Power System Flexibility:
Key elements in the Chilean Power System

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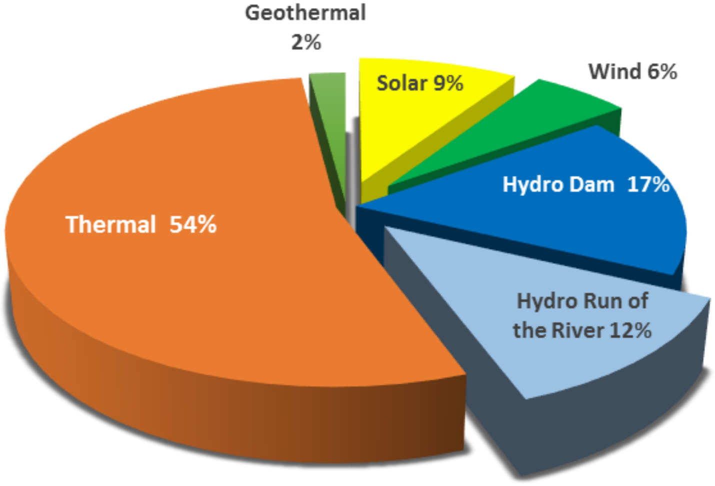
Portland, August 2018

Motivation

- **Projections**
  - **High penetration of variable renewable energy (VRE)**

Technology	Installed [MW]
Solar	2,090
Wind	1,299
Hydro Dam	3,858
Hydro Run of the River	2,803
Thermal	12,110
Geothermal	465

Installed Capacity 2018



VRE SEN: 3.389 MW
Total SEN: 22.654 MW

Total VRE SEN ~ 15%
(Variable Renewable Energy, i.e., Solar and Wind)

How fit is our system for a high penetration of VRE?

Motivation

- **Normalized Flexibility Index (NFI)**
  - Calculation based on the installed capacity without considering the operation point
    - Min capacity, Startup/Down time, Ramp rate

$$flex(i) = \frac{\frac{1}{2}[P_{max}(i) - P_{min}(i)] + \frac{1}{2}[Ramp(i)]}{P_{max}(i)}$$

$$FLEX_{system} = \sum_{i \in A} [\frac{P_{max}(i)}{\sum_{i \in A} P_{max}(i)} \cdot flex(i)]$$

Flexibility Level	$FLEX_{System}$
High	0.63
Medium	0.48
Low	0.43

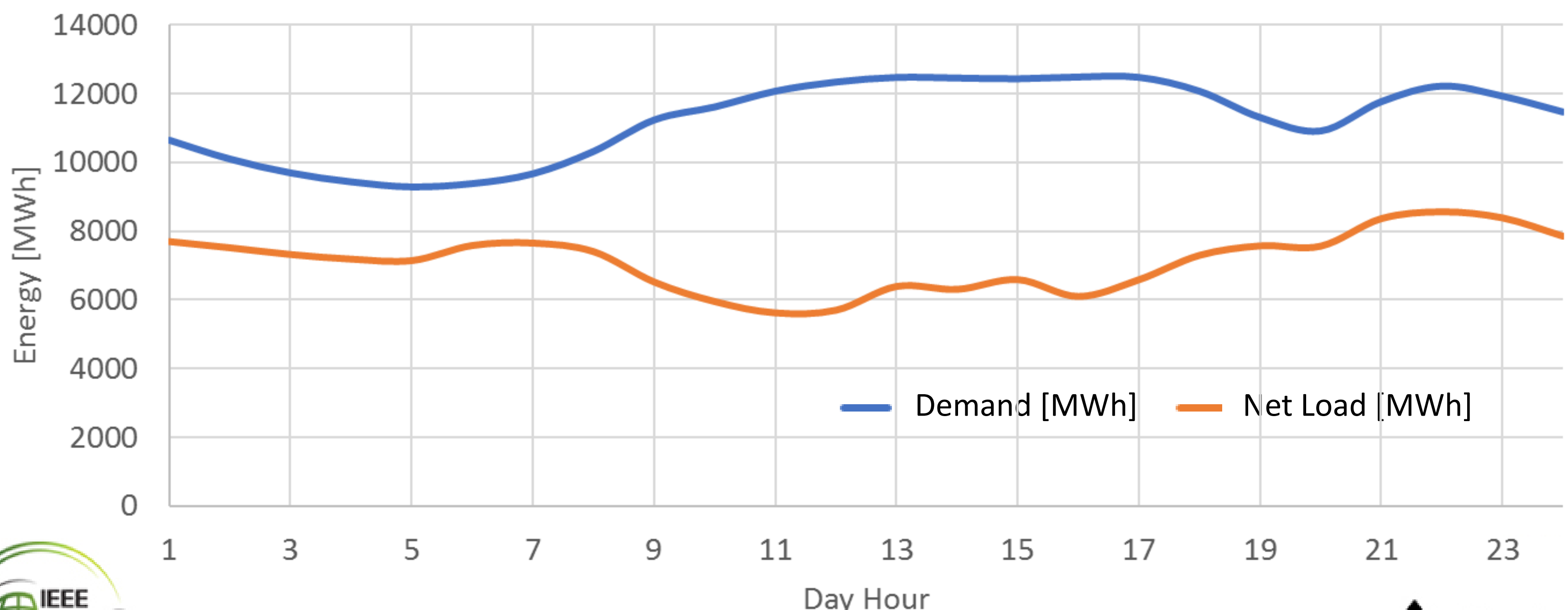
Caso	$FLEX_{System}$
Real 2017	0.679

- **Consideration**
  - Base on the index, the Chilean fleet can be considered flexible
  - Question: is the Chilean system flexible without hydro – dams?

Motivation

Why do we need to have some level of flexibility?

- **Demand**
  - Max 14,496 [MW]
  - Average 11,029 [MW]
  - Mín 8,225 [MW]
- **Net Load**
  - Max 8,720 [MW]
  - Average 7,929 [MW]
  - Min 5,723 [MW]



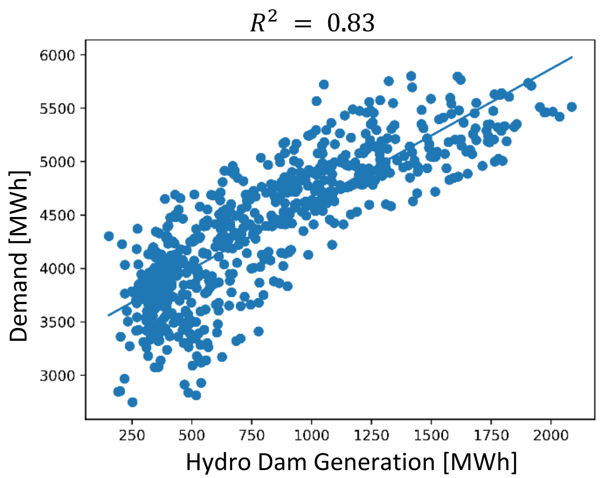
Who is following the demand?

➢ Correlation between Net Load and generation for different technologies

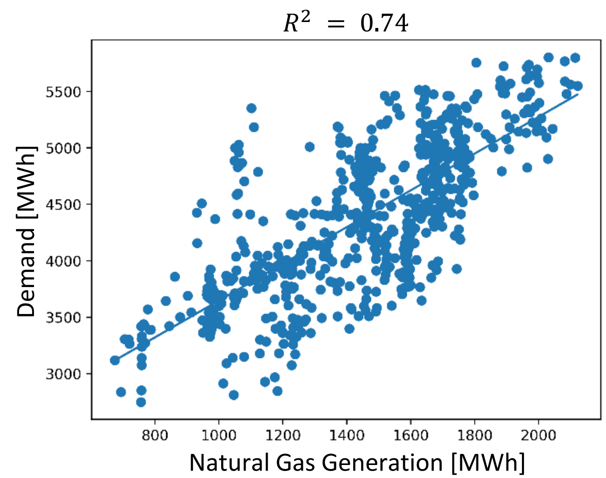
Real - 2017

February

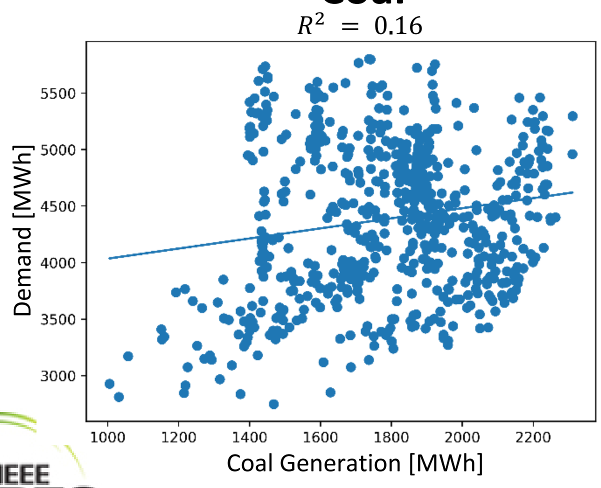
Hydro Dam



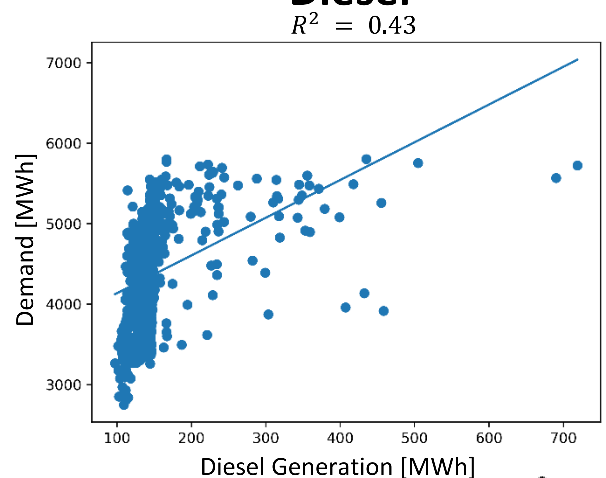
Natural Gas



Coal



Diesel



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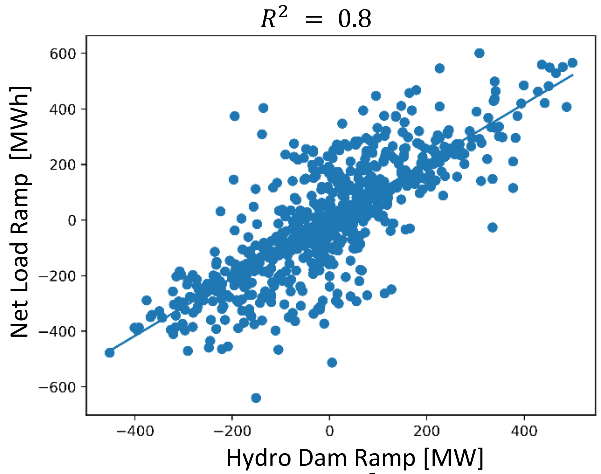
Net Load Tracking

- Correlation between Net Load and generation ramp for different technologies
  - **Today, who is responsible for the system flexibility?**

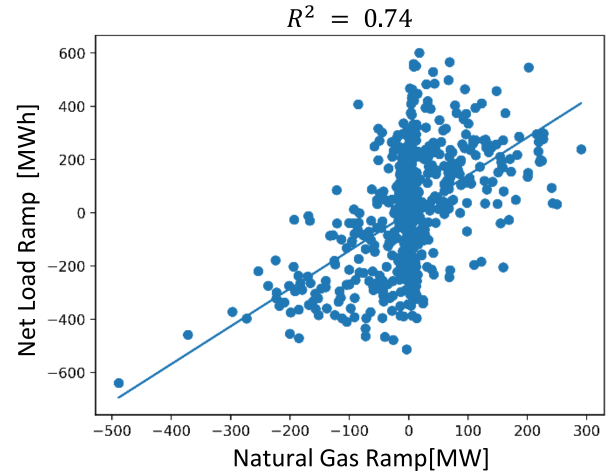
Hydro Dam



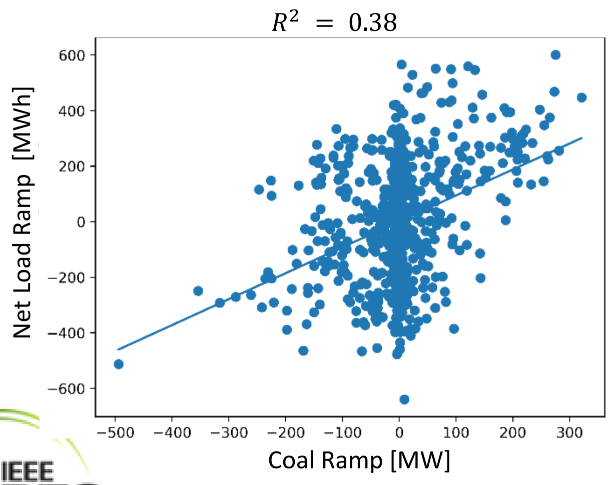
Real - 2017

February

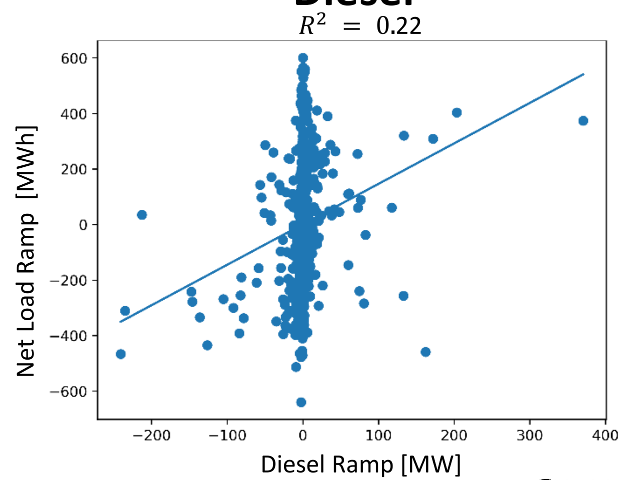
Natural Gas



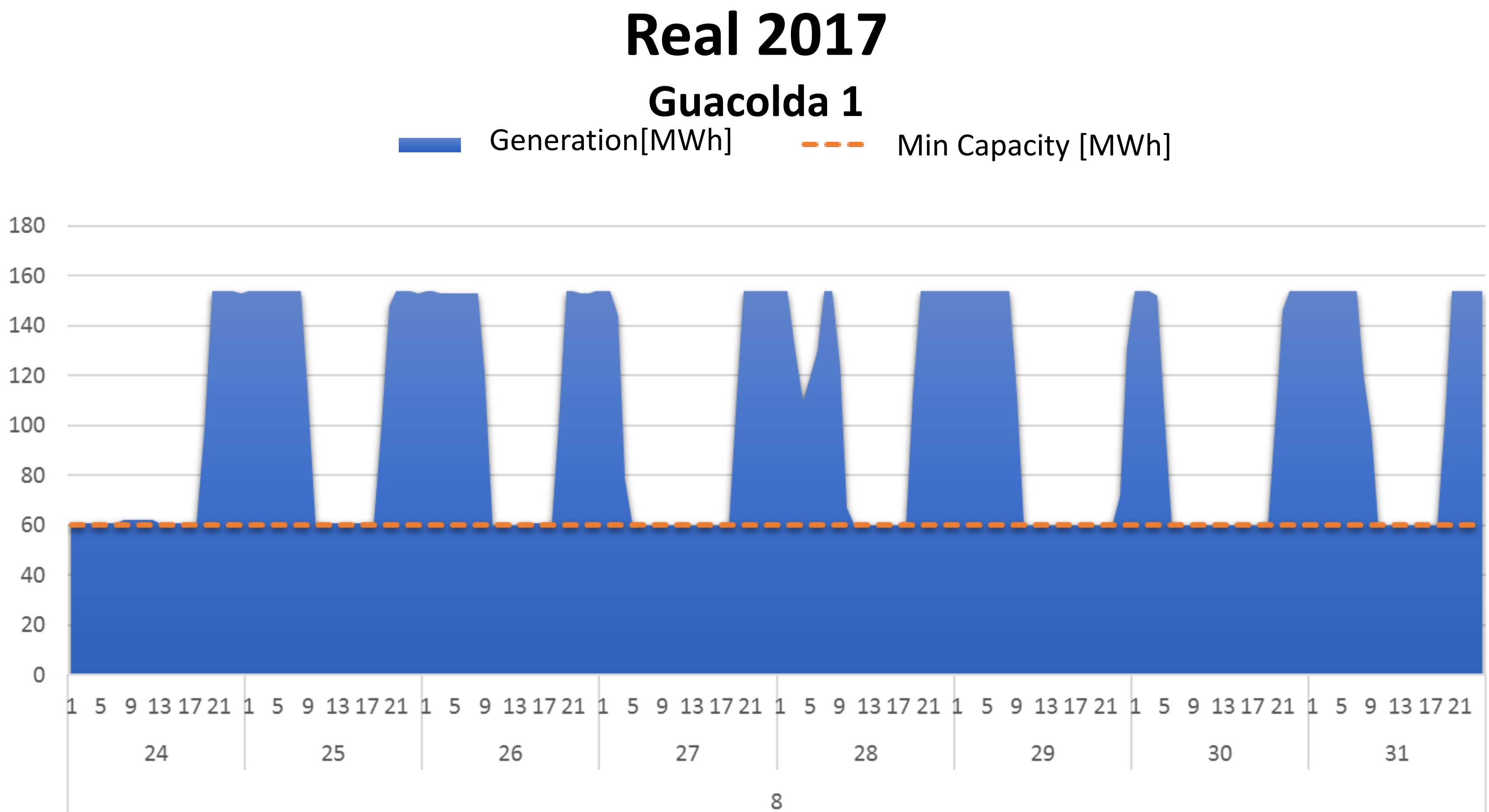
Coal



Diesel



What is going on today?



What is going to happen in the future with a high penetration of ERV?

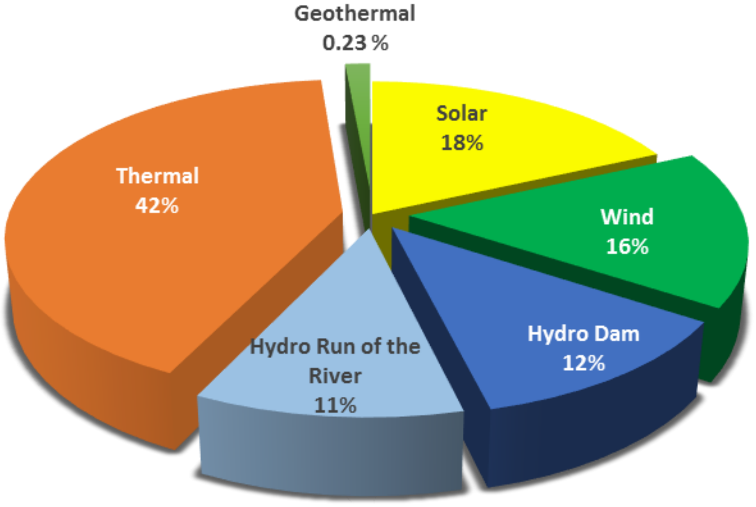
Case Study: Understanding Power System Flexibility

- **Base Case**
- Contribution from
  - Transmission
  - Hydro Power Dams
  - Batteries

Base Case

- Installed capacity in Base case in **2027**
  - **Demand**
    - Max 14,496 [MW]
    - Average 11,029 [MW]
    - Min 8,225 [MW]
  - **Topology**
    - 588 Bus Bar
    - 724 Transmission lines
  - **Units**
    - 245 Thermal
    - 149 VRE
    - 11 Hydro Dam
    - 70 Hydro Run of the River

Technology	Installed [MW]
Solar	2,090
Wind	1,299
Hydro Dam	3,858
Hydro Run of the River	2,803
Thermal	12,110
Geothermal	465

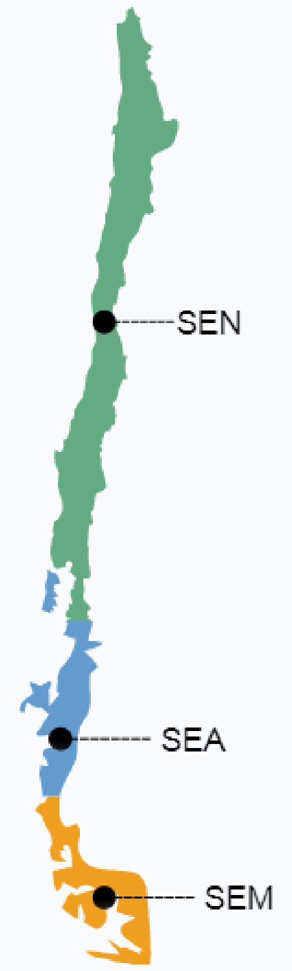


VRE SEN: 11,274 MW
Total SEN: 30,875 MW

Total VRE SEN ~ 36%
(Variable Renewable Energy, i.e., Solar and Wind)

Assumptions

- **Real topology of Chilean national electricity system (SEN)**
  - Generators available today
  - Realistic new entrances for conventional generators
- **Demand**
  - Compound growth rate ~ 3.3%
- **Deterministic simulations**
  - 3 hydrological scenarios (Dry, Medium, Wet)
  - One fuel price scenario
  - One representative week for each month
- **Resolution of the problem**
  - Hourly resolution
- **Simulations in two stages**
  - Long term with OSE2000
  - Short term model HELO (MILP)



Hourly electric operation model - HELO

Methodology developed by Systep

Long-term dispatch model (OSE2000 - SDDP)
- Initial & final reservoir volume
- Water opportunity cost

Hourly inputs
- Demand
- Profiles VRE
- Maintenance plans

Technical parameters
- Min capacity
- Start-up and Shutdown times
- Ramp up/Down
- Spinning reserve

HELO MODEL [4]

Optimizer FICO

Hourly Outputs
- Marginal Cost
- Hourly generation
- Line flows

Analysis
- Cycling
- Renewable curtailment
- Operation to min capacity
- MgC Day/Night
- Flexibility
- Ancillary services

Description of operation model - HELO

Simulated model dimension

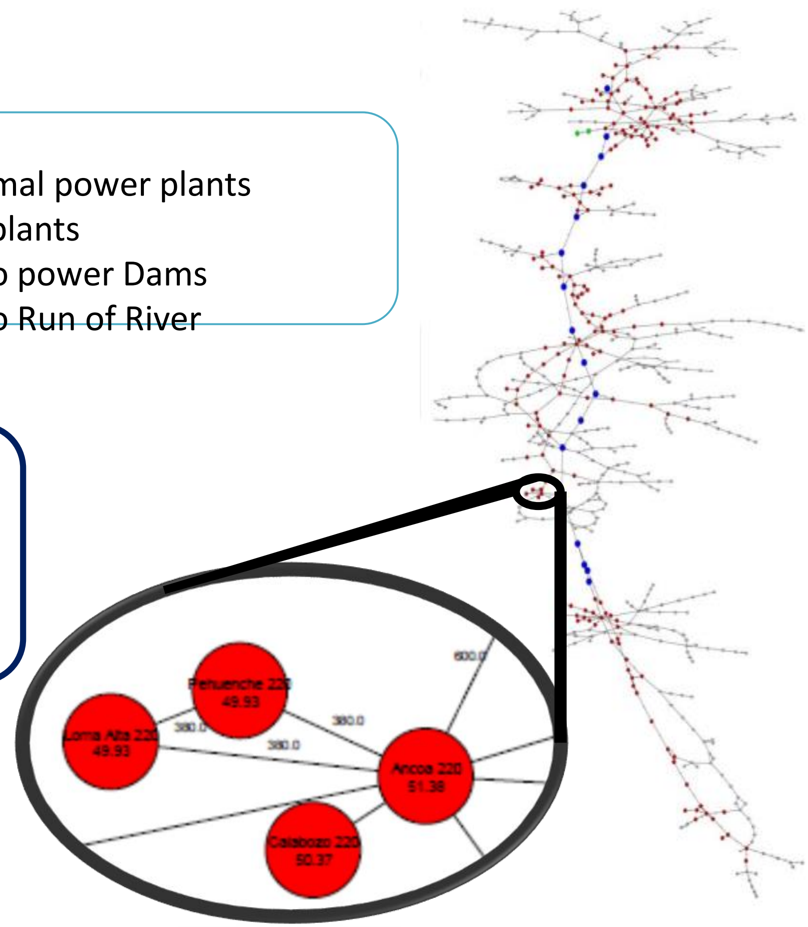
➤ **Chilean national grid**

Topology
- 588 Bus Bar
- 724 Transmission lines

Units
- 245 Thermal power plants
- 149 VRE plants
- 11 Hydro power Dams
- 70 Hydro Run of River

Complete model:

- **+ 79,000 Constraints**
- **+ 280,000 Lineal variables**
- **+ 19,000 Integer Variables**



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Base Case Results

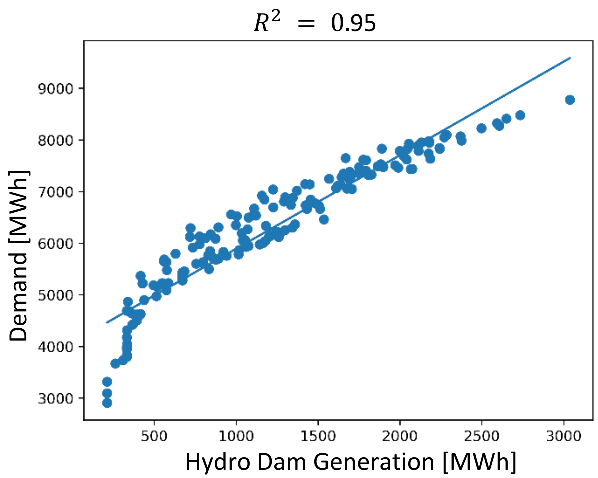
Base Case: Net Load Tracking

- Correlation between Net Load and generation for different technologies

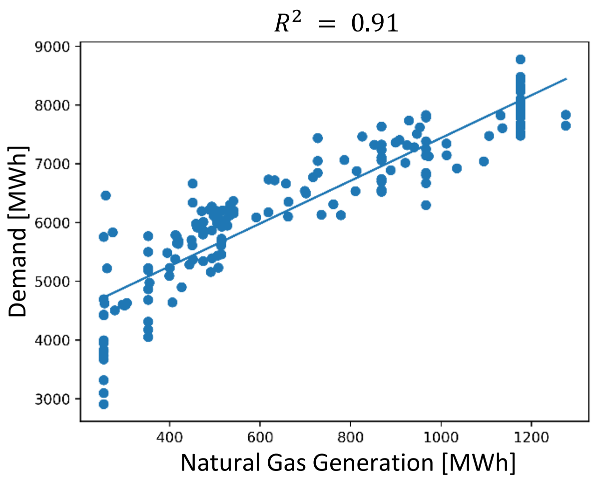
Base - 2027

February

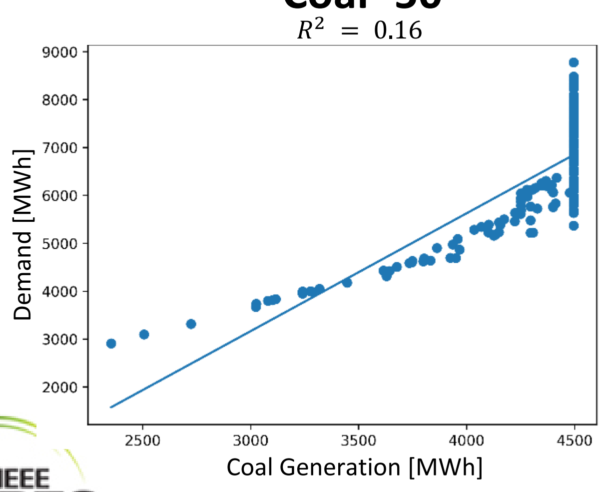
Hydro Dam - 50



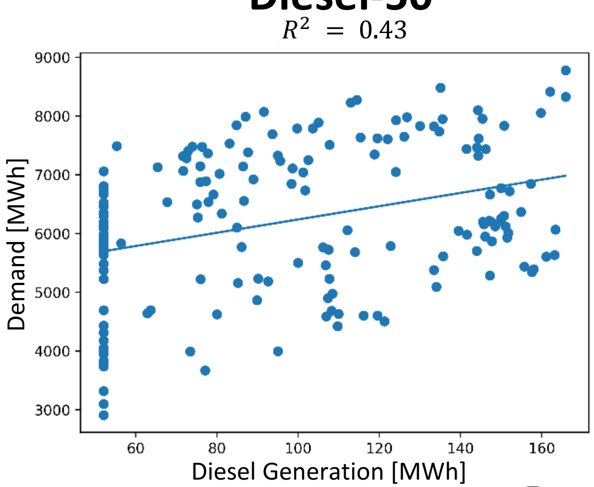
Natural Gas - 50



Coal -50



Diesel-50



Net Load Tracking

➢ Correlation between Net Load and generation ramp for different technologies

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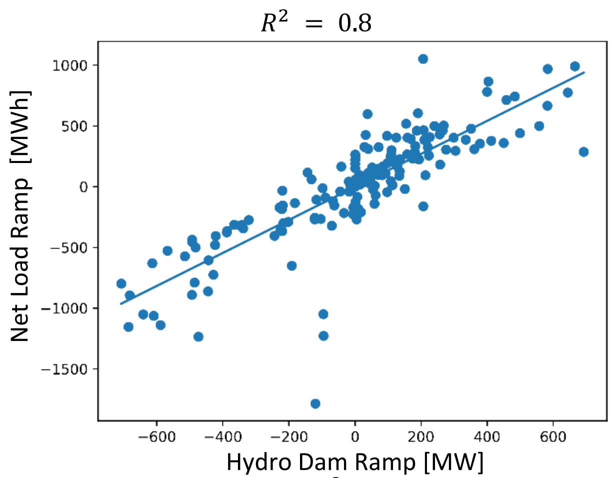

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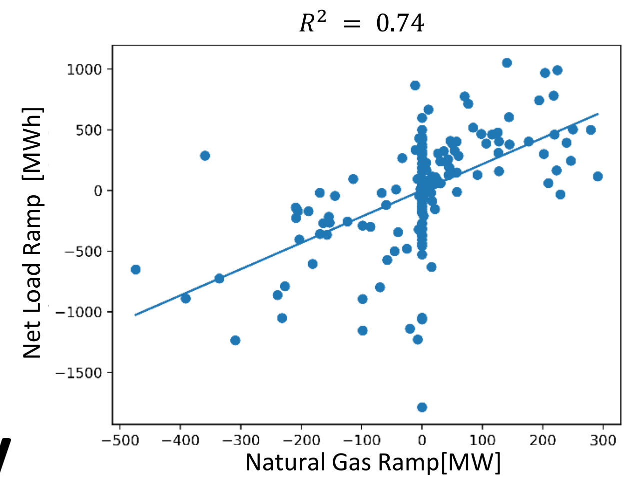

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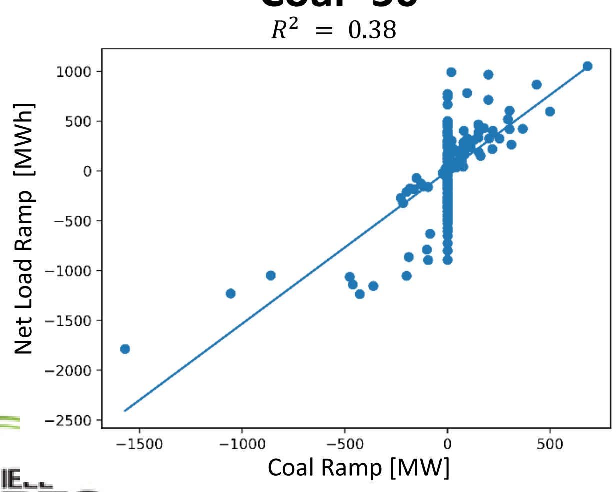
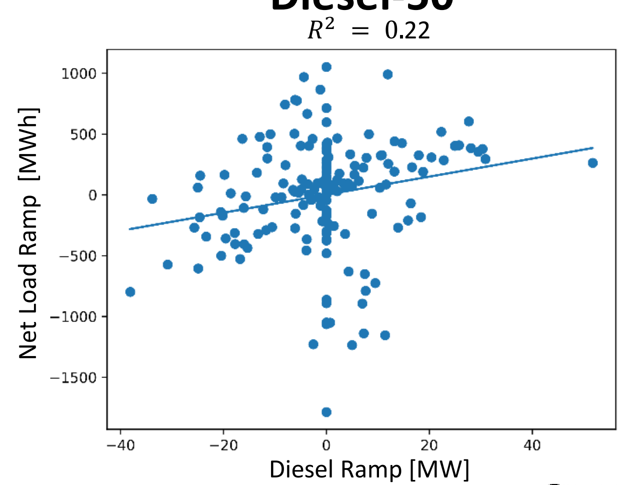


Diesel-50



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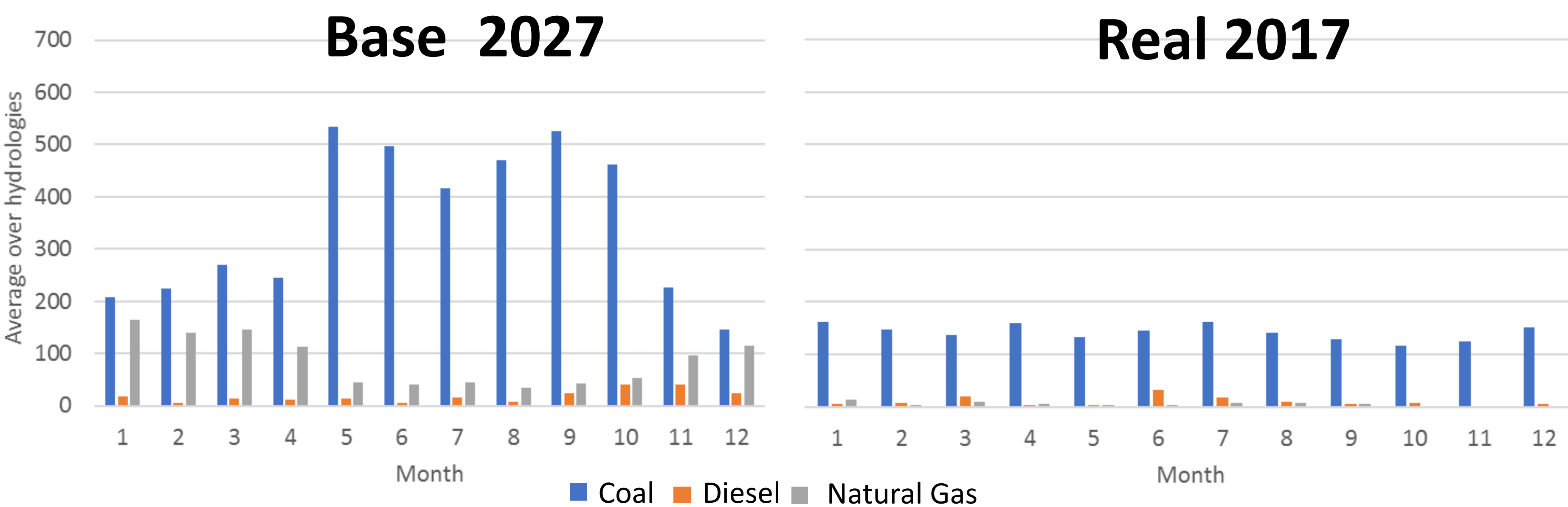
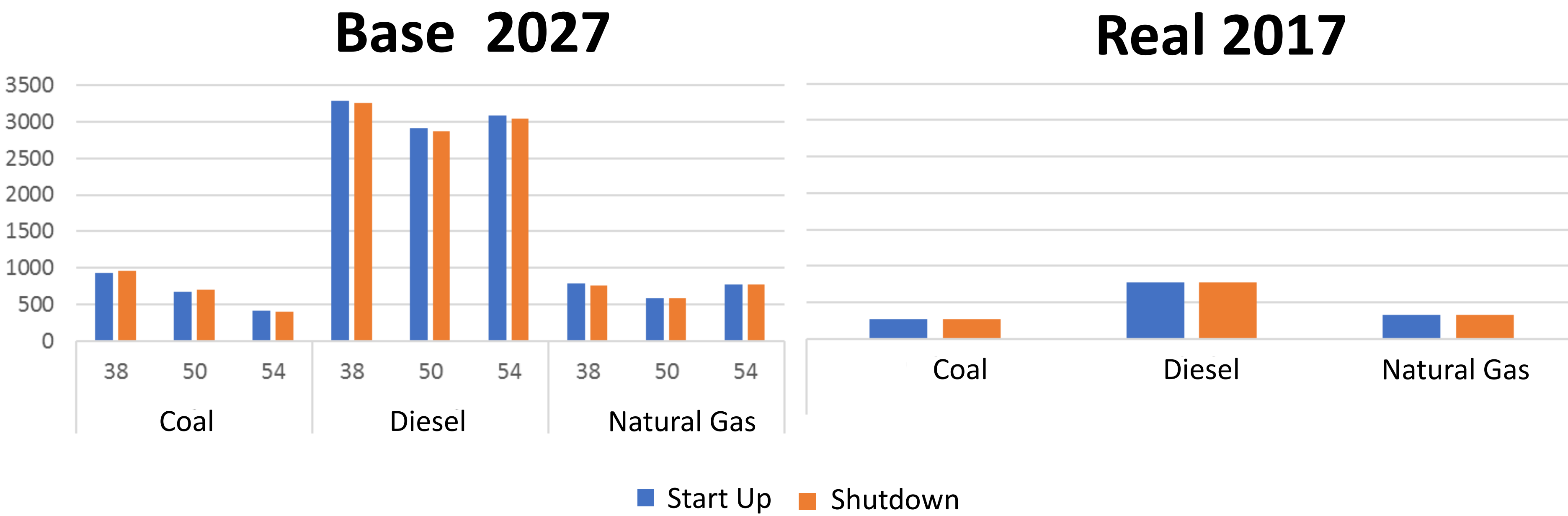
Base Case: Cycling Analysis



Average annual cycling (3 hydrologies)		
Technology	**Base 2027**	**Real 2017**
Coal	4220	391
Diesel	216	25
Natural Gas	1032	13
Total	**5468**	**429**

Base Case: Start-up and Shutdown Analysis



Average annual cycling (3 hydrologies)		
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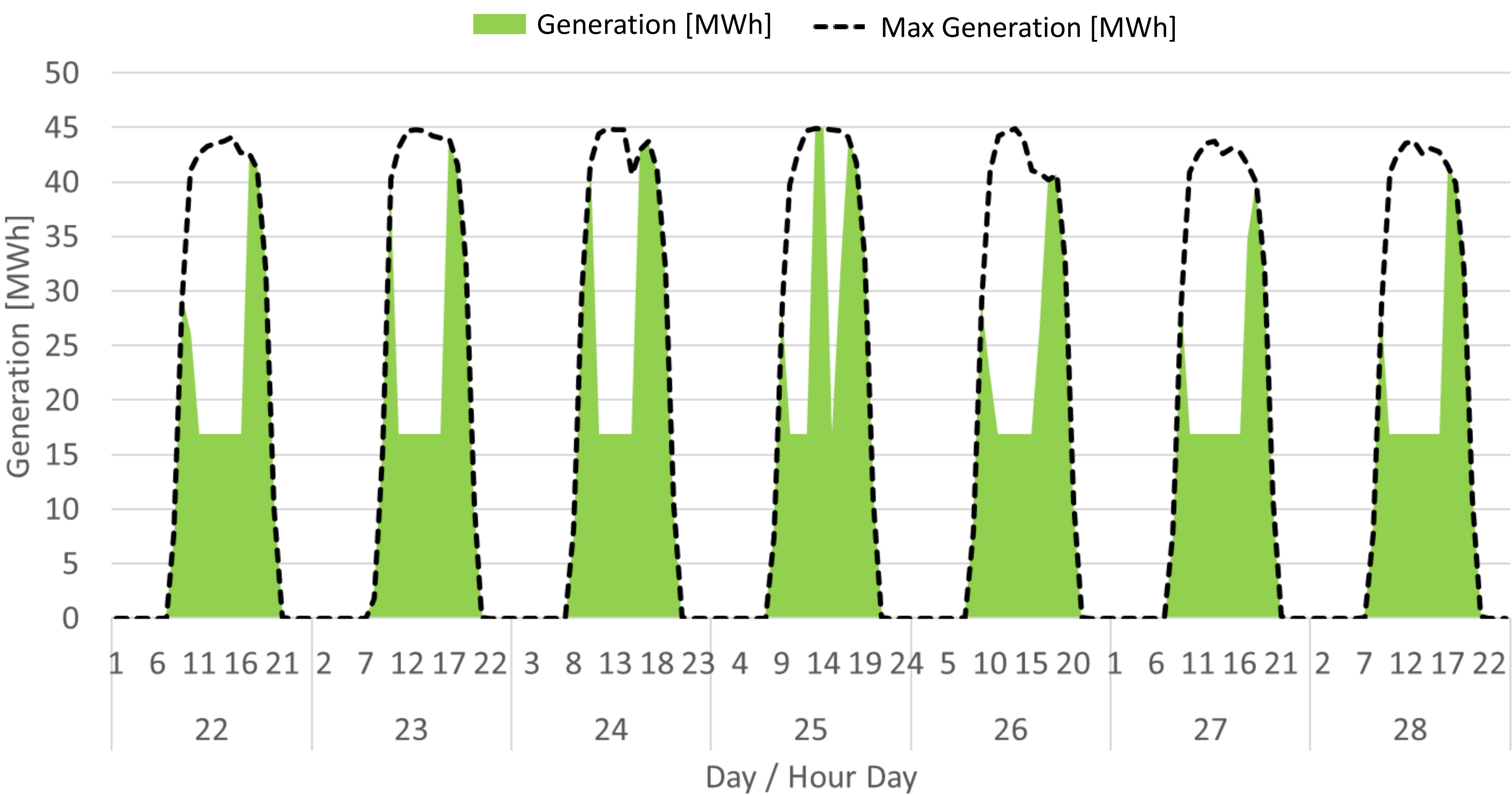
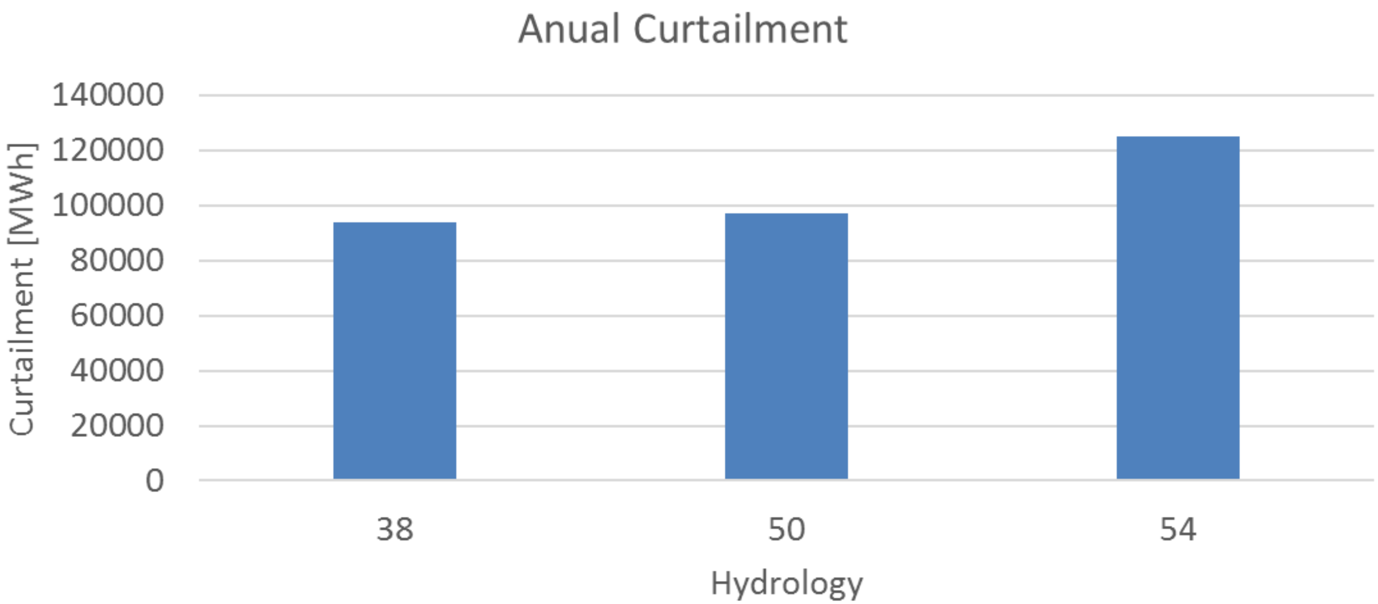
Base Case: Curtailment Analysis



Base Case: Curtailment Analysis



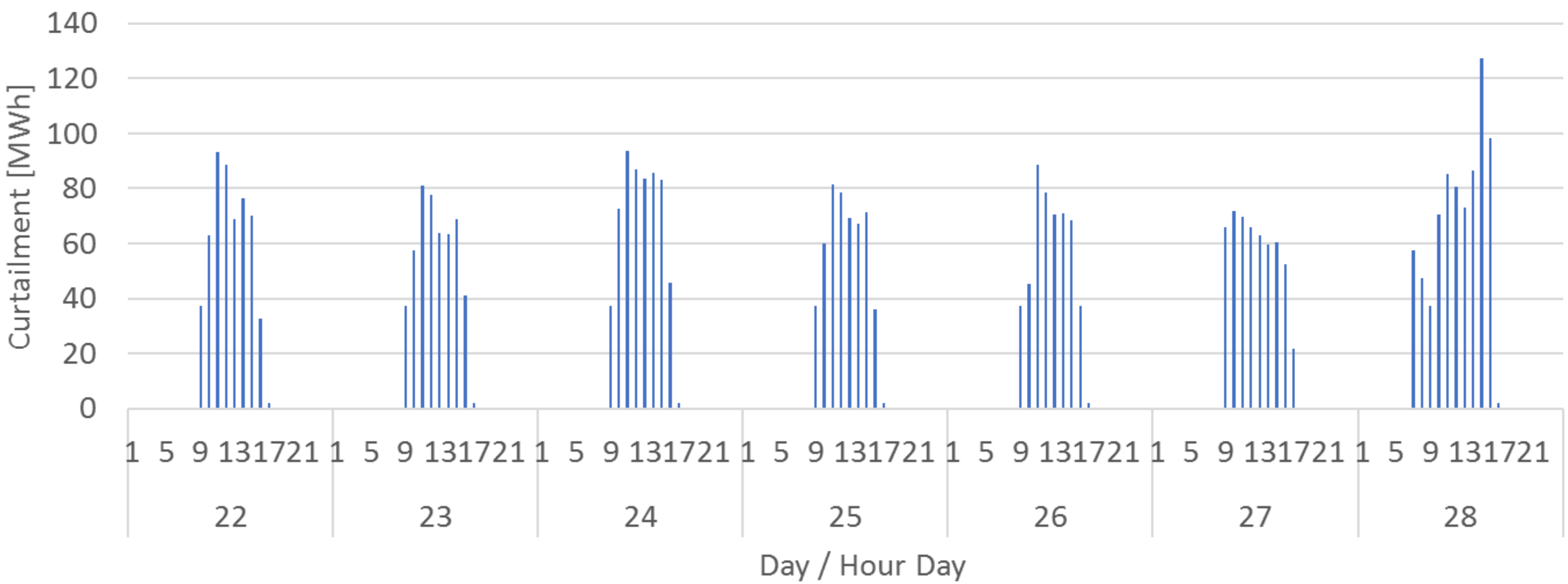
Total Anual Curtailment [GWh]	
Hydrology	**Base 2027**
38	92
50	96
54	124

Case Study: Understanding Power System Flexibility

- Base Case
- Contribution from
  - **Transmission**
  - Hydro Power Dams
  - Batteries

Case Study: Transmission contribution

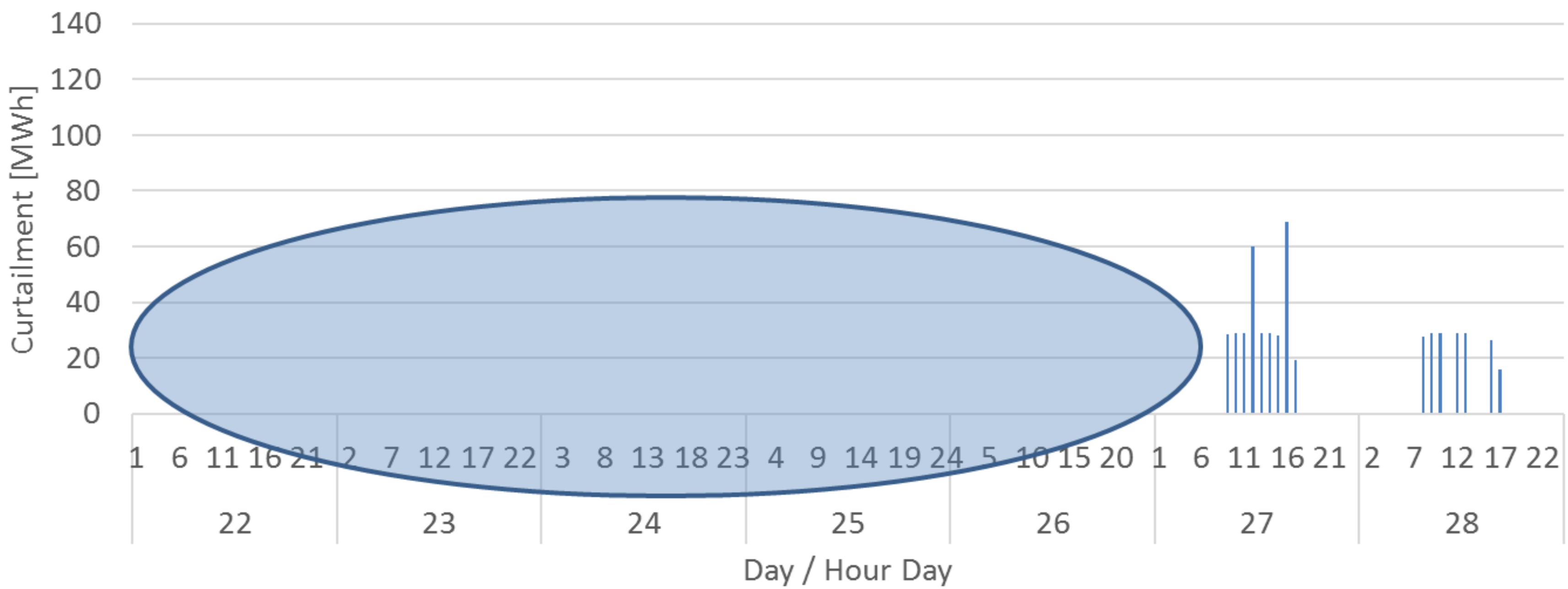
Curtailment considering the transmission system in the optimization/simulation process



These curtailments are potentially caused by transmission problems and/or lack of flexibility of the power system

Case Study: Transmission contribution

TEST 1: Curtailment **without** transmission restrictions

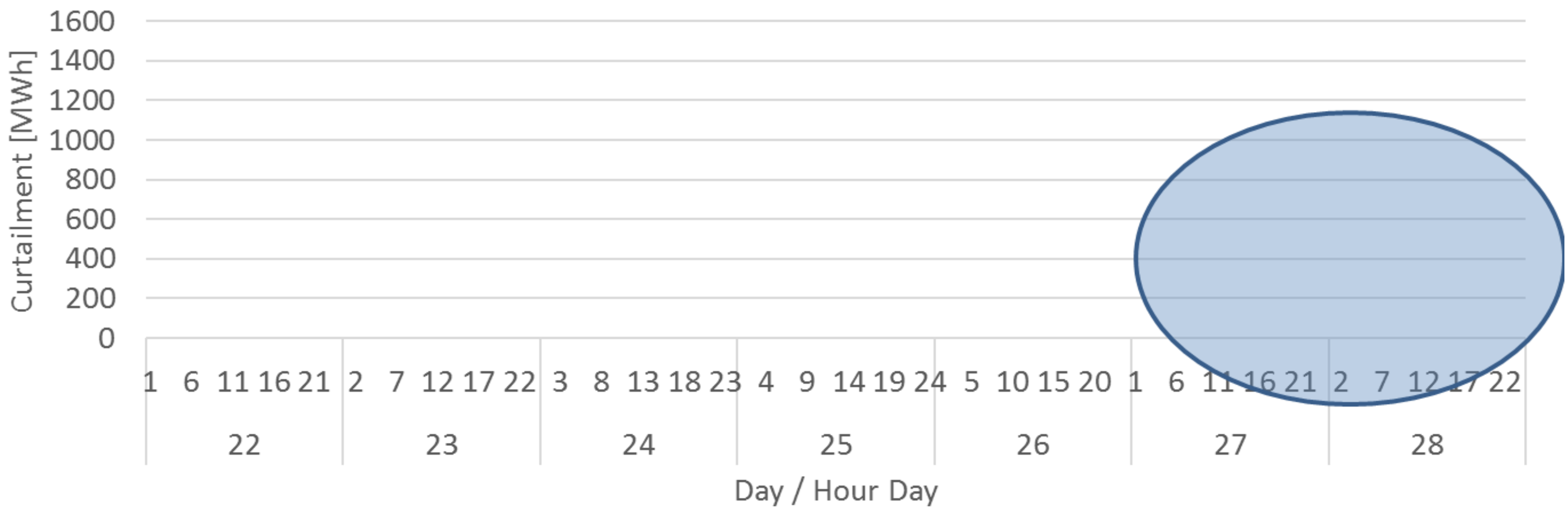


Problems eliminated had their origin in the transmission system.
Are the remaining issues due to the flexibility of the installed fleet?

Case Study: Transmission contribution

➢ **Case of analysis: LP resolution and without transmission**

TEST 2: Curtailment **without** transmission and Resolution LP (without binary constraints)

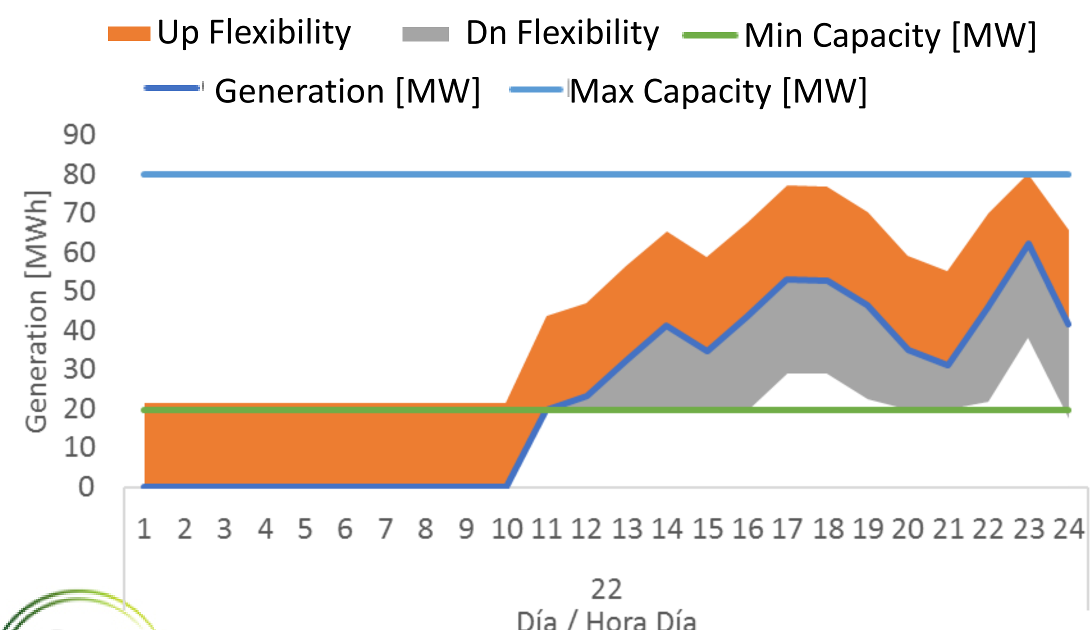


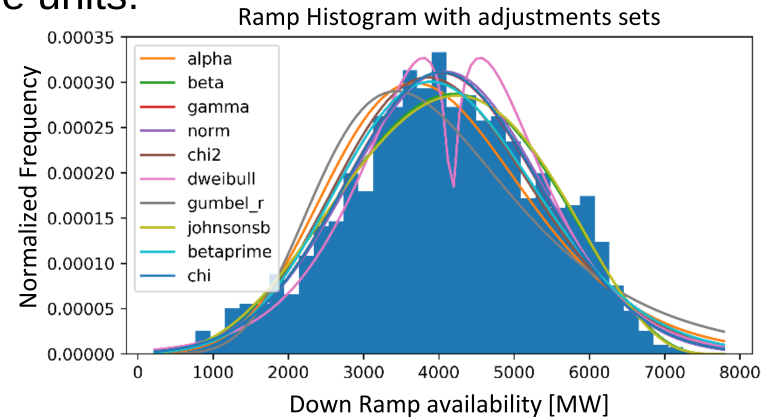
Remaining issues have their origin in the lack of flexibility of the system

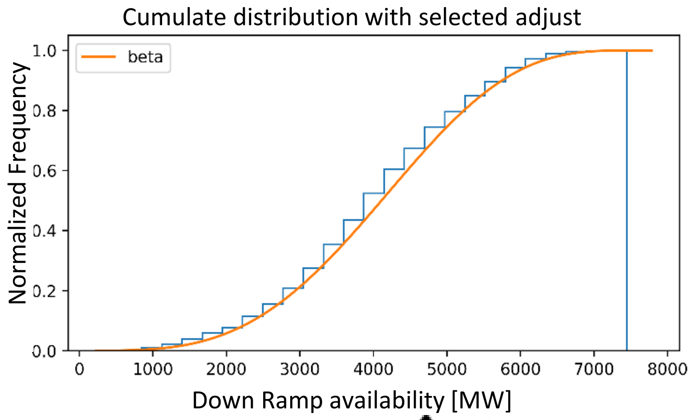
Therefore, the possibility to move flexibility through the system is also important

Transmission system operation & Flex: IRRE

- **IRRE: Insufficient ramping resource expectation:** metric based on the probability that the system does not have enough ramp
- Considering the fact that the capacity of ramp up and down depends on the point of power system operation
- Calculation depends on the technical characteristics of the units:
  - Start up / Down time
  - Minimum and maximum Capacity
  - Ramp up/ Down







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Transmission system operation & Flex: IRRE

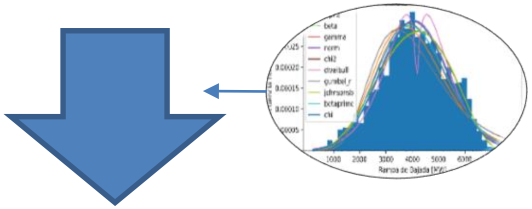
- **IRRE = Insufficient Ramping Resource Expectation**

$$Flex_{t,i} = Ramp_{up} \cdot (1 - (1 - Online_{t,i}) \cdot S_i)$$

$$Flex_t^{System} = \sum_{\forall i} Flex_{t,i}$$

IRRE Up		
Hydrology	**Base 2027**	**Real 2017**
38	0	
50	0	0
54	0.001	

IRRE Dn		
Hydrology	**Base 2027**	**Real 2017**
38	1.39	
50	4.09	0.16
54	6.69	



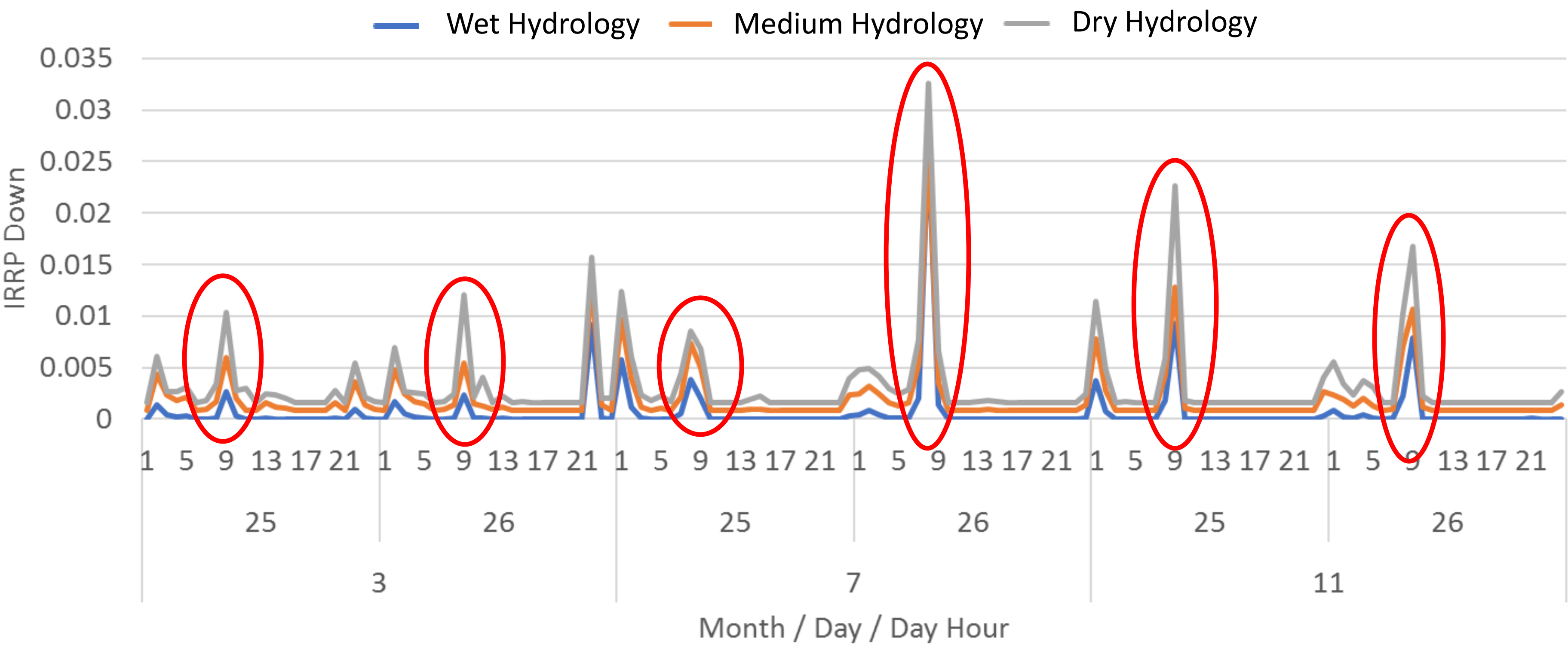
$$IRRP_t = AFD_t(Ramp_{carga} - 1)$$

$$IRRE = \sum_{\forall t \in T} IRRP_t$$

Parameter descriptions	
$Ramp_{up}$	Ramp up of generator i
$Online_{t,u}$	Operation state of generator i in hour t
S_i	Star up time of generador i
AFD_t	Distribution adjust evaluated in hour t

Transmission system operation & Flex: IRRE

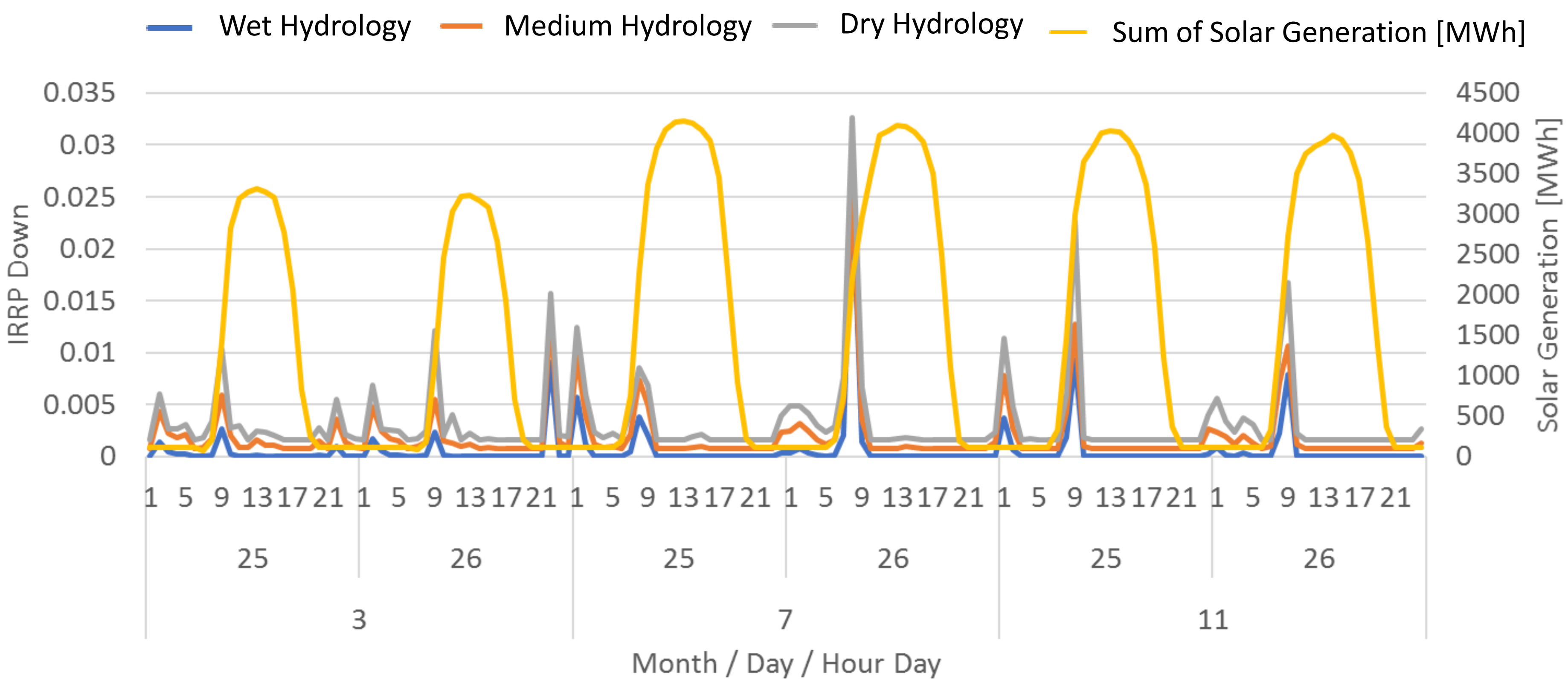
- **IRRE =** Probability that the system does not have enough ramp



Largest flexibility problems are due to the solar ramp-up

Transmission system operation & Flex: IRRE

- **IRRE =** based on the probability that the system does not have enough ramp



Largest flexibility problems are due to the solar ramp-up

Case Study: Understanding Power System Flexibility

- Base Case
- Contribution from
  - Transmission
  - **Hydro Power Dams**
  - Batteries

Hydro Power Dams contribution to the system

- **Normalized Flexibility Index (NFI)**
  - Calculation based on the installed fleet without considering the operation point
    - Min capacity, Startup/Down time, Ramp rate

$$flex(i) = \frac{\frac{1}{2}[P_{max}(i) - P_{min}(i)] + \frac{1}{2}[Ramp(i)]}{P_{max}(i)}$$

$$FLEX_{system} = \sum_{i \in A} [\frac{P_{max}(i)}{\sum_{i \in A} P_{max}(i)} \cdot flex(i)]$$

Flexibility Level	$FLEX_{System}$
High	0.63
Medium	0.48
Low	0.43

Caso	$FLEX_{System}$
Real	0.679
Without Hydro Dams	0.621

- **Consideration**
  - Base on the index, the Chilean fleet is considered flexible
  - Without Hydro Power Dams: Chilean fleet is still flexible, but the operation (and costs) change considerable.

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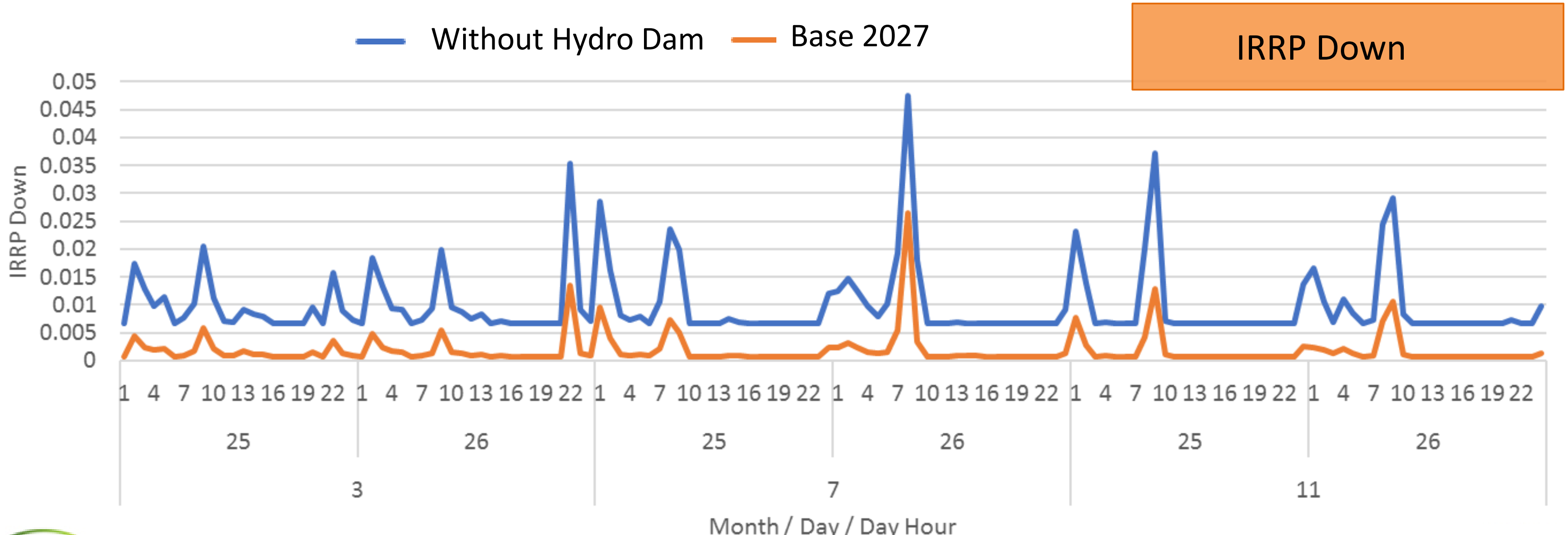
Hydro Power Dams contribution to the system

➢ IRRE – Without Hydro Dams

IRRE Up		
Hydrology	Base 2027	Without Hydro Dam
38	0	0.1489
50	0	0.213
54	0.001	0.28

IRRE Down		
Hydrology	Base	Without Hydro Dam
38	1.39	25.84
50	4.09	20.31
54	6.69	11.43

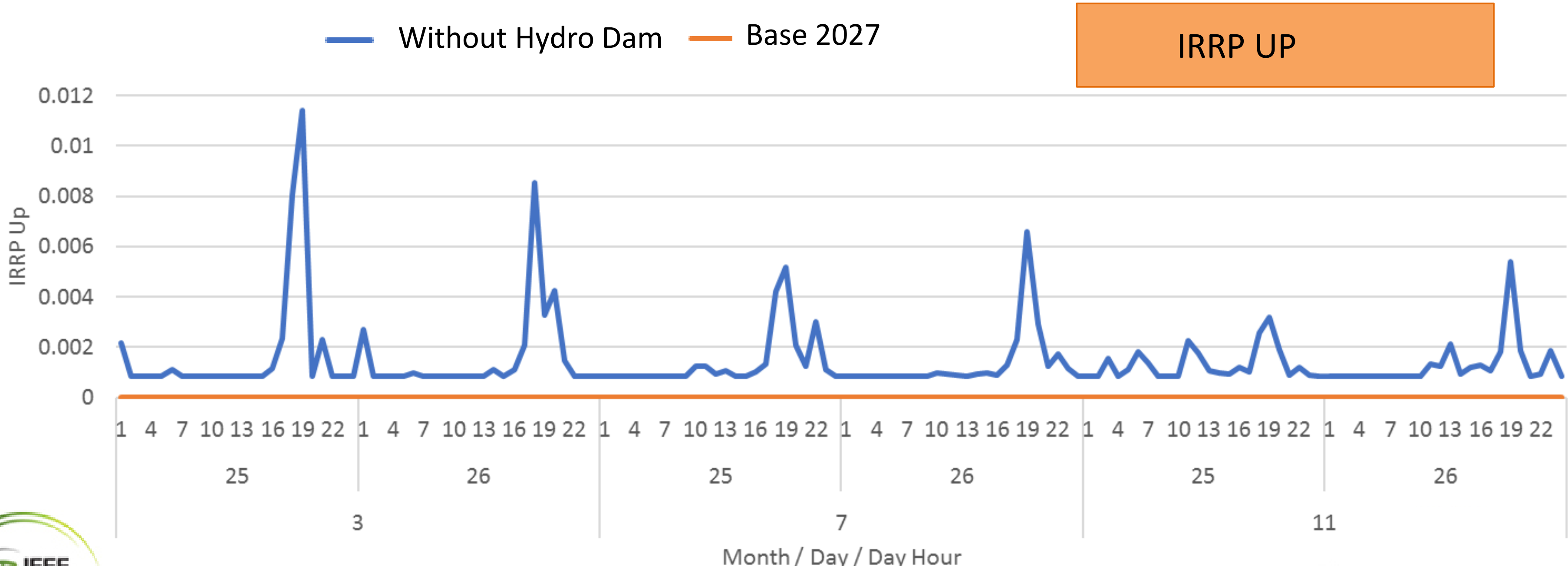


Hydro Power Dams contribution to the system

➢IRRE – Without Hydro Dams

IRRE Up		
Hydrology	**Base 2027**	**Without Hydro Dam**
38	0	0.1489
50	0	0.213
54	0.001	0.28

IRRE Down		
Hydrology	**Base**	**Without Hydro Dam**
38	1.39	25.84
50	4.09	20.31
54	6.69	11.43



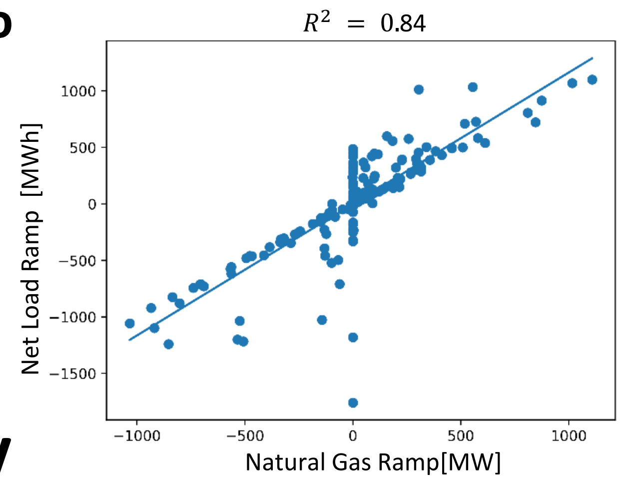
Net Load Tracking

➢ Correlation between Net Load and generation ramp for different technologies

Hydro Dam - 50

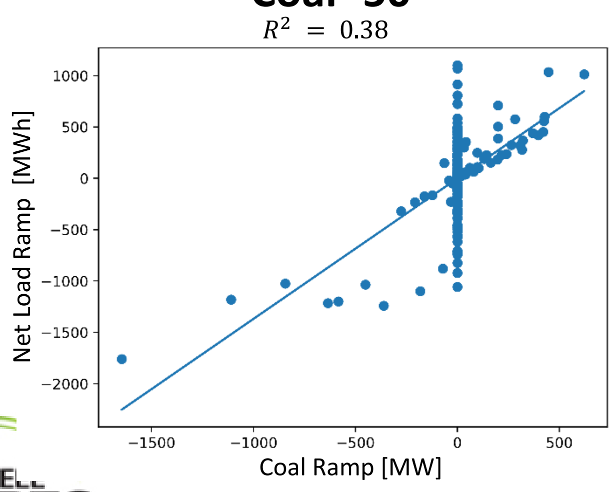
Without Hydro Dams - 2027

Natural Gas - 50

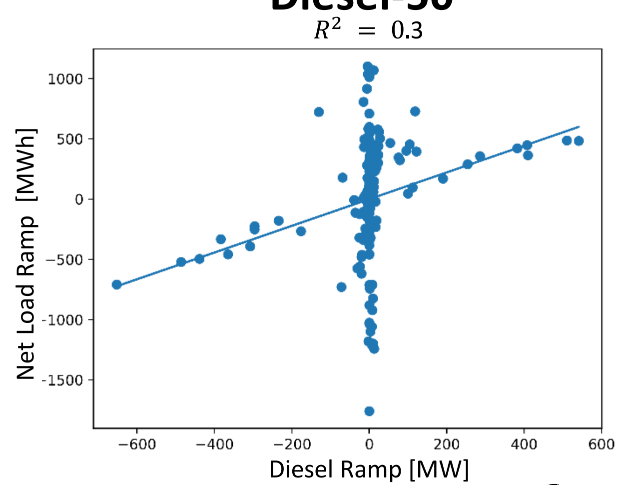


February

Coal -50



Diesel-50



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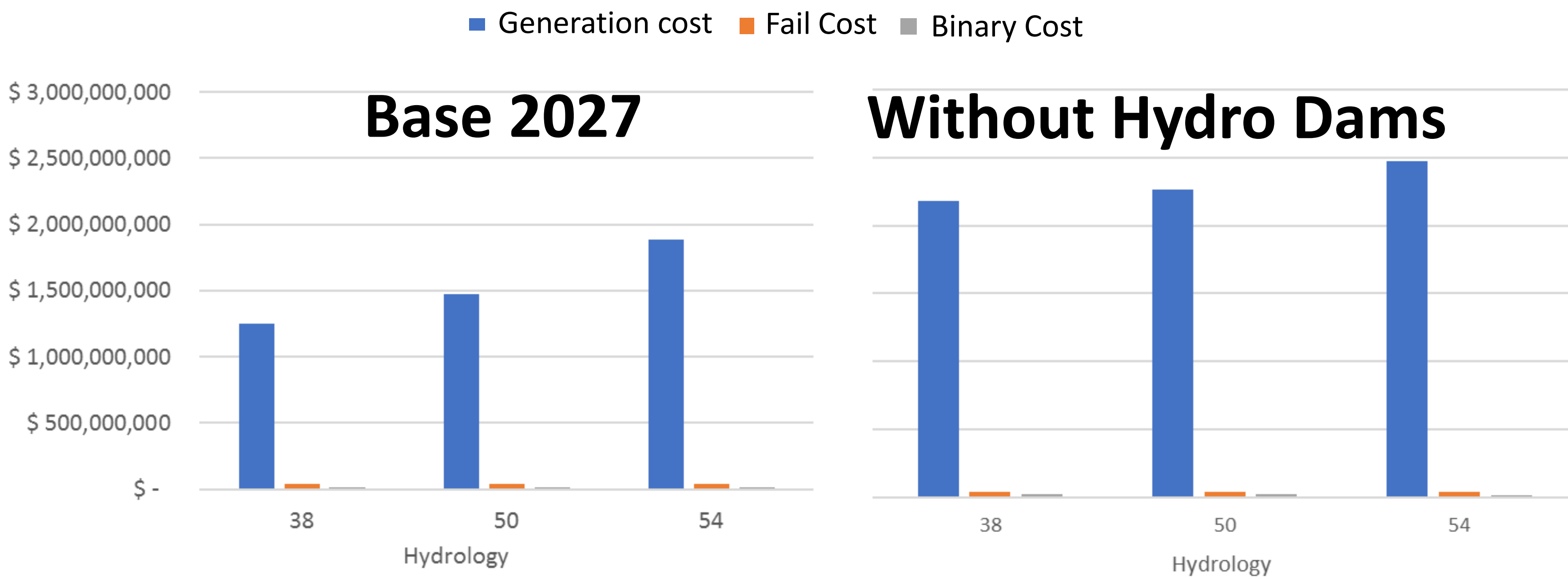
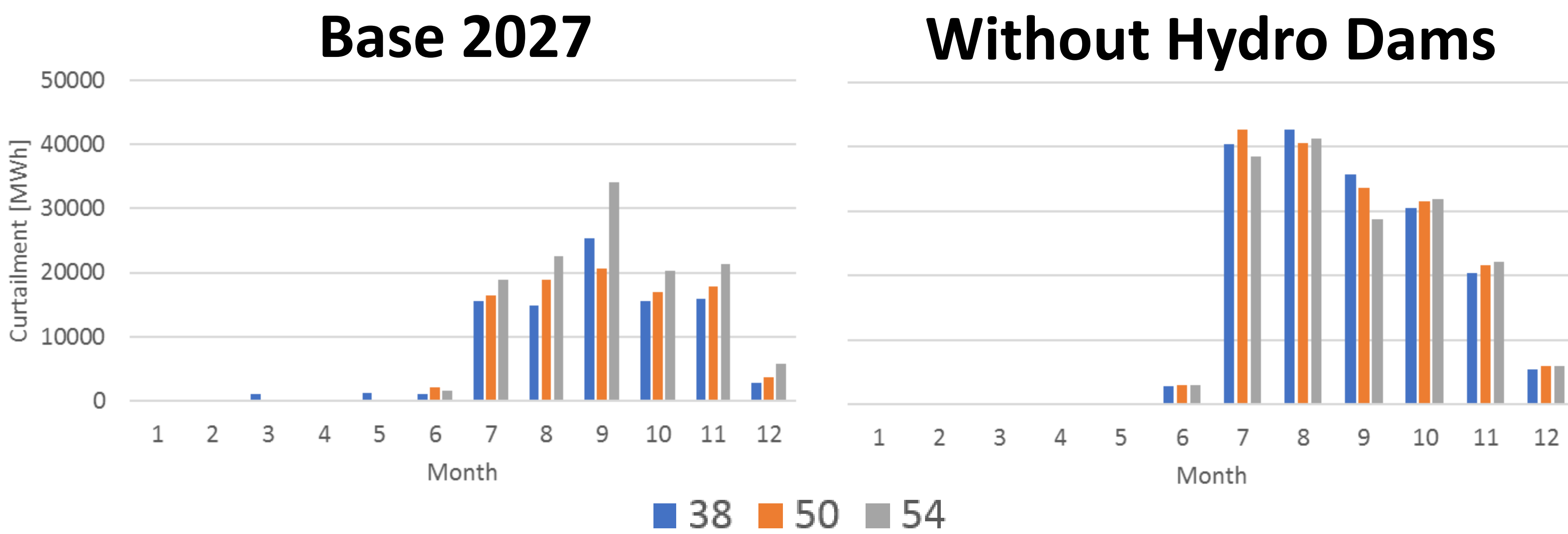
Operational cost analysis 2027



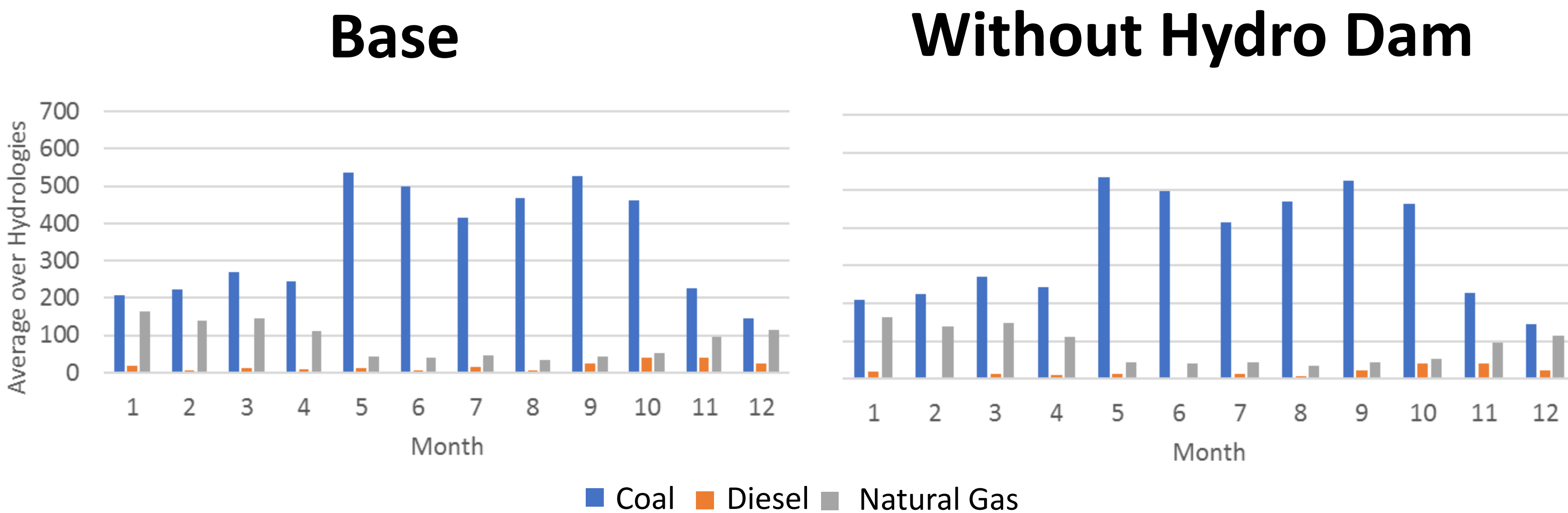
Annual Total Cost [USD]	
Case	**Total Average Cost**
Base	$ 1,590,433,567
Without Hydro Dams	$ 2,411,513,066

Curtailment analysis 2027



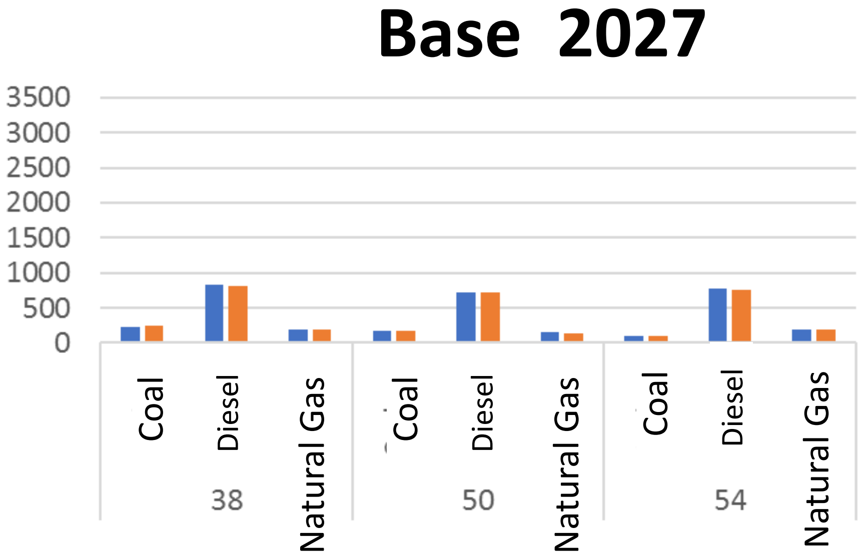
Total Annual Curtailment [GWh] Base 2027	
Case	**Average**
Base	105
Without Hydro Dams	176

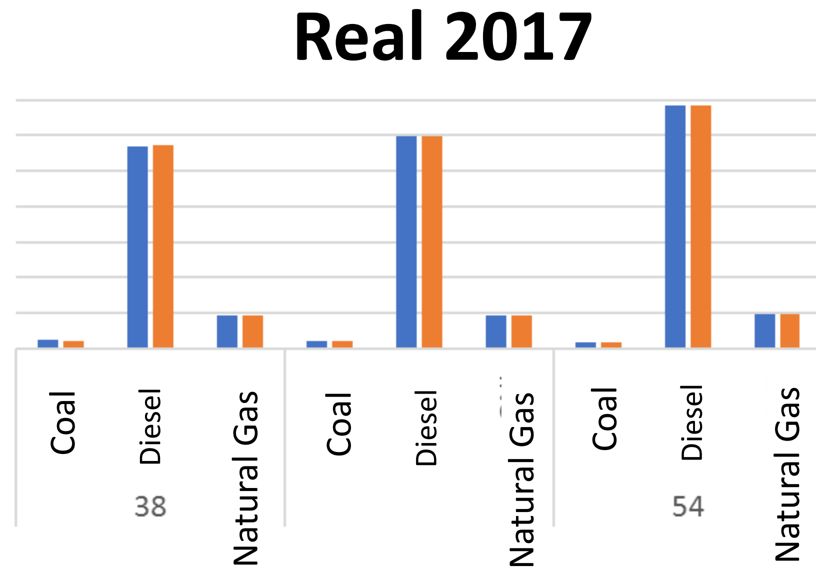
Cycling analysis 2027



Average of Annual cycling (Over hydrologies)		
Technology	Base 2027	Without Hydro dams
Coal	4,220	3,376
Diesel	216	301
Natural Gas	1,032	1,516
Total	**5,468**	**5,193**

Base Case: Start-up and Shutdown Analysis





Total Annual Start-Up			
Technology	**Base**	**Without Hydro Dams**	**Real**
Coal	671	423	273
Diesel	3,093	12,356	776
Natural Gas	715	1,903	327
Total	**4,241**	**14,681**	**1,376**

Total Annual shutdown			
Technology	**Base**	**Without Hydro Dams**	**Real**
Coal	688	403	270
Diesel	3,059	12,353	772
Natural Gas	701	1,904	328
Total	**4,448**	**14,660**	**1,370**

Case Study: Understanding Power System Flexibility

- Base Case
- Contribution from
  - Transmission
  - Hydro Power Dams
  - **Batteries**

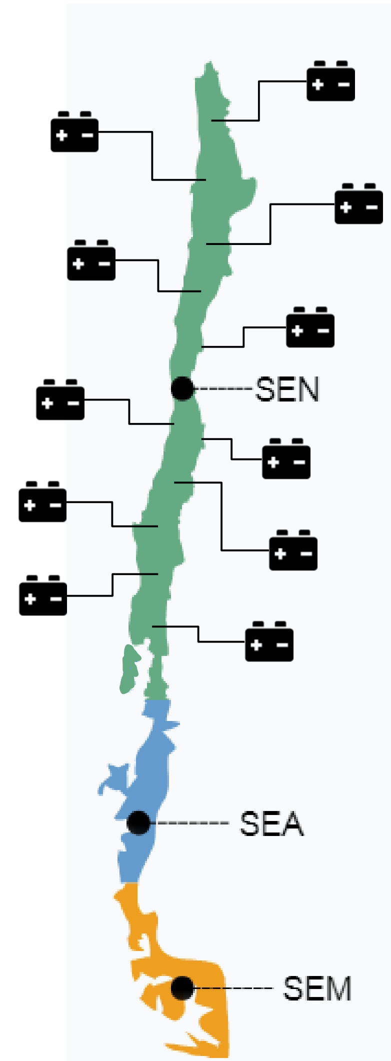
Batteries contribution to the system flexibility

- Implementation in Base Case 2027

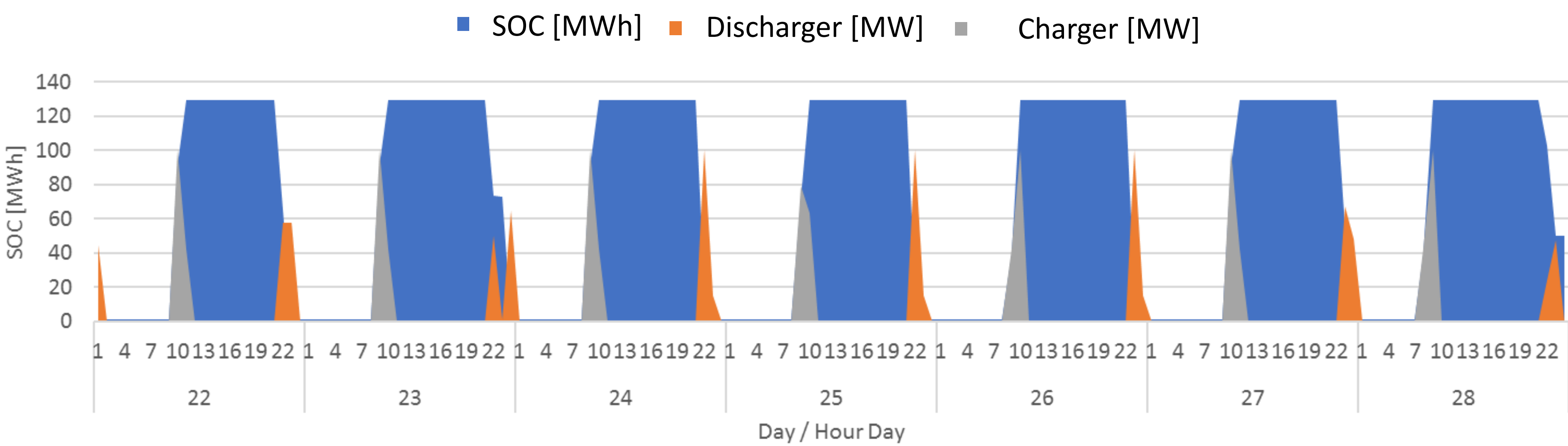
- **Simulated case**
  - **Capacity and size equivalent to Tesla batteries in Australia for each location**
    - Realistic operation with batteries
    - Capacity of 100 [MW] / 129 [MWh] each
    - Location in representative nodes of the system

Batteries in 11 locations:

- Crucero 220
- Atacama 220
- Diego de Almagro 220
- Cardones 220
- Pan de Azúcar 500
- Polpaico 220
- Alto Jahuel 220
- Ancoa 220
- Charrúa 220
- Valdivia 220
- Puerto Montt 220



Batteries contribution to the system flexibility



Battery	Capacity [MWh]	Duration [Hrs]
Battery Alto Jahuel 220	100	1.26
Battery Ancoa 220	100	1.26
Battery Atacama 220	100	1.26
Battery Cardones 220	100	1.26
Battery Charrúa 220	100	1.26
Battery Crucero 220	100	1.26
Battery Diego de Almagro 220	100	1.26
Battery Pan de Azúcar 500	100	1.26
Battery Polpaico 220	100	1.26
Battery Puerto Montt 220	100	1.26
Battery Valdivia 220	100	1.26

The New York Times

Australia Powers Up the World's Biggest Battery — Courtesy of Elon Musk

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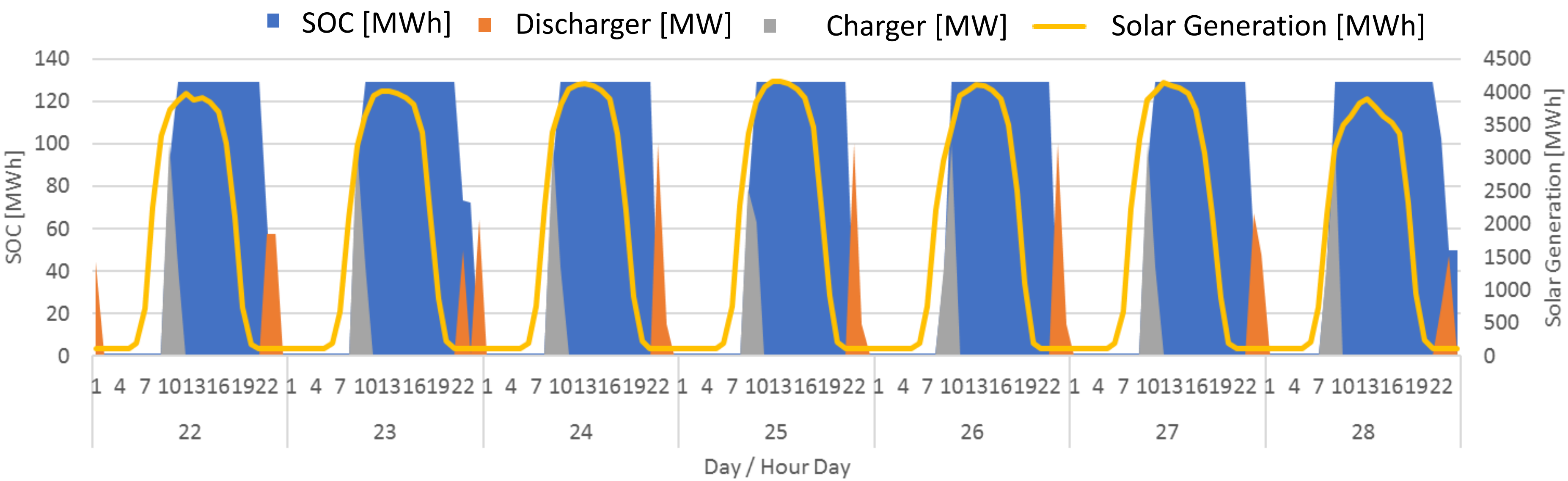
Batteries contribution to the system flexibility



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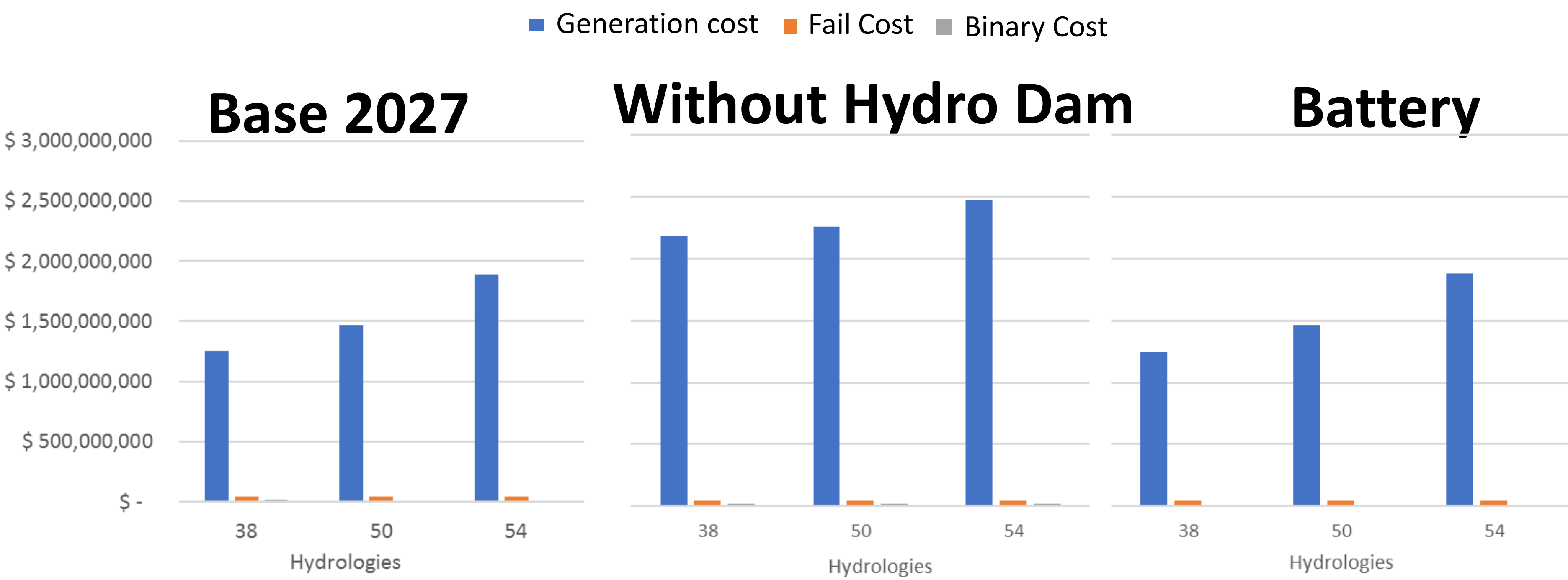
Battery Charrúa 220	100	1.26
Battery Crucero 220	100	1.26
Battery Diego de Almagro 220	100	1.26
Battery Pan de Azúcar 500	100	1.26
Battery Polpaico 220	100	1.26
Battery Puerto Montt 220	100	1.26
Battery Valdivia 220	100	1.26

Batteries are not charging at the moment of cheapest marginal cost, but when the system needs them the most (in the solar ramping up)

Batteries contribution to the system flexibility

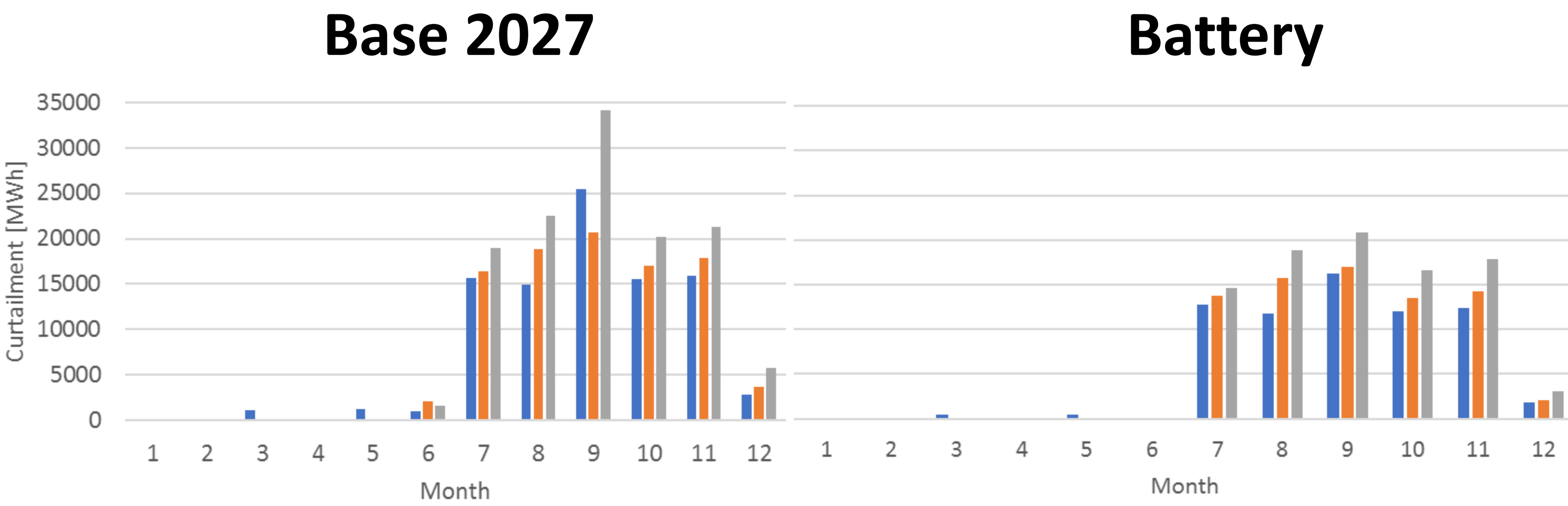
➤ **Cost Analysis**



Annual Total Cost [USD]	
Case	**Total Average Cost**
Base	$ 1,590,433,567
Without Hydro Dam	$ 2,411,513,066
Battery	$ 1,573,937,200

Batteries contribution to the system flexibility

➢ **Curtailment**



Total Annual Curtailment [GWh]	
Tipo	**Total**
Base	105
Without Hydro Dam	176
Battery	32

Batteries contribution to the system flexibility

➢ Cycling Analysis

Average of Annual cycling (3 Hydrologies)			
Technology	**Base**	**Without Hydro Dams**	**Battery**
Coal	4,220	3,376	3,500
Diesel	216	301	220
Natural Gas	1,032	1,516	916
Total	**5,468**	**5,193**	**4,632**

➢ Start-Up and shutdown Analysis

Total Annual Start-Up			
Technology	**Base**	**Without Hydro Dams**	**Battery**
Coal	671	423	592
Diesel	3,093	12,356	2,684
Natural Gas	715	1,903	484
Total	**4,241**	**14,681**	**3,760**

Final Remarks

- The current and projected installed fleet is flexible, according to the metrics analyzed for the VRE adoption levels studied (36% - 2027).

- The storage capacity (hydro power dams) in the Chilean system is an important factor in its flexibility (i.e., possibility to follow the ramping requirements)

- The transport capacity is crucial to “move” flexibility throughout the system.

- The short-term batteries do not charge and discharge at times of maximum price difference. On the contrary, it is convenient, from a system perspective, if they charge during the solar ramping-up.

Bibliography

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Power System Flexibility:
Key elements in the Chilean Power System

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Portland, August 2018