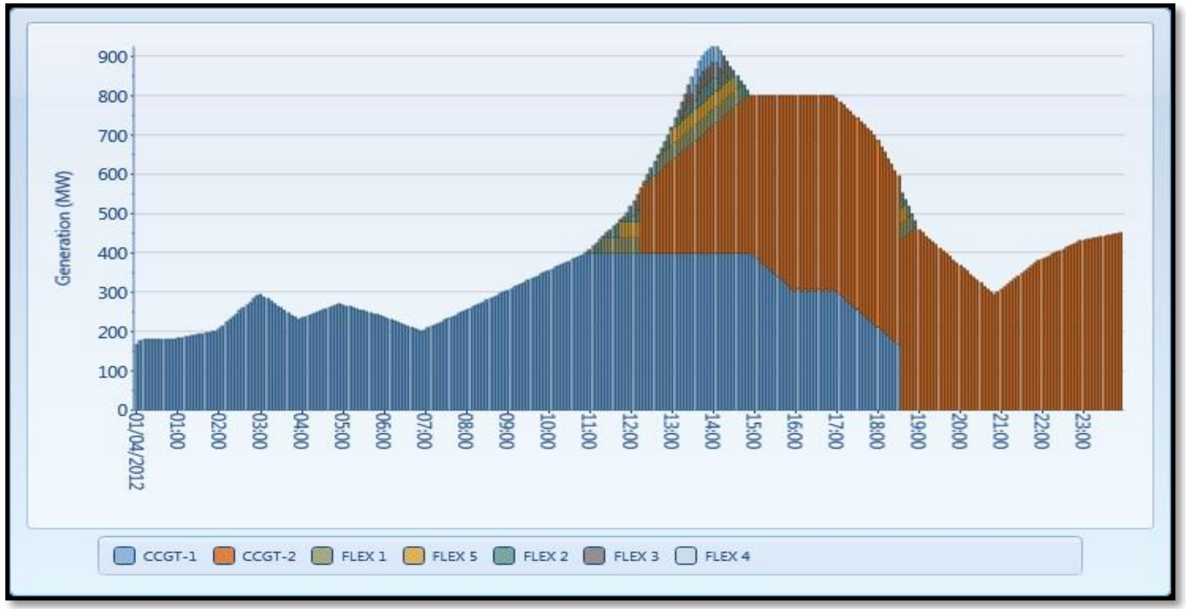
3 a) PLEXOS Case Studies. Sub Hourly Modelling

How to evaluate impact in sudden changes that can only be covered by flexible units?

Generation Dispatch: Hourly



Generation Dispatch: 5 Minute Basis



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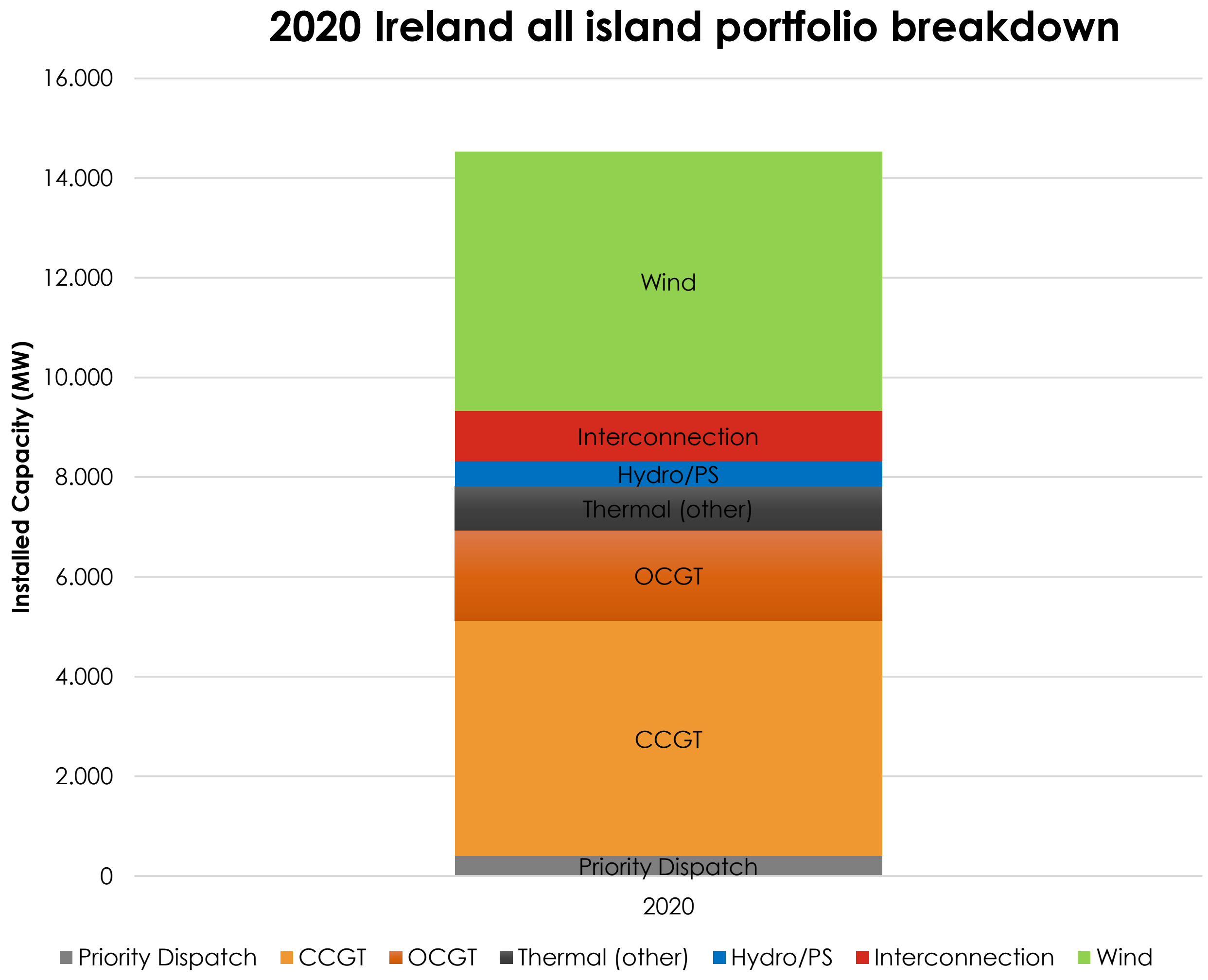
3 a) PLEXOS Case Studies. Sub Hourly Modelling



4 cases with different resolution were analyzed:

Optimization interval (min)	Optimization period (day)	Optimization horizon (year)
5	7	1
15	7	1
30	7	1
60	7	1

Deane, J.P., Drayton, G., Ó Gallachóir B., 2014. *The impact of sub-hourly modelling in power systems with significant levels of renewable generation*. **Applied Energy** 113 pp 152-158

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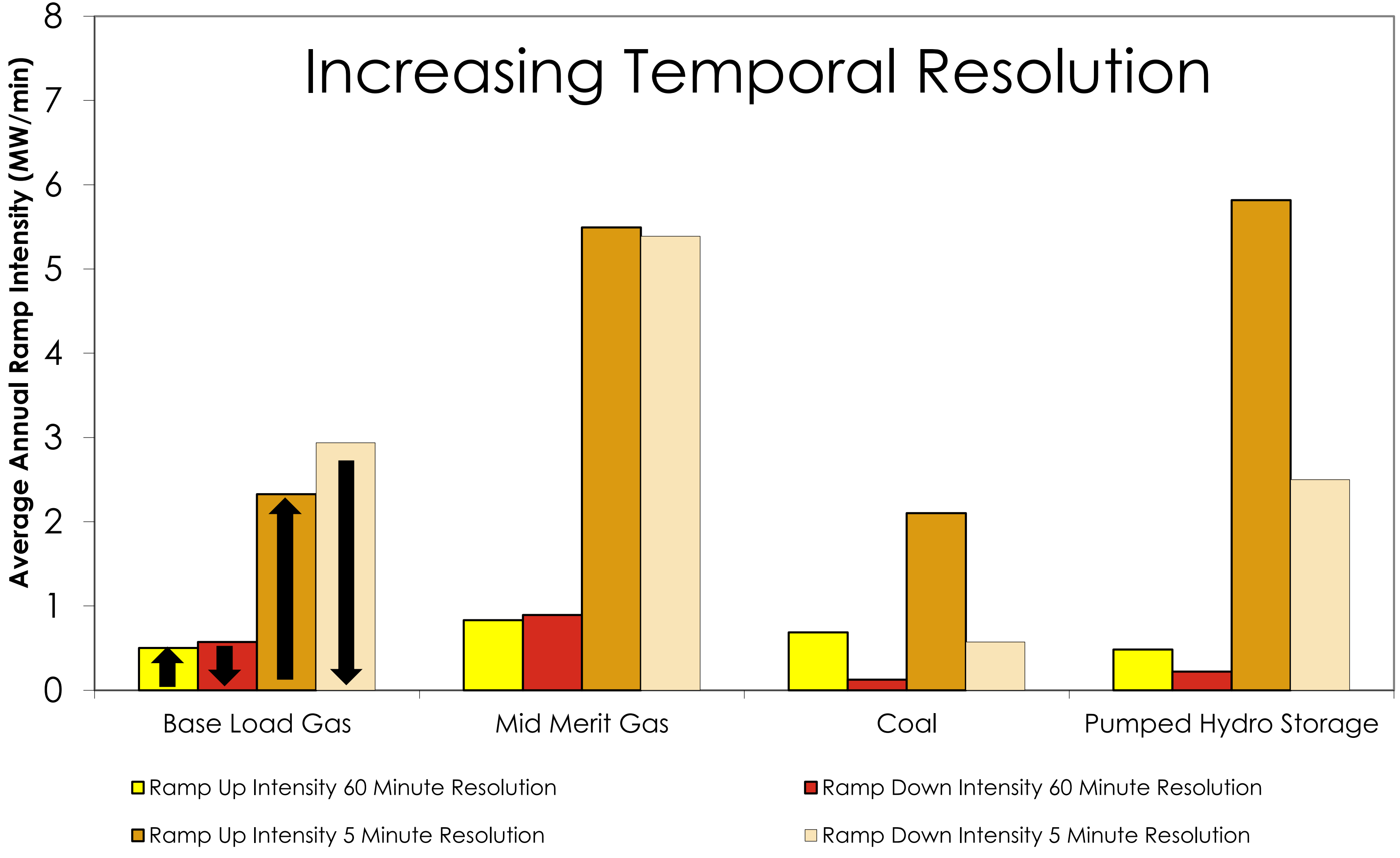
3 a) PLEXOS Case Studies. Sub Hourly Modelling



Investigate the impact of temporal resolution on power system modelling. A case study on Ireland's power system.

Higher resolution modelling allows a more in depth representation of real time conditions.

Deane, J.P., Drayton, G., Ó Gallachóir B., 2014. *The impact of sub-hourly modelling in power systems with significant levels of renewable generation*. **Applied Energy** 113 pp 152-158

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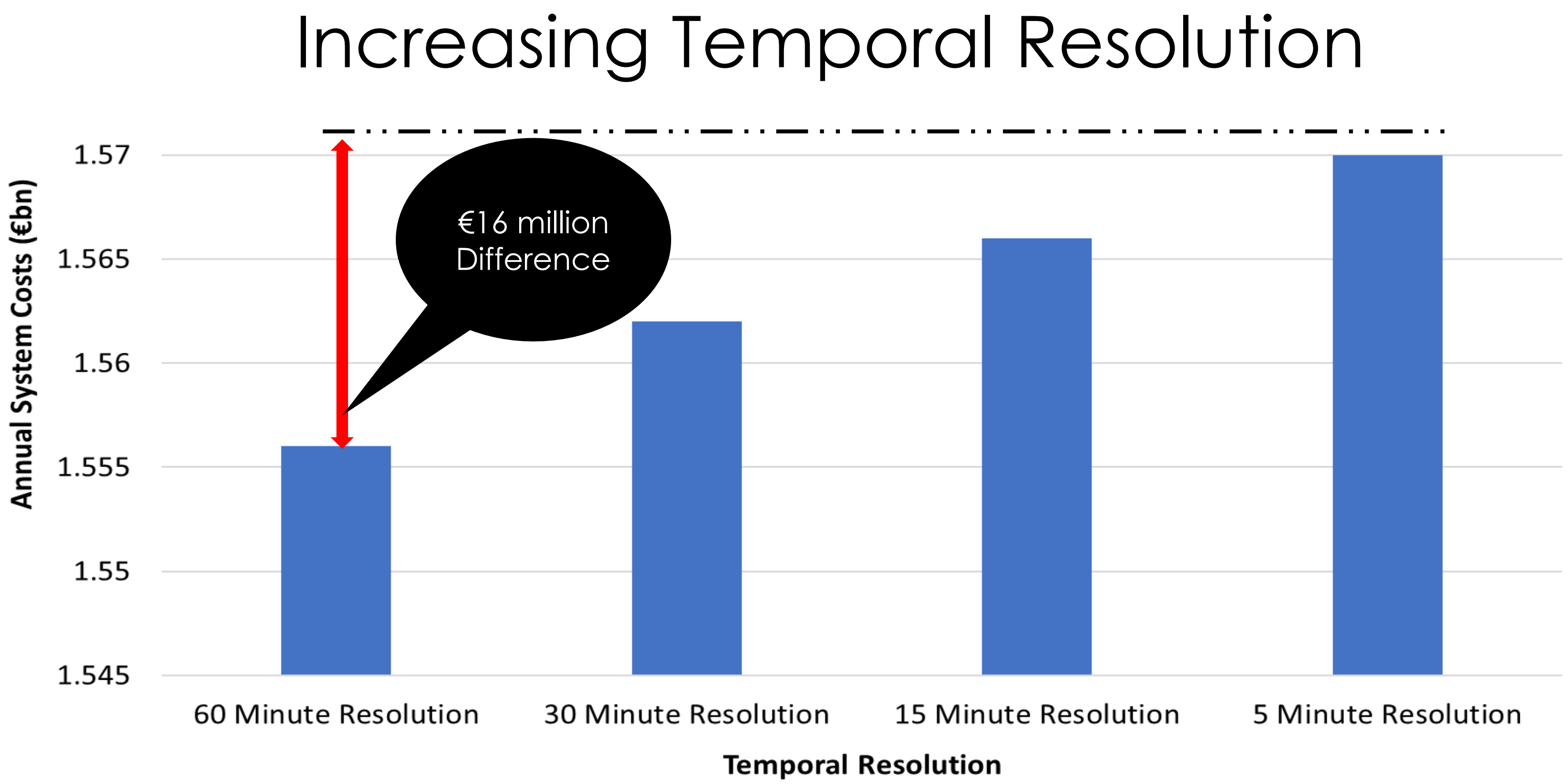
3 a) PLEXOS Case Studies. Sub Hourly Modelling



Investigate the impact of temporal resolution on power system modelling. A case study on Ireland's power system.

Increasing temporal resolution from 60 minutes to 5 minutes increases annual system costs by €16 million, equating to an approximate 1% increase.

Deane, J.P., Drayton, G., Ó Gallachóir B., 2014. *The impact of sub-hourly modelling in power systems with significant levels of renewable generation*. **Applied Energy** 113 pp 152-158

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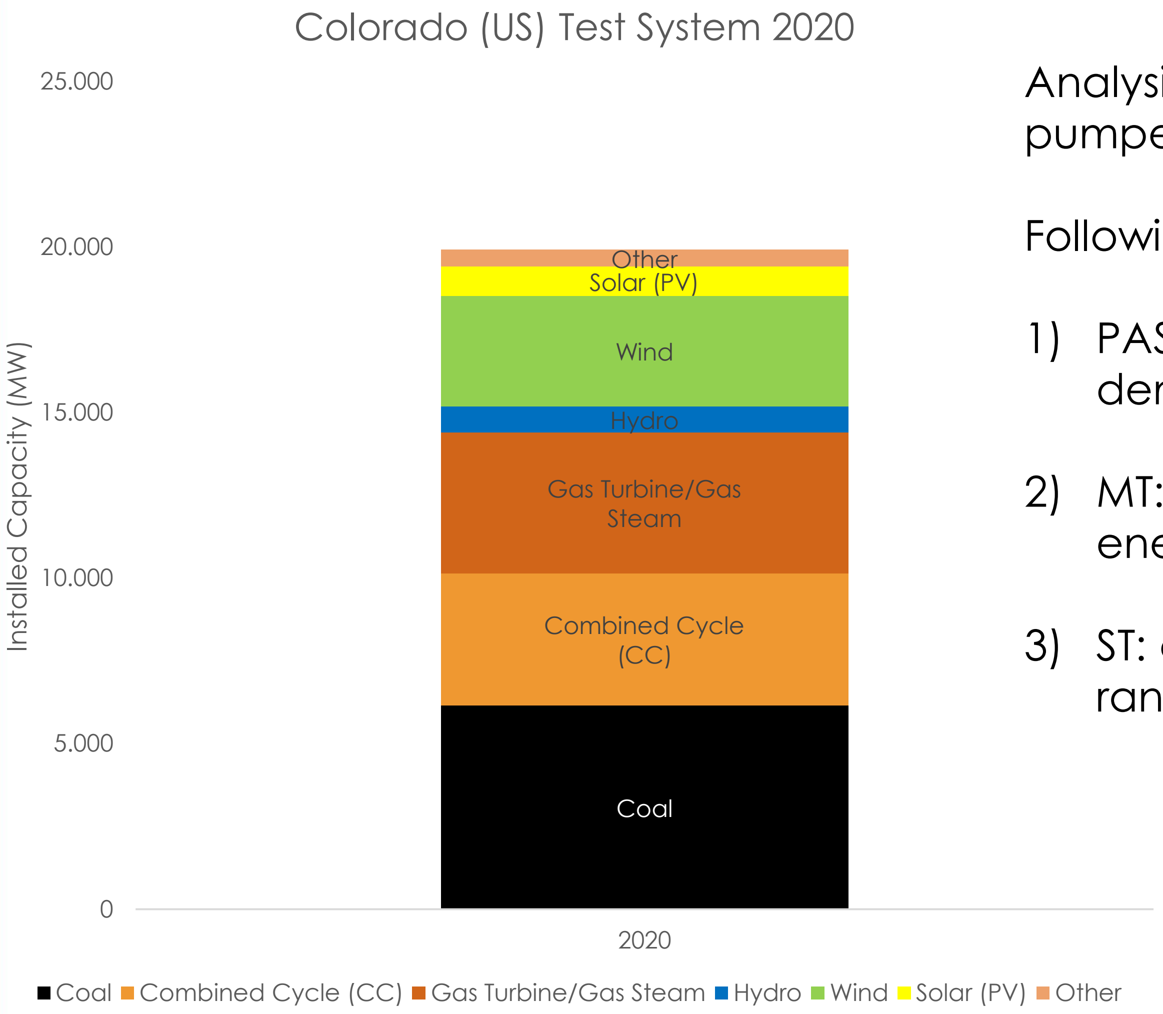
3. PLEXOS Case Studies:
b) Pumped Storage
Colorado US test system

3 b) PLEXOS Case Studies. Pumped Storage: Colorado



Analysis was performed to assess the impact of a single 300 MW pumped storage device, with 8 hours of capacity at full output

Following phases were used:

1) PASA: is used to assign planned outages to periods of low net demand.

2) MT: Uses monthly load duration curves to assign limited energy resources, such as certain hydro units.

3) ST: chronological commitment and dispatch model including random forced outages based on plant-level outage rates.

Optimization interval (min)	Optimization period (day)	Optimization horizon (year)
60	2	1

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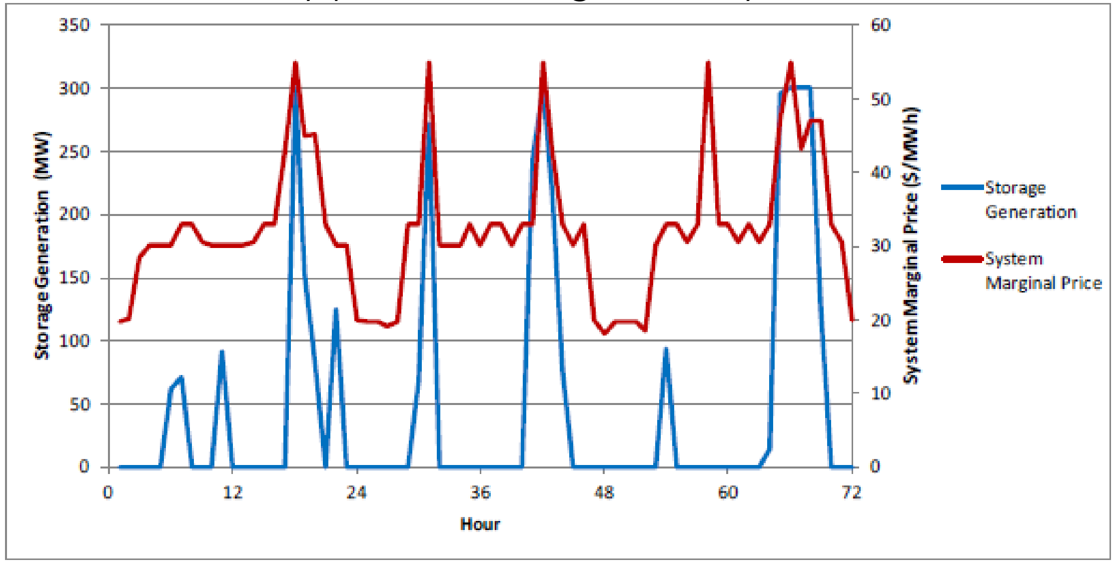
Denholm, Jorgenson, Hummon, Jenkin, Palchak, Kirby, Ma, O'Malley. *The Value of Energy Storage for Grid Applications*. Technical report, **NREL**/TP-6A20-58465. May 2013

3 b) PLEXOS Case Studies. Pumped Storage: Colorado

3 day period starting February 3



Observations:

1. Storage plant output tends to follow periods of high prices.

2. Storage output does not exactly match periods of high price because the model is not optimizing the operation of the storage plant in isolation as considers the interaction of the storage plant with the rest of the system.

3. The model often uses storage to reduce the number of plant starts:

   - During off-peak periods, by increasing load and reducing the frequency of plant shut downs.

   - During on-peak periods, by reducing starts of peaking generators.

Denholm, Jorgenson, Hummon, Jenkin, Palchak, Kirby, Ma, O'Malley. *The Value of Energy Storage for Grid Applications*. Technical report, **NREL**/TP-6A20-58465. May 2013

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3 b) PLEXOS Case Studies. Pumped Storage: Colorado

	Base Case	With Storage (300 MW)	Increased with Storage
Generation (GWh)			
Coal	46,134	46,375	2 241
Hydro	3,792	3,792	-
Gas CC	14,761	14,947	3 186
Gas CT	1,024	763	-260
Other	103	89	-14
Existing Pumped Storage	1,054	1,050	-4
New Storage	-	465	465
PV	1,834	1,834	0
Wind	10,705	10,705	0
Total Generation (GWh)	*79,407*	*80,020*	1 *613*
Fuel Use (1,000 MMBtu)			
Coal	488,140	490,930	4 2790
Gas	126,651	124,728	-1923
Total Fuel	*614,719*	*615,658*	*867*

Observations:

1) Adding storage increases the total generation requirement a small amount due to losses in the storage device.

2) Adding storage shifts energy production to lower cost units.

3) This case increases generation from coal and CCGT while decreasing generation from gas turbines.

4) This case increases the use of coal by about 0.6%, while decreasing the use of gas by about 1.5%.

Denholm, Jorgenson, Hummon, Jenkin, Palchak, Kirby, Ma, O'Malley. *The Value of Energy Storage for Grid Applications*. Technical report, **NREL**/TP-6A20-58465. May 2013

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3 b) PLEXOS Case Studies. Pumped Storage: Colorado

	Base Case	With Storage (300 MW)	Increased with Storage
Total Fuel Cost (M$)	1210.5	1204.7	-5.8 2
Total O&M Cost (M$)	152.1	152.8	0.7
Total Start Cost (M$)	58.2	52.8	-5.5 2
Total Regulation "Adder" Cost (M$)	4.7	4.8	0.1
Total Production Cost (M$)	1425.6	1415.1	-10.5 1

Observations:

1. the difference in production cost between these two cases represents an annual operational value of storage of about $10.5 million.

2. About half of the total difference is in the fuel costs, with the other half derived from the ability of flexible energy storage to avoid unit starts

3. The difference in production costs can be translated into an annualized benefit. in the base case the difference of $10.5 million is divided by 300 MW to produce an annual benefit of about $35/kW-year

Denholm, Jorgenson, Hummon, Jenkin, Palchak, Kirby, Ma, O'Malley. *The Value of Energy Storage for Grid Applications*. Technical report, **NREL**/TP-6A20-58465. May 2013

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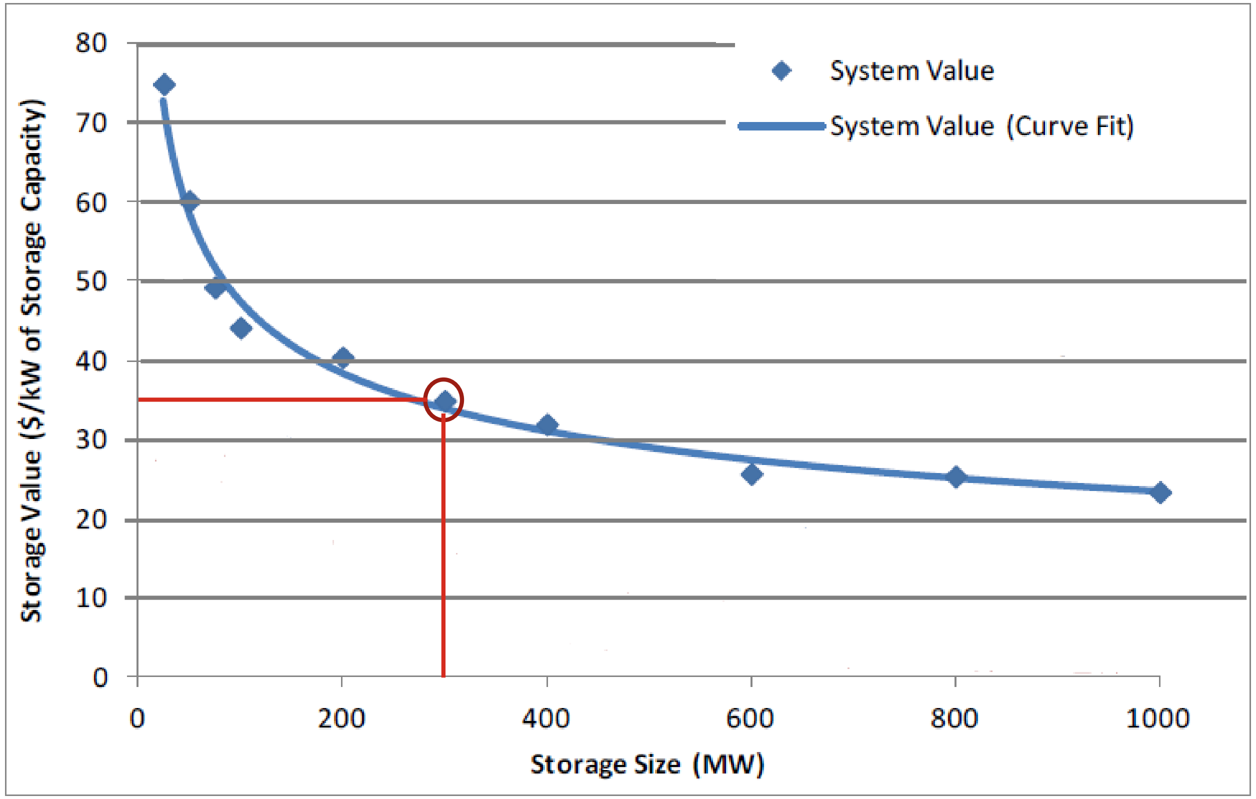
3 b) PLEXOS Case Studies. Pumped Storage: Colorado

Storage operational value as a function of size for an energy only device



Observations:

1. The sensitivity of this benefit is analyzed with plant size.

2. As storage is added, it flattens the load and reduces the on-/off-peak price differential.

More sensitivities available in the full report:

Denholm, Jorgenson, Hummon, Jenkin, Palchak, Kirby, Ma, O'Malley. *The Value of Energy Storage for Grid Applications*. Technical report, **NREL**/TP-6A20-58465. May 2013

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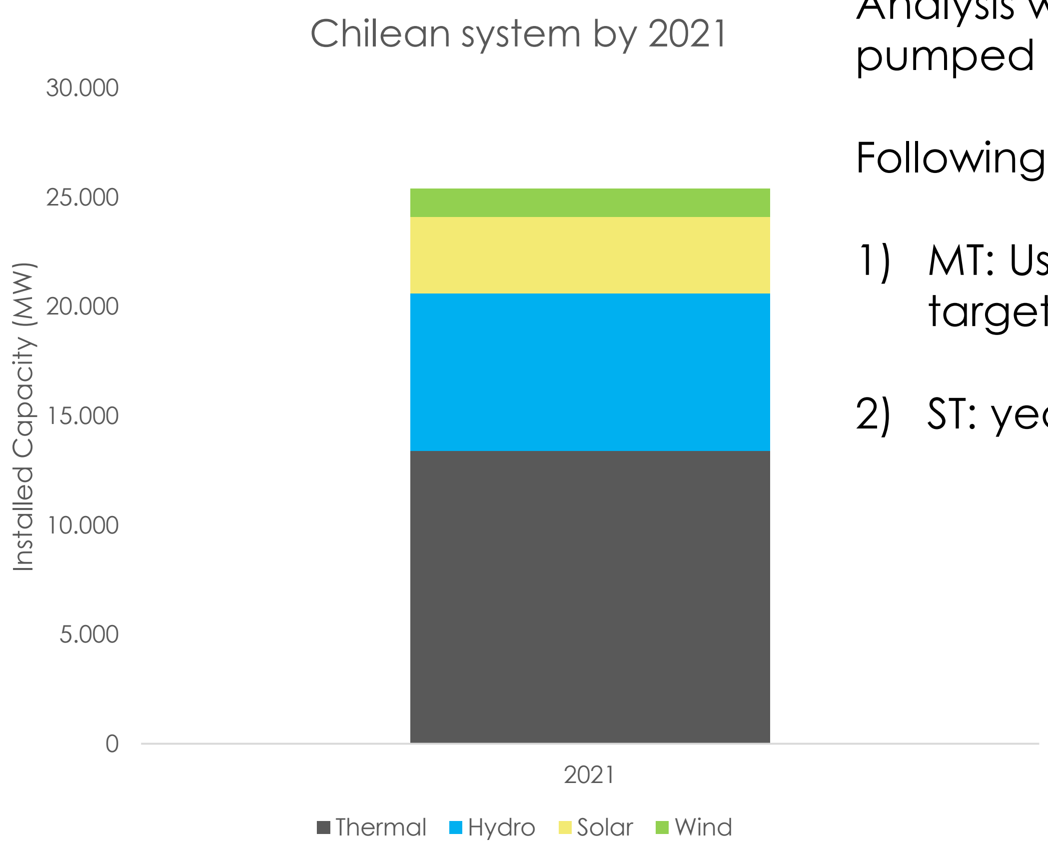
3. PLEXOS Case Studies:
b) Pumped Storage
Chilean system

3 b) PLEXOS Case Studies. Pumped Storage: Chile



Analysis was performed to assess the impact of one and two 300 MW pumped storage device.

Following phases were used:

1) MT: Uses load duration curves and yearly steps to assign reservoir targets for certain hydro units.

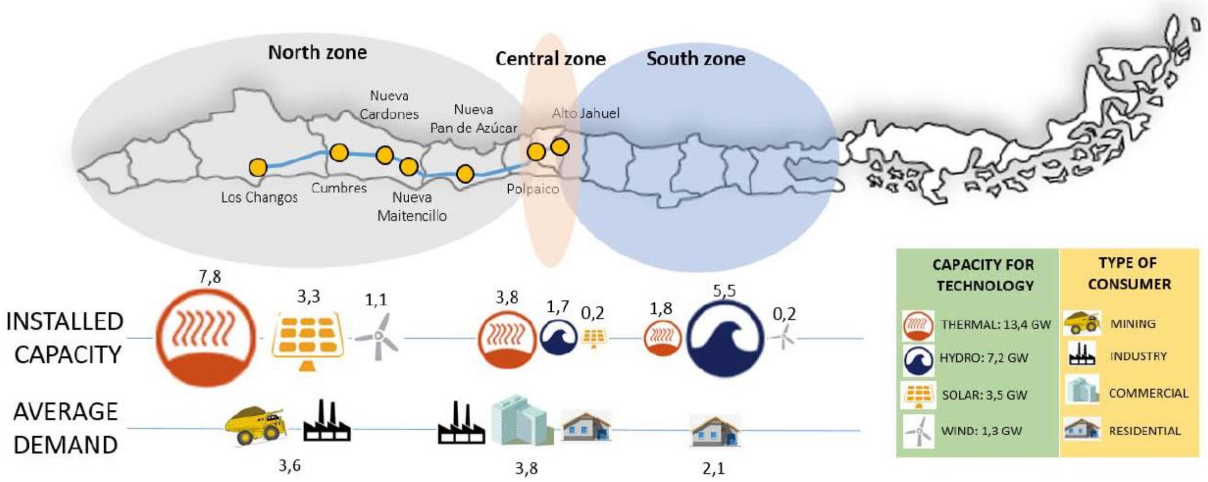
2) ST: yearly chronological unit commitment with hourly resolution.

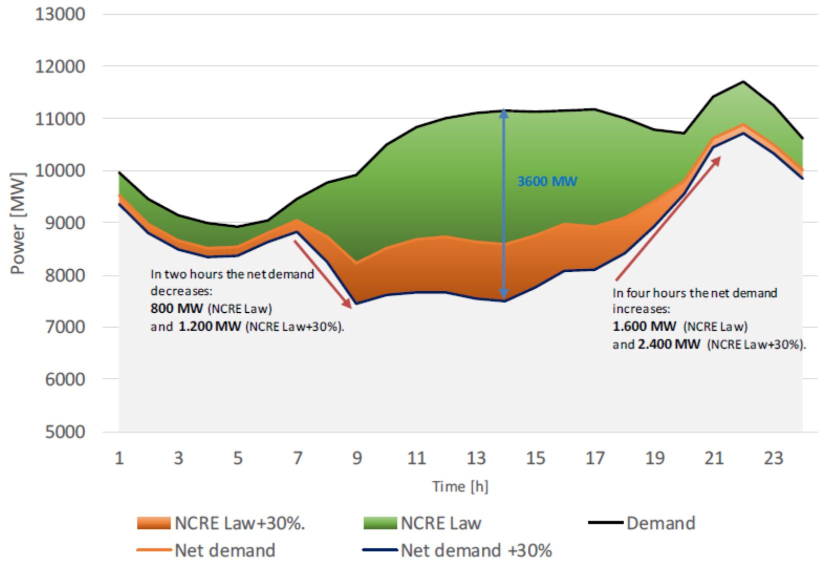
Optimization interval (min)	Optimization period (day)	Optimization horizon (year)
60	4	1

Avalos, Araneda, Galvez, Guacucano, Guenul, Leyton. *Assessment of Energy Storage Systems for Contribution to Flexibility in Electrical Power System with High Level Intermittent Renewables Energy*. **CIGRE** Dublin, 2017

Energy Exemplar

3 b) PLEXOS Case Studies. Pumped Storage: Chile





Chilean power system characteristics:

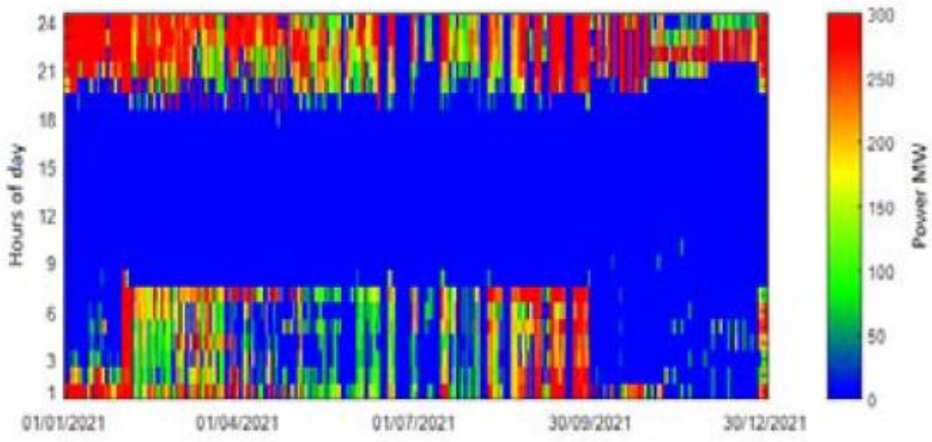
- 2 interconnected systems connected through a 1,700 MVA 2x500 kV line consisting in a system of 3,200 km extension
- Gross demand and net demand for a summer day shows the challenge to operate this projected system, in term of ramps and big renewable blocks.

Challenges:

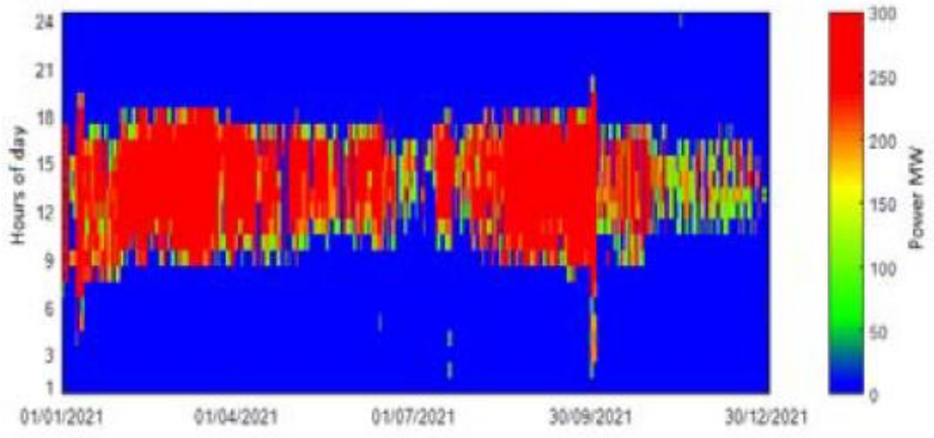
1) **Transmission**: High bidirectionality in power flows and thermal constraints of the most important transmission lines in the north
2) **Cycling:** Increase in startups between 16 and 21 hours (Solar gen decrease) and shutdowns between 6 and 12 hours (Solar gen increase).
3) **Ramping**: High ramping requirements with solar generation increase/decrease.

3 b) PLEXOS Case Studies. Pumped Storage: Chile

Operation of a single 300 MW pumped storage device in the north of the country.



Hourly generation of the pumped storage



Hourly pumping of the pumped storage

Solar photovoltaic influence is evidenced based on the pumped storage power plant behavior because this plant is in generation mode mainly between 18 pm to 7 am while in pumping mode between 7 am to 18 pm.

Avalos, Araneda, Galvez, Guacucano, Guenul, Leyton. *Assessment of Energy Storage Systems for Contribution to Flexibility in Electrical Power System with High Level Intermittent Renewables Energy*. **CIGRE** Dublin, 2017

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3 b) PLEXOS Case Studies. Pumped Storage: Chile

Adding pumped storage (PS) power plants in the Chilean system have a direct impact in:

1. Reducing the quantity of cycling. 25% reduction for one 300 MW PS and 30% for two 300 MW PS.

2. Reducing the ramping on thermal generation plants. 18% reduction for one 300 MW PS and 30% for two 300 MW PS.

3. This effect is increased when adding more renewables energies, especially photovoltaic (PV) plants.

4. In general, the pumped storage daily operational pattern consists of nightly generation (period of higher marginal cost) and daily pumped (period of lower marginal cost).

Avalos, Araneda, Galvez, Guacucano, Guenul, Leyton. *Assessment of Energy Storage Systems for Contribution to Flexibility in Electrical Power System with High Level Intermittent Renewables Energy*. **CIGRE** Dublin, 2017

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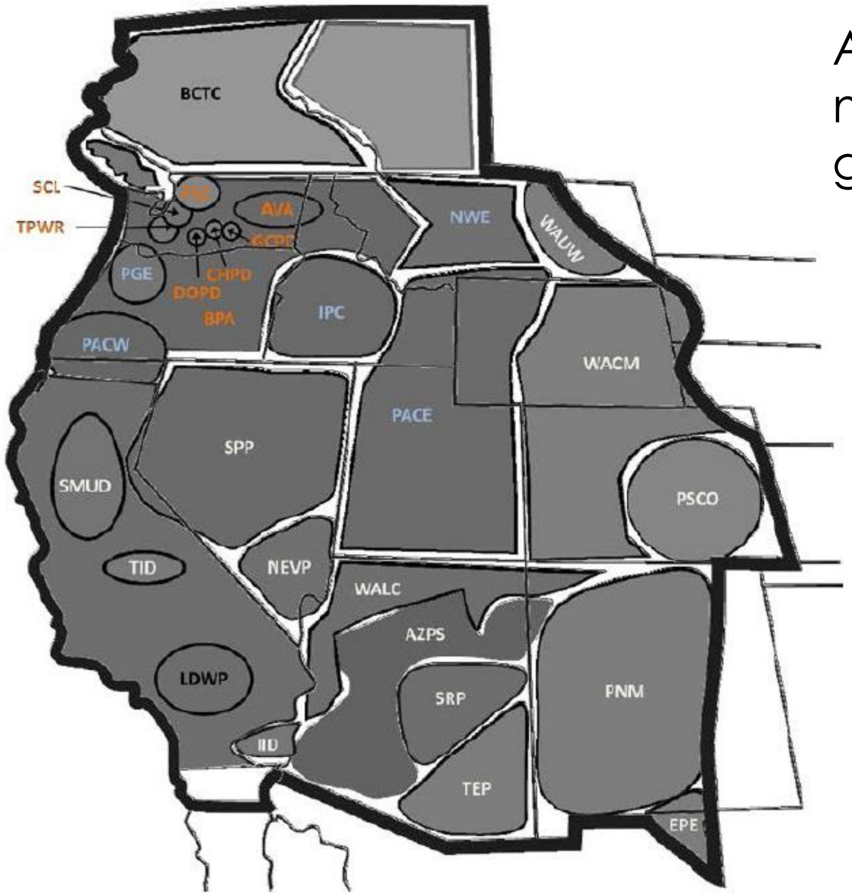
3. PLEXOS Case Studies:
b) Pumped Storage
WI US (Western Interconnection)

3 b) PLEXOS Case Studies. Pumped Storage: WI



Analysis to quantify the value of pumped storage under different market conditions and different level of variable renewable generation in WI.

Power system consisting:

- More than 17,000 buses
- More than 22,000 transmission lines
- More than 3,700 generators
- 8 existing pumped storage power plants.
- 3 new pumped storage power plants.
- Peak load equal to 168,972 MW.

Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

3 b) PLEXOS Case Studies. Pumped Storage: WI

1) Production costs for 2022. Pumped storage (PSH) case adds 6,475 MW

	Total Generation (GWh)	PSH Generation (GWh)	Production Cost ($ million)	Annual Cost Reduction per kW of PSH Capacity ($/kw-yr)
No Pumped Storage	997,546	-	14,737	-
With Pumped Storage	1,008,135	8,244	14,426	48.06

The total annual production cost in the WI is reduced by 2.11%

2) Curtailments of renewable generation for 2022.

	Curtailed Energy (GWh)	Reduction (%)
No Pumped Storage	1,921	0
With Pumped Storage	964	50

The operation of PSH plants in the system allow for significant reduction of curtailments

Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

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3 b) PLEXOS Case Studies. Pumped Storage: WI

3) System reserve provision for 2022.

	Total req. (GWh)	No PSH case Provision (GWh)	PSH case Provision (GWh)
Non-spinning reserve	29,564	-	3,757
Spinning reserve	29,564	-	679
Flexibility down	10,732	-	1,463
Flexibility up	10,732	-	299
Regulation down	12,423	-	1,652
Regulation up	12,441	-	580

PSH plants can contribute substantially to the system operating reserves.

The greatest increase is observed in provisions of regulation down and flexibility-down reserves because of:

1) Larger operating capacity range in the generating mode, and

2) The capability to provide regulation reserve in the pumping mode.

Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

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3 b) PLEXOS Case Studies. Pumped Storage: WI

4) Emissions for 2022. Pumped storage (PSH) case adds 6,475 MW

	CO_2 (kTon)	NOX (kTon)	SO_2 (kTon)
No Pumped Storage	388,463	573,025	410,404
With Pumped Storage	393,954	589,914	425,151

Coal generation increases during night to provide pumping energy which increases overall system emissions.

5) Thermal generation cycling for 2022.

	Total Number of Thermal Starts	Total Thermal Start Cost (million $)
No Pumped Storage	40,852	176
With Pumped Storage	31,925	145

The number of starts and startup costs of thermal generators are reduced substantially as PSH is introduced into the system.

6) Generator ramp-up and ramp-down for 2022.

	Total Generator Ramp-up (MW)	Total Generator Ramp-Down (MW)
No Pumped Storage	11,501	16,508
With Pumped Storage	8,081	11,691

The needs for ramping up and down of thermal generators are significantly reduced if more PSH capacity is available in the system.

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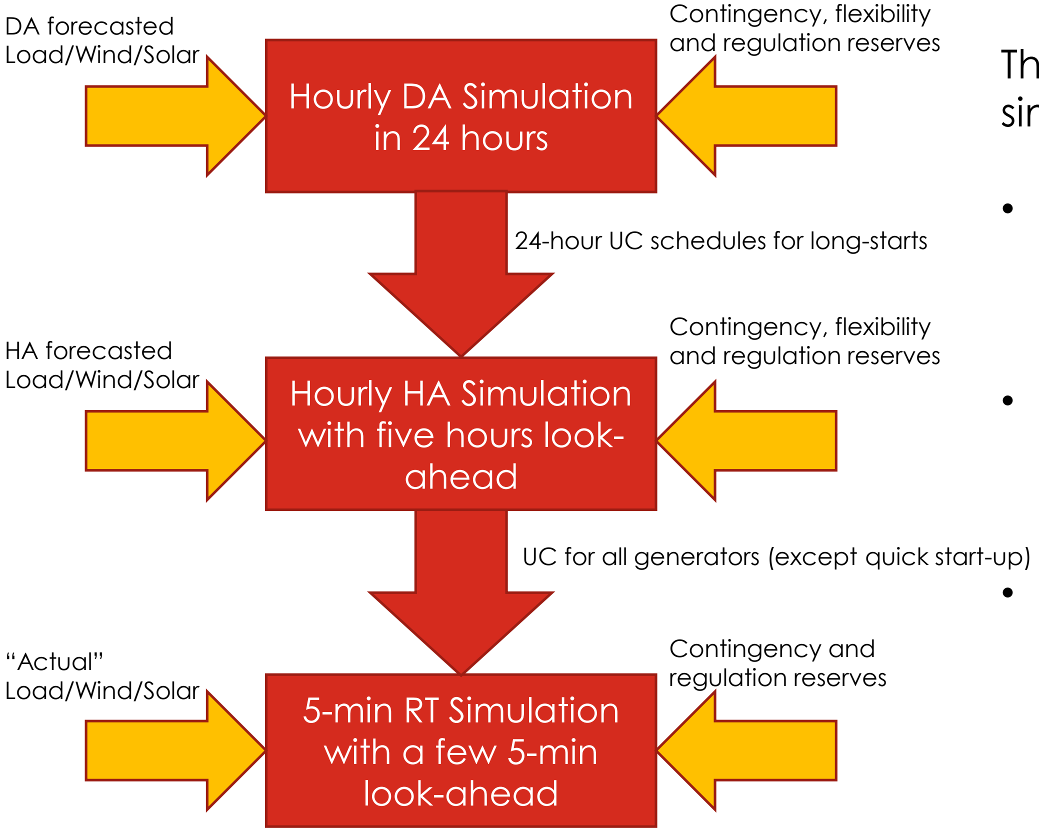
Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

3 b) PLEXOS Case Studies. Pumped Storage: WI

How to evaluate the adequacy of system ramping capabilities to **compensate** for renewable generation variability and uncertainty?



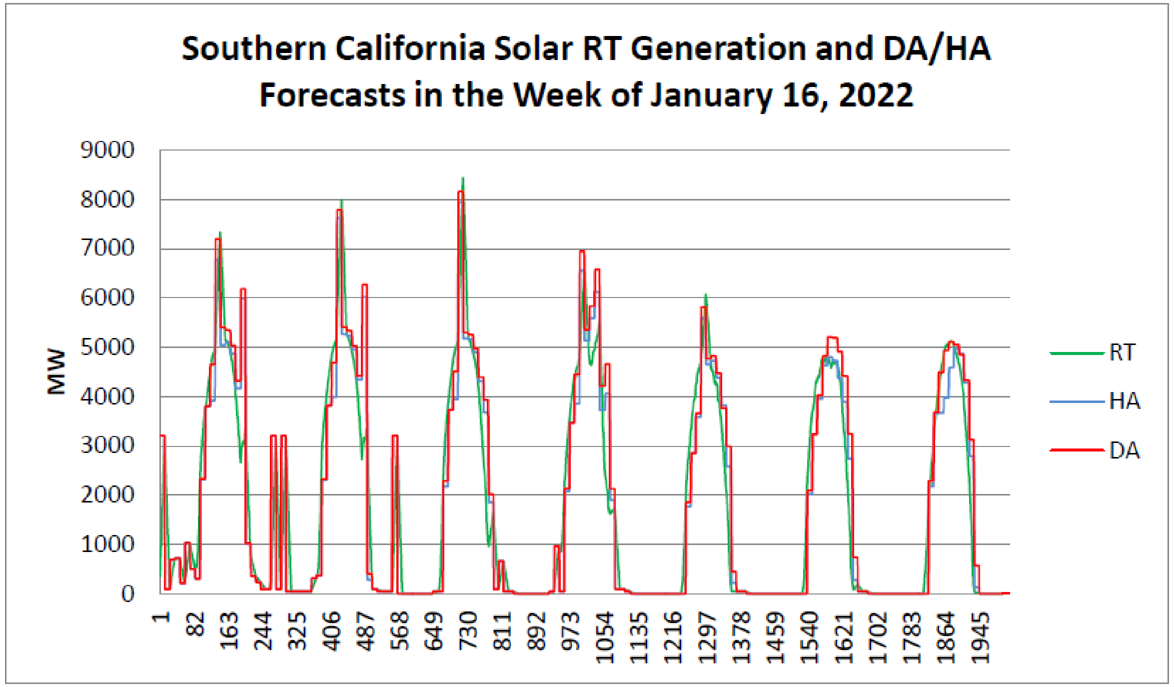
The following methodology uses a three-stage DA-HA-RT sequential simulation approach to solve this issue:

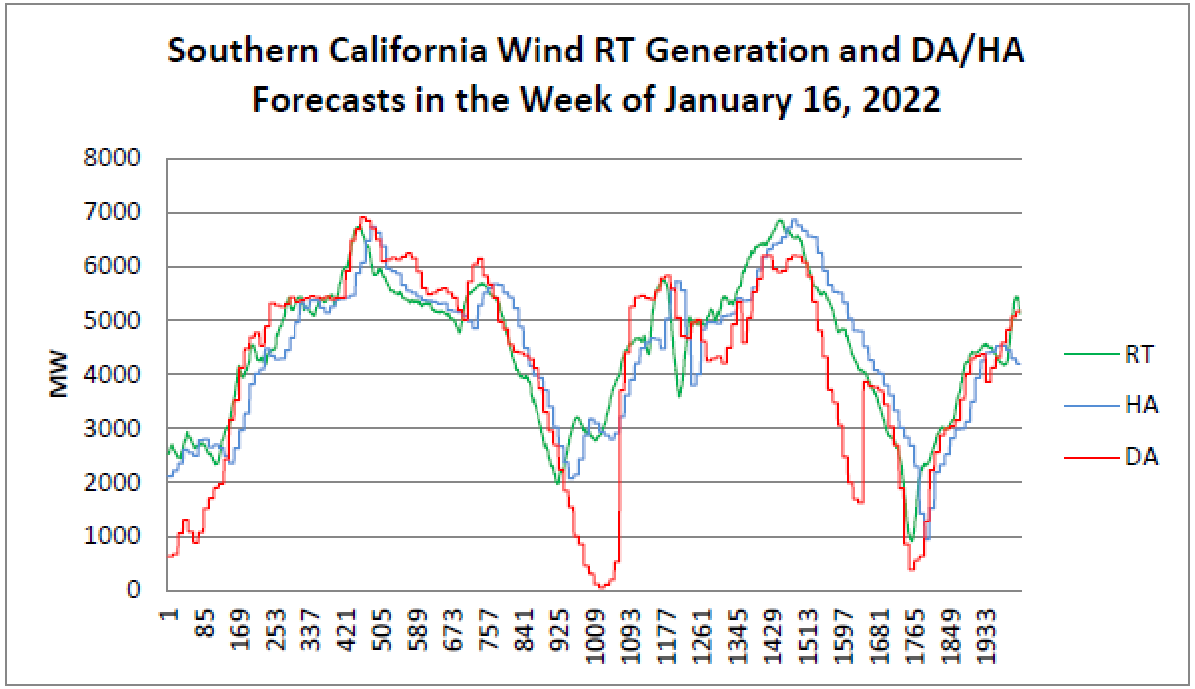
- Day Ahead (DA) simulations mimics the Day Ahead dispatch. Hourly simulation.
- Hour Ahead (HA) simulation mimics the intra-day dispatch. Hourly simulation
- Real Time (RT) simulation mimics the 5-min RT dispatch. 5-min simulation

Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

3 b) PLEXOS Case Studies. Pumped Storage: WI

To compensate for the sub-hourly variability and uncertainty of renewable generation, the system needs to ramp generators more and/or to cycle the quick-startup generators more.





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Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

3 b) PLEXOS Case Studies. Pumped Storage: WI

1 typical week 2022. Generation Costs

	DA ($1,000)	HA ($1,000)	RT ($1,000)
No Pumped Storage	313,533	331,003	368,063
Pumped Storage	307,278	325,511	355,829

1 typical week 2022. Starts & Shutdown Costs

	DA ($1,000)	HA ($1,000)	RT ($1,000)
No Pumped Storage	4,904	4,711	6,949
Pumped Storage	3,836	3,851	5,262

1 typical week 2022. Thermal ramp up

	DA (MW)	HA (MW)	RT (MW)
No Pumped Storage	278,785	237,843	647,133
Pumped Storage	215,443	196,595	445,140

1) The results for system production costs, startup and shutdown costs, unit ramping needs, typically increase if a higher-resolution simulation is performed.
2) Ramp ups are increased substantially in RT simulations compared with DA simulations. The reason is that the 5 min simulation time step captures not only ramping needs from hour to hour, but also within the hour.
3) Pumped storage are able to significantly reduce the ramping of thermal generating units.
4) Pumped storage true impact on power system operation and costs can be seen from the RT simulations.

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Argonne National Laboratory. *Modelling and Analysis of Value of Advanced Pumped Storage hydropower in the United States*. June 2014

4. Conclusions

1. PLEXOS long, medium- and short-term phases can be used to model hydrothermal systems with high presence of renewable generation and pumped storages power plants.

2. Several studies in different parts of the world have been performed with PLEXOS in hydrothermal systems to show the potential benefit of pumped storages power plants.

3. PLEXOS is suitable to model Brazilian power market, proposing and evaluating expansion plans in order to value renewable generation and energy storage.

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Thanks for attending

Contact Information

- Lucia Parra
LATAM Sales Director
\+ 56 9 87293181
lucia.parra@energyexemplar.com

- Felipe Valdebenito:
LATAM Presales Leader
+56 9 31771748
felipe.valdebenito@energyexemplar.com

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