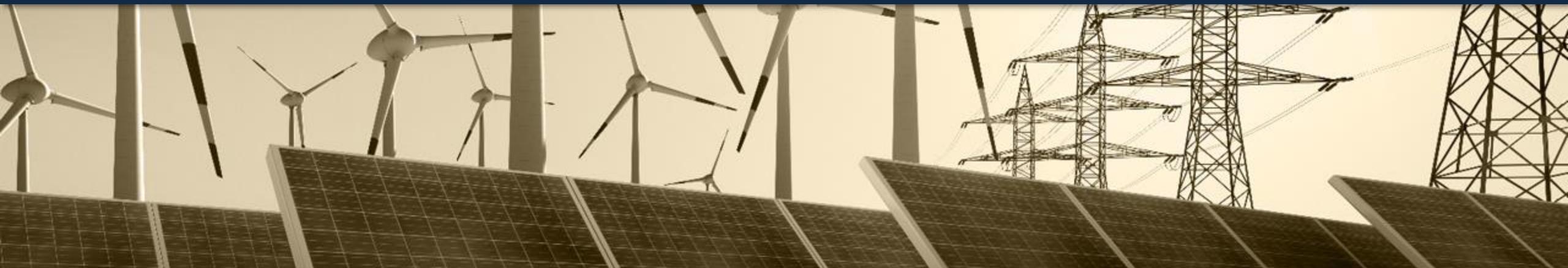


# A Julia/JuMP based Integrated Energy Resource Planning Model

[alessandro@psr-inc.com]



## Quick Introduction

- ▶ Graduated in Electrical and Control Engineering at PUC-Rio
- ▶ Currently doing Masters in Optimization at PUC-Rio
- ▶ Optimization Engineer and Developer at PSR since 2017

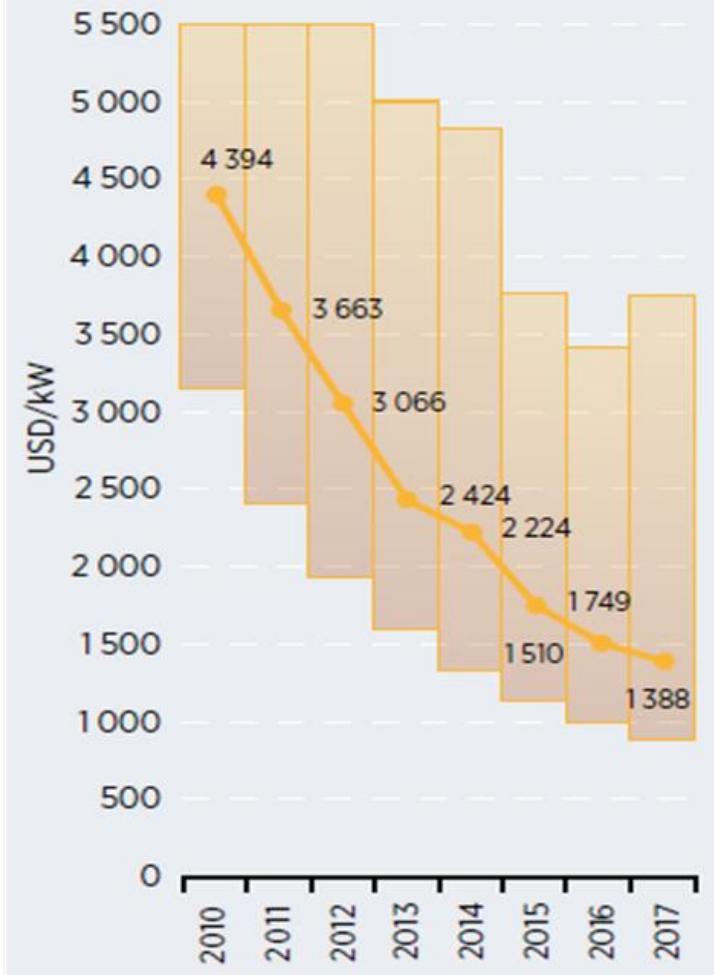


## Motivation

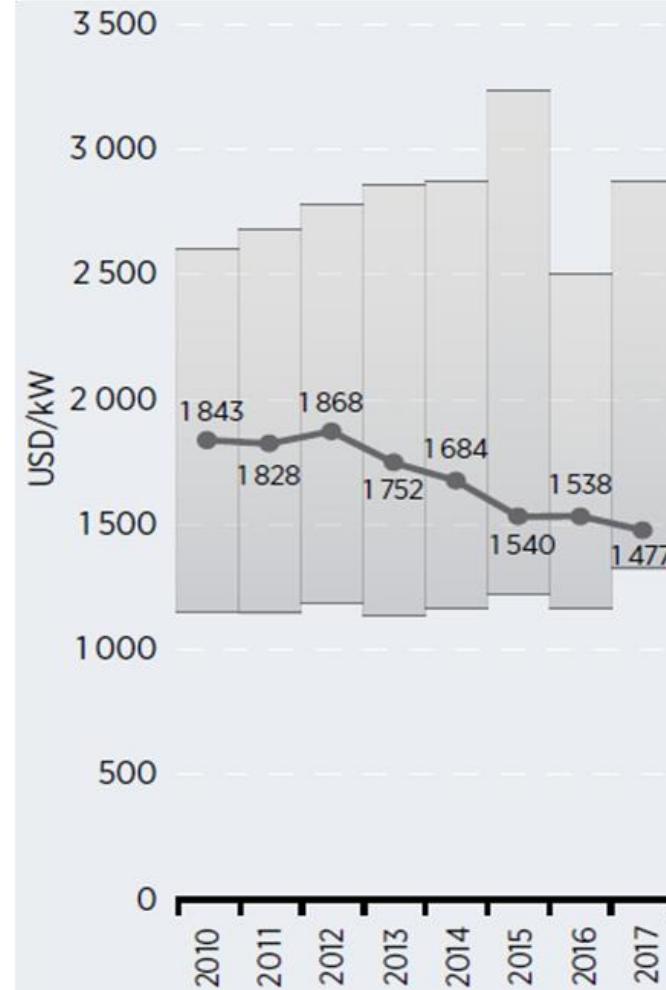
- ▶ Hourly resolution
- ▶ Unit commitment constraints
- ▶ Ramping constraints
- ▶ Exogenous calculation of system requirement reserve due to VRE intermittency and unpredictability

## Renewable generation - Investment Cost

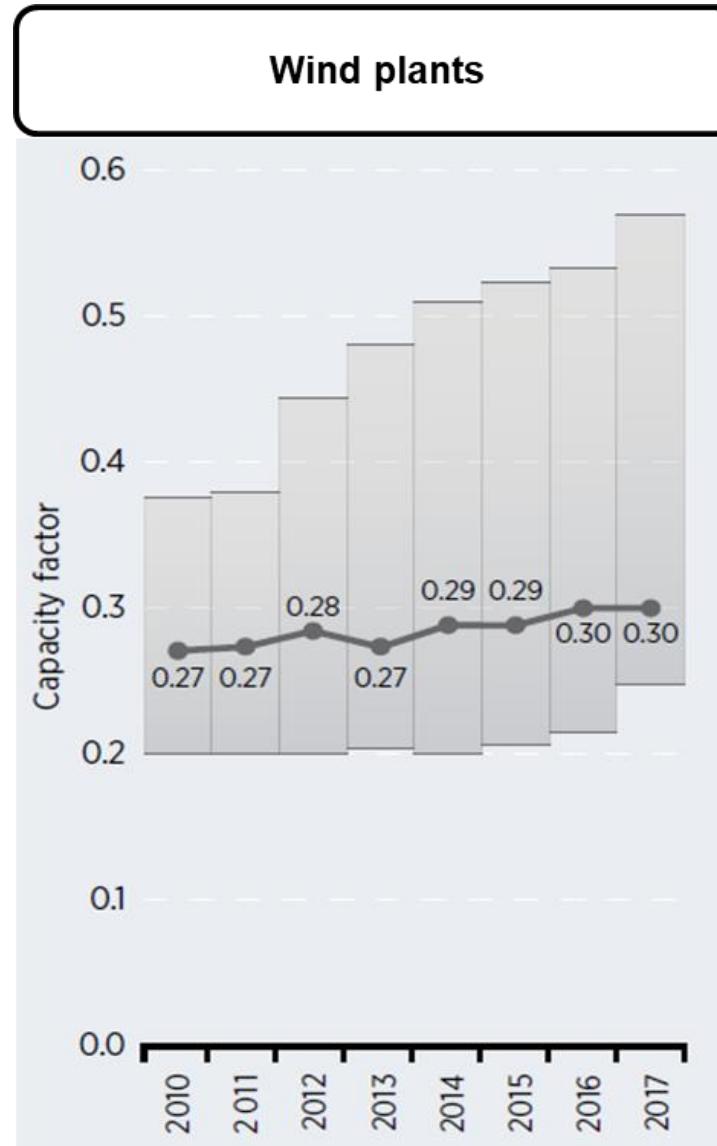
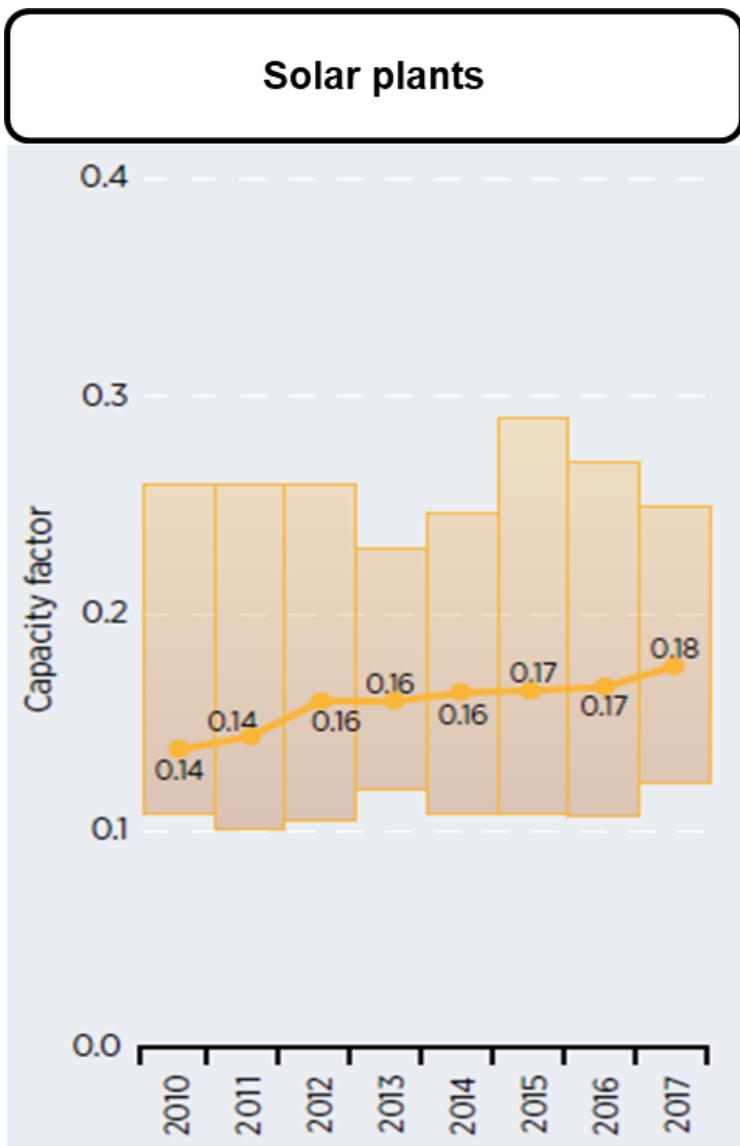
Solar plants



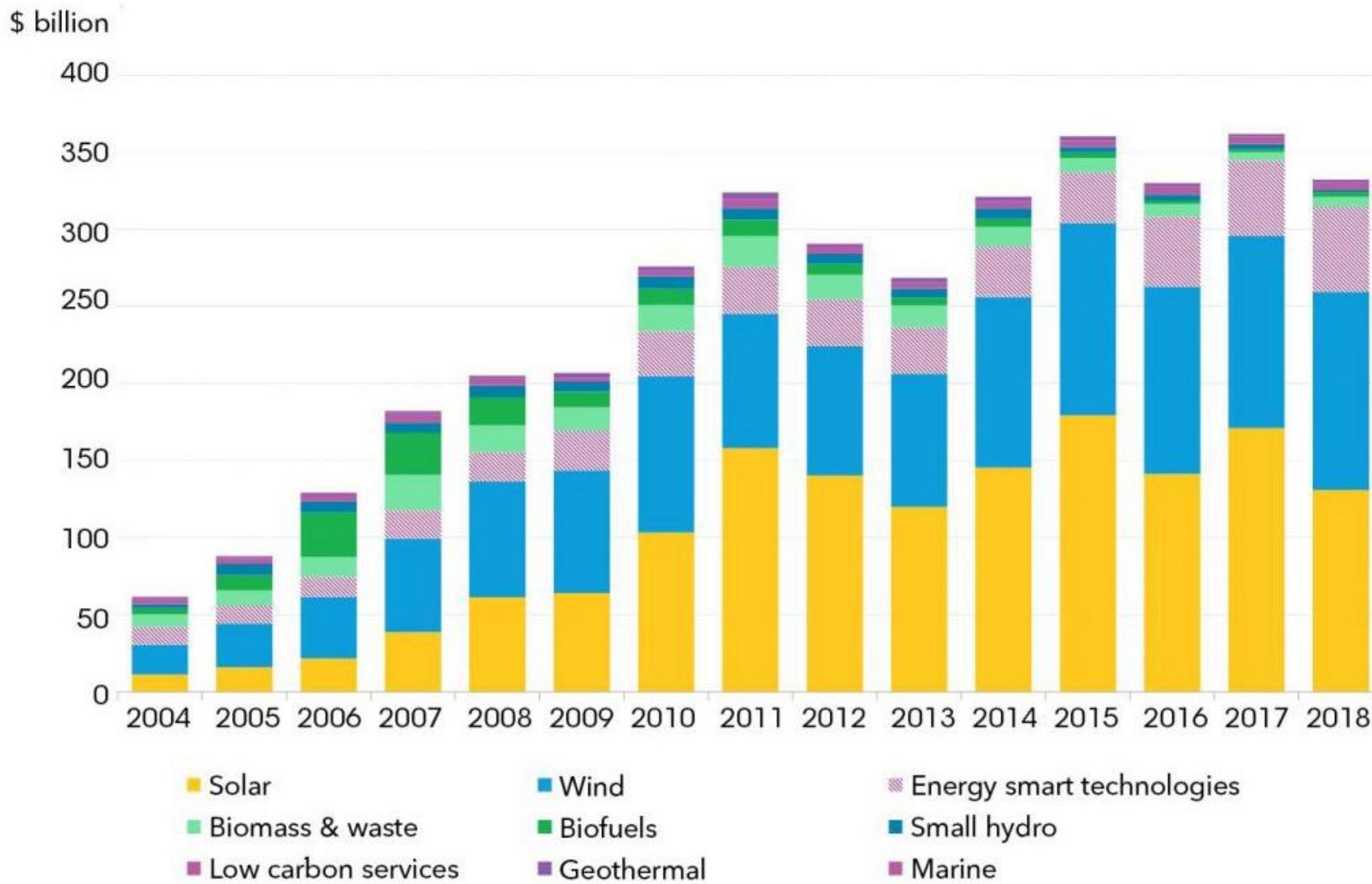
Wind plants



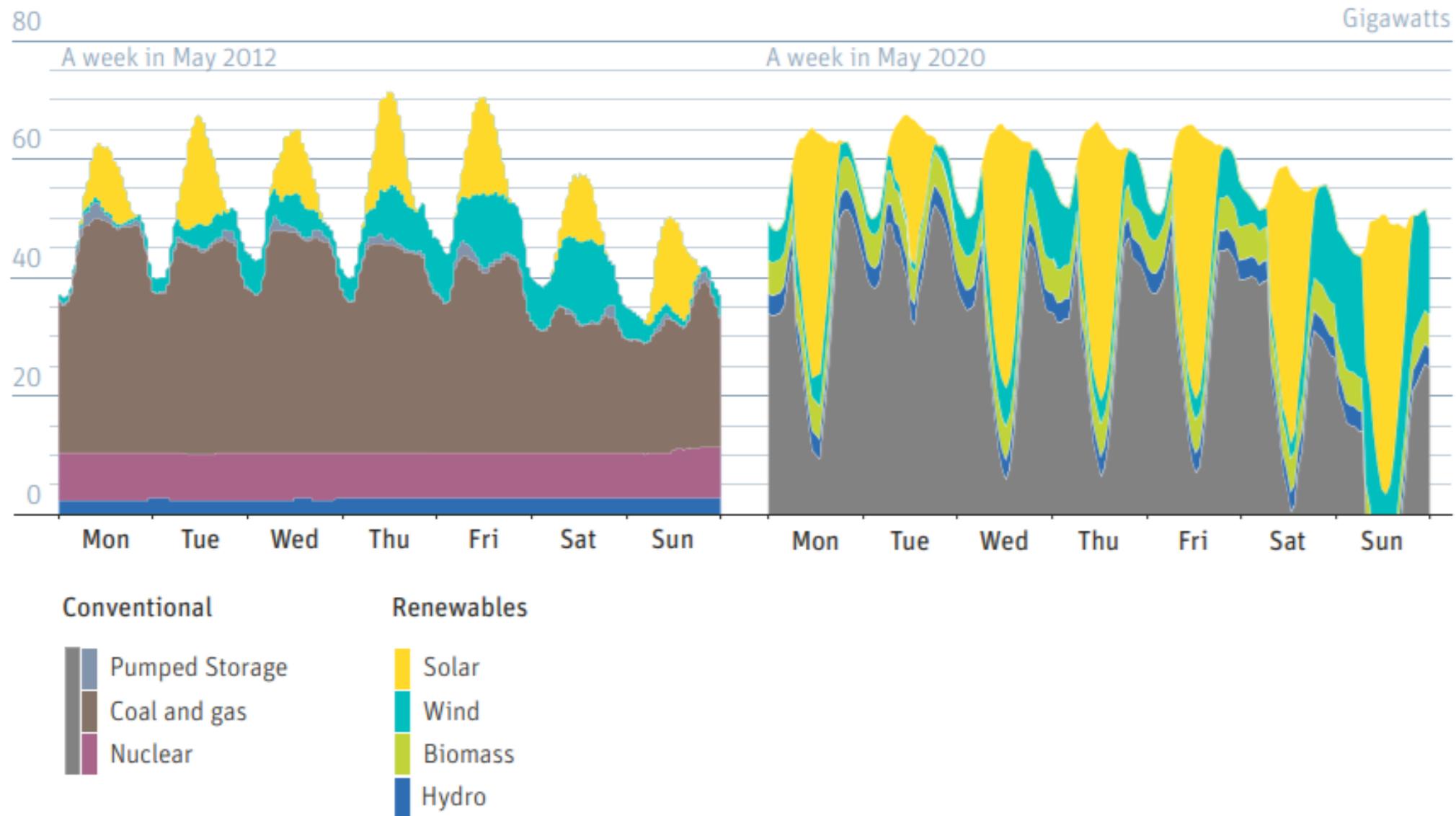
## Renewable generation - Capacity Factor (efficiency)



# Global investments in renewable energy - Bloomberg



# German system - Challenges



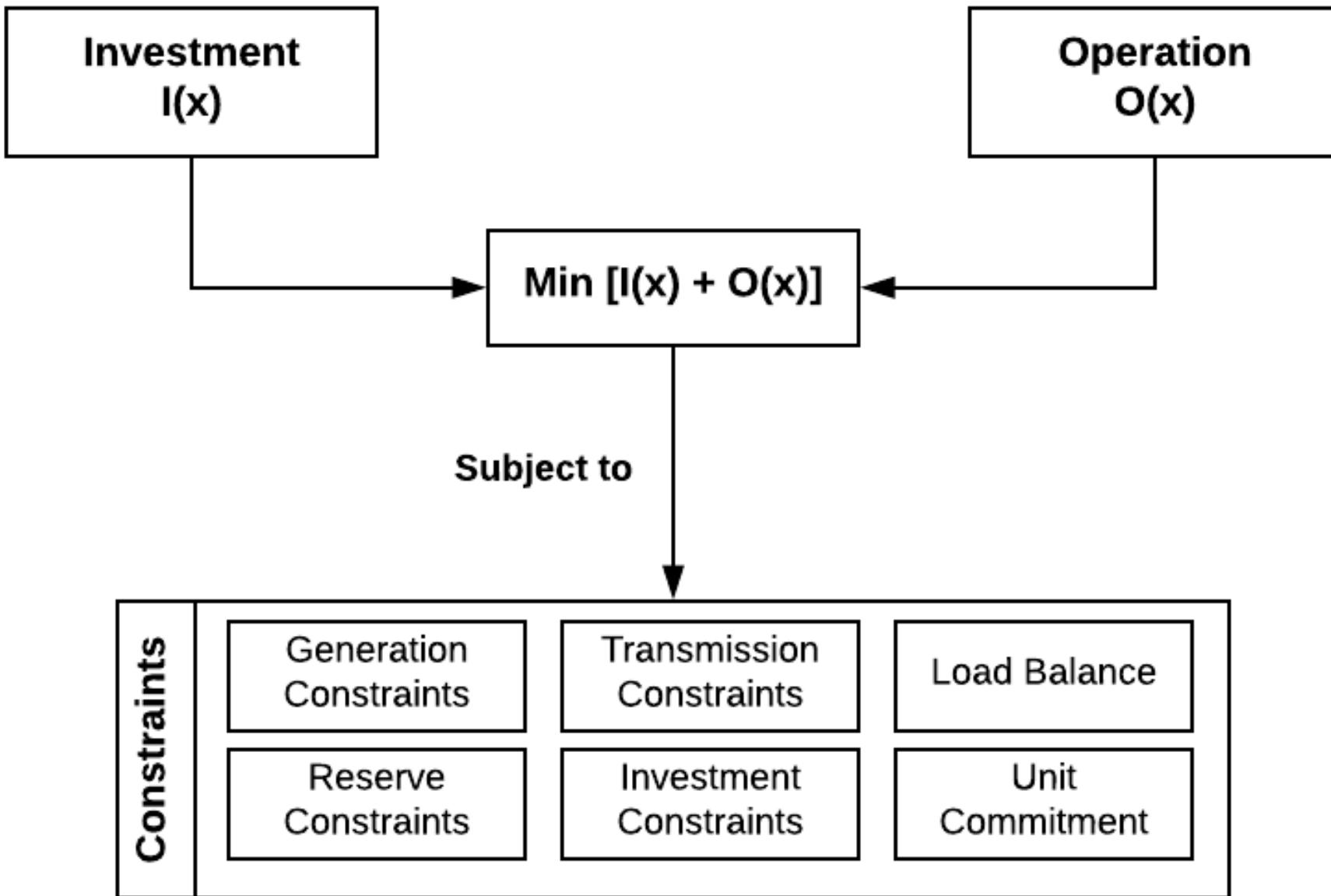
## Consequences?

- ▶ High variability and uncertainty in the offer
- ▶ Large generation ramps
- ▶ Excess/Lack of generation
- ▶ Need for more system reserve
- ▶ Need for more thermal flexibility
- ▶ Thermal unit commitment influences expansion planning decision!

## Challenges

- ▶ An **expansion planning model** with an **hourly** time step
- ▶ **Unit commitment** in expansion planning
- ▶ Co-optimization of expansion planning and **system reserve requirement** (due to renewable penetration) modeled as an exogenous variable
- ▶ Solving a **MIP** with all of that in a reasonable amount of **time!**

## The Model - OptGen

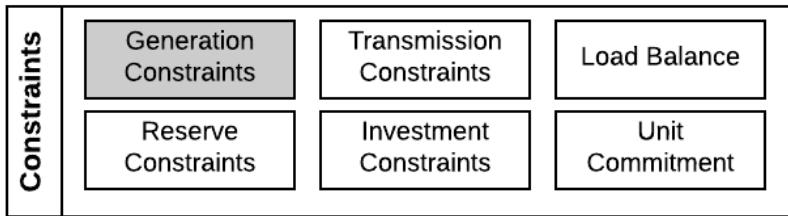


## Formulation – Objective Function

Min [I(x) + O(x)]

$$\min_{x,g,q,v} \sum_{t \in \mathbb{T}} \sum_{i \in I} I_i x_{i,t} + \sum_{h \in H} \sum_{j \in G} c_j g_{j,h}$$

## Formulation – Constraints



$$v_{i,t}^s \leq \bar{v}_i \sum_{\tau=1}^t x_{i,\tau}$$

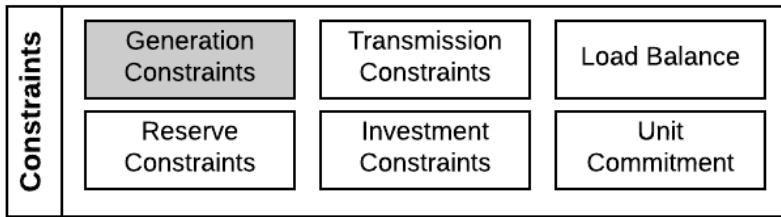
$$q_{i,h}^s \leq \bar{q}_i \sum_{\tau=1}^t x_{i,\tau}$$

Hydro maximum storage

$$v_{i,t+1}^s = v_{i,t}^s + a_{i,t}^s - q_{i,t}^s - w_{i,t}^s + \sum_{j \in M(i)} (q_{j,t}^s + w_{j,t}^s)$$

Water balance constraint

## Formulation – Constraints



$$\underline{g}_j y_{j,h}^s \leq g_{j,h}^s \leq \bar{g}_j y_{j,h}^s$$

Thermal min/max generation

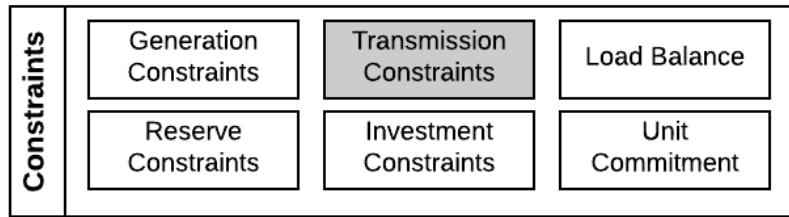
$$y_{j,h}^s \leq \sum_{j=1}^t x_{j,\tau}$$

Commitment constrained by investment decision

$$g_{l,h}^s \leq G_l^s \sum_{\tau=1}^t x_{l,\tau}$$

Wind and Solar max generation

## Formulation – Constraints



$$f_{k,h}^{+s} \leq \bar{F}_k$$

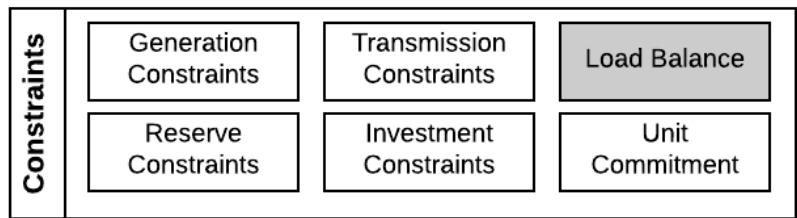
$$f_{k,h}^{-s} \leq \bar{F}_k$$

$$f_{k,h}^{+s} - f_{k,h}^{-s} = \frac{1}{A_k} \Delta \Theta_{k,h}$$

Max capacity

Second Kirchhoff Law

## Formulation – Constraints



$$\sum_{j \in J} g_{j,h} + \sum_{i \in H} \rho_i q_{i,h} + \sum_{i \in R} g_{l,h} + \sum_{b \in B} (D_{b,h} - C_{b,h}) \sum_{k \in B_{to}} (f_{k,h}^{+s} - f_{k,h}^{-s}) - \sum_{k \in B_{from}} (f_{k,h}^{+s} - f_{k,h}^{-s}) + \epsilon_h = d_h$$



Thermal  
Generation

Hydro  
Generation

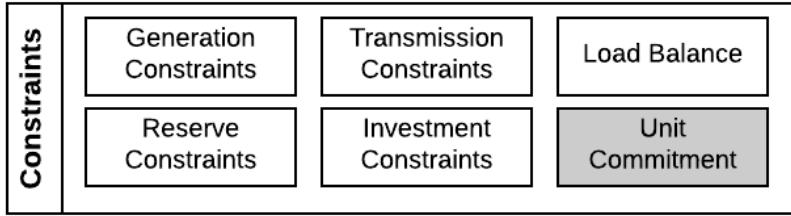
Renewable  
Generation

Battery Net  
Generation

First Kirchhoff Law

Deficit  
and  
Load

## Formulation – Constraints



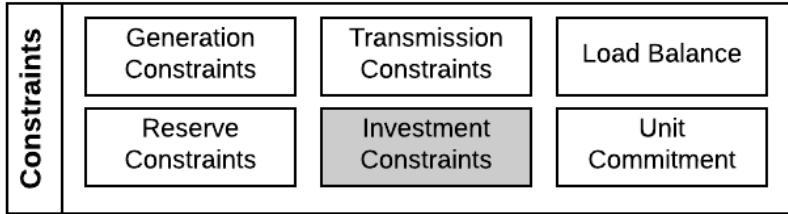
$$g_{j,h}^s - g_{j,h-1}^s \leq R^{UP}$$
$$g_{j,h-1}^s - g_{j,h}^s \leq R^{DN}$$

Ramp

$$st_{j,h}^s \geq y_{j,h}^s - y_{j,h-1}^s$$

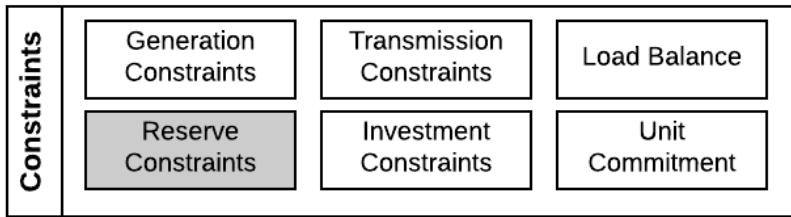
Start-up

## Formulation – Constraints



$$\left. \begin{array}{l} \sum_{t \in \mathbb{T}} x_{i,t} \leq 1 \\ \sum_{t \in \mathbb{T}} x_{j,t} \leq 1 \\ \sum_{t \in \mathbb{T}} x_{l,t} \leq 1 \end{array} \right\} \text{Investment Decision Constraint}$$

## Formulation – Constraints



$$\sum_{j \in a} r_{j,h}^s + \sum_{i \in a} r_{i,h}^s + \sum_{b \in a} r_{b,h}^s \geq R_{a,h}^{UP}$$

Reserve Balance

$$g_{j,h}^s + r_{j,h}^s \leq \bar{G}_j y_{j,h}^s$$

Thermal reserve

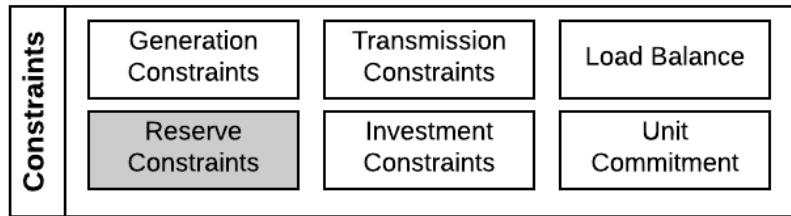
$$g_{i,h}^s + r_{i,h}^s \leq \bar{H}_i x_{i,t}$$

Hydro reserve

$$g_{b,h}^s + r_{b,h}^s \leq \bar{B}_b x_{b,t}$$

Battery reserve

## Formulation – Constraints



$$\hat{v}_{l,h} = E[g_{l,m,h}^s]$$

Forecast Generation

$$\delta_{a,h}^s = \sum_{l \in A_l^a} (g_{l,h}^s - \hat{v}_{l,h}) x_{l,t}$$

Forecast error

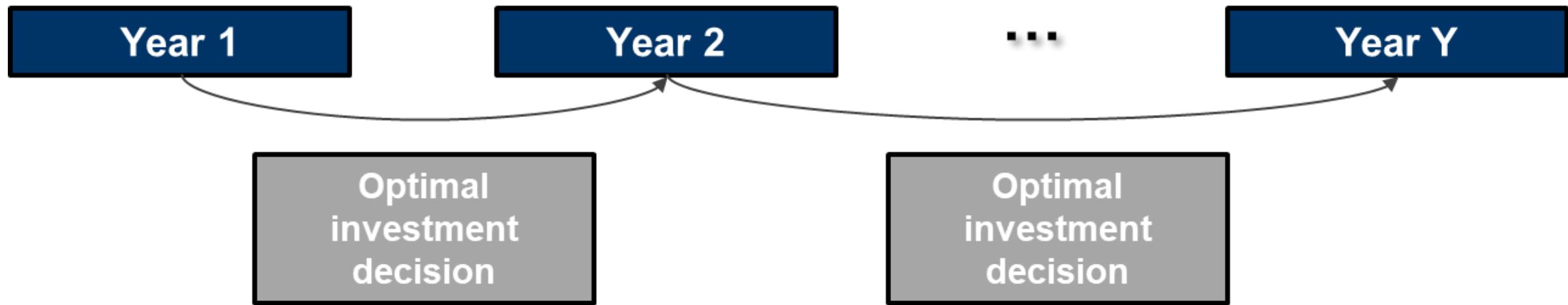
$$\Delta_{a,h}^s \geq \delta_{a,h}^s - \delta_{a,h-1}^s$$

Hourly Variation in Forecast error

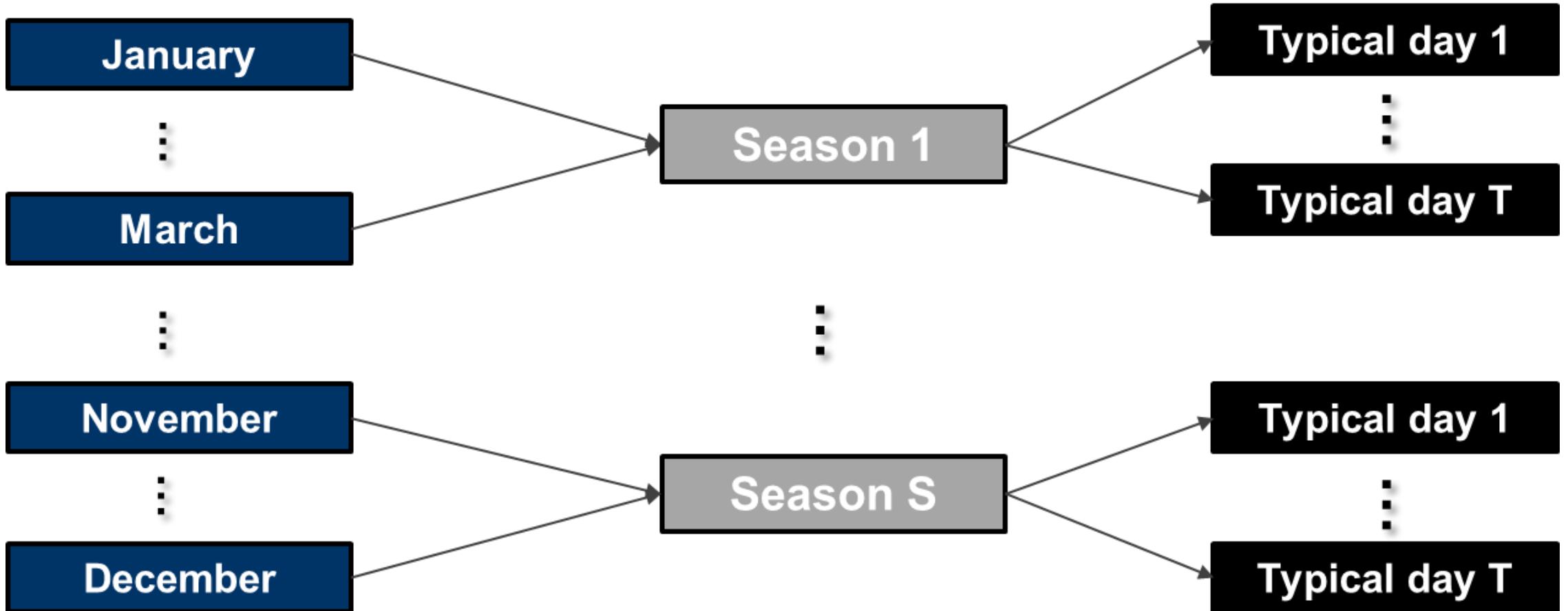
$$R_{a,h}^{UP} \geq (1 - \lambda)E[\Delta_{a,h}^s] + \lambda CVaR_\alpha[\Delta_{a,h}^s]$$

Dynamic Probabilistic Reserve Criteria

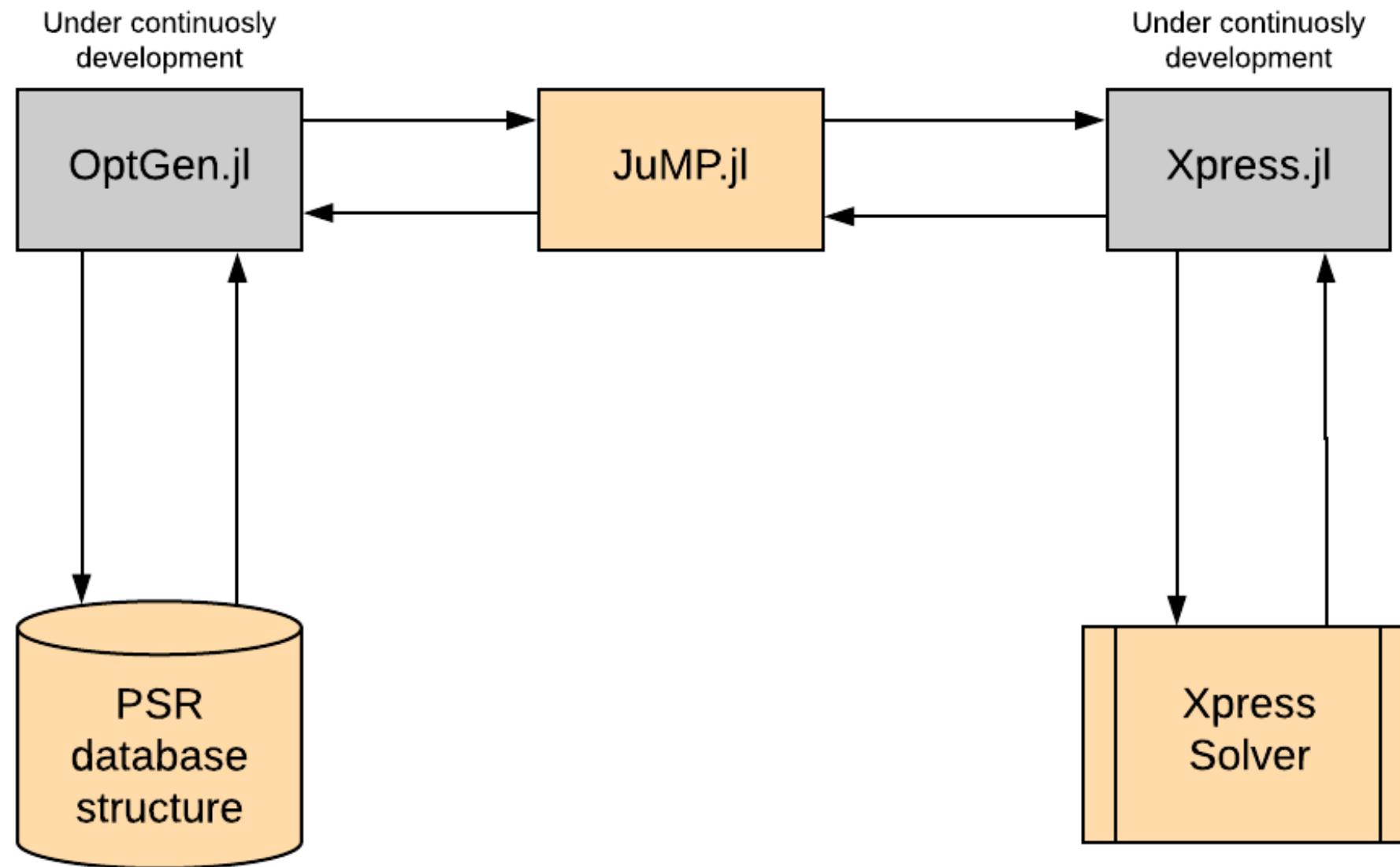
## Assumptions and Approximations – Rolling Horizon



## Assumptions and Approximations – Daily Aggregation



## Basic Structure





Generación eléctrica en Chile   Quiénes somos   Empresas asociadas   Prensa   Documentos

Inicio / Prensa / Mayor aporte solar y eólico reducirá al...

## NOTICIAS

29/01/2018

### Mayor aporte solar y eólico reducirá al 25% la generación térmica al 2030 en Chile

El 75% restante provendría de energías renovables, según estudio de PSR-Moray.

Eso sí, el análisis encargado por la Asociación de Generadoras señala que el gas, carbón y los embalses aportarán flexibilidad al sistema que se enfrentará a tecnologías variables.

La energía solar representaría 30% de la generación a 2030, lo que aumentaría los costos de flexibilidad que, actualmente, no son remunerados.



<http://generadoras.cl/prensa/mayor-aporte-solar-y-eolico-reducira-al-25-la-generacion-termica-al-2030-en-chile>

<http://generadoras.cl/prensa/generadoras-participo-en-seminario-internacional-de-energia-renovable-variable-erv>



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Inicio / Prensa / Generadoras participó en Seminario Inter...

30/05/2018

### Generadoras participó en Seminario Internacional de Energía Renovable Variable (ERV)

El Director del Centro de Energía UC, Enzo Sauma y el Presidente Ejecutivo de Generadoras de Chile, Claudio Seebach, estuvieron a cargo de la apertura de este encuentro organizado por el Centro de Energía UC y cuyo tema principal fue la integración de ERV al sistema eléctrico chileno.



## Energy systems of the future in Brazil

### Project description

**Title:** Energy Systems of the Future

**Commissioned by:** German Federal Ministry for Economic Cooperation and Development (BMZ)

**Country:** Brazil 

**Lead executing agency:** Ministry of Mines and Energy (MME)

**Overall term:** 2016 to 2021



### Context

Brazil's demand for energy will continue to increase, although the rapid economic growth of the last few years has weakened significantly. Yet based on the economic and population growth forecast for the next 10 years alone, the energy planning authority (EPE) estimates an increase of over 3 per cent in annual electricity demand by 2026.

<https://www.giz.de/en/worldwide/12565.html>



Empresa de Pesquisa Energética

### ► Press Room

News

Clipping

## "CEM Days - Integration of Renewables in the Electric Sector: Paths and Challenges to Energy Planning"

On 21-23 November 2018, Rio de Janeiro hosted the workshop "CEM Days - Integration of Renewables in the Electric Sector: Paths and Challenges to Energy Planning". The event, organized by EPE, took advantage of the framework enabled by the Clean Energy Ministerial (CEM), and its aim to empower energy decision makers around the world with the up-to-date information and tools, as means to accelerate transition to low carbon energy. The workshop brought together experts and policy makers to discuss strategies to support a secure and cost-effective integration of higher shares of VRE – Variable Renewables Energy, such as wind and PV power. The event was promoted and supported by the International Energy Agency – IEA, of which Brazil is associate since October 2017, and GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit (German Agency for International Cooperation). The event also had special participation by the Brazilian National System Operator (ONS) and the National Laboratory for Renewable Energy – NREL.

In addition to the above mentioned institutions, we had participants from power generation and distribution utilities, industry associations, consulting companies, universities, banks, among others.

It was possible to identify many challenges to adapt the energy planning methodologies and tools, related to emerging technologies that redefine the profile of power generation and the use of transmission and distribution assets, as well as business models, market and regulatory framework, consumer behavior and electricity demand profile, all that transforming the industry, the energy mix and its associated infrastructure.

By organizing this event, EPE strengthens its engagement in high-level technical discussions regarding challenges for the integration of VREs in the power system and consolidates important partnerships with national and international institutions aiming to exchange valuable experiences for energy planning.

The agenda can be accessed at this [link](#)

<http://www.epe.gov.br/en/press-room/news/-cem-days-integration-of-renewables-in-the-electric-sector-paths-and-challenges-to-energy-planning>

## Chilean System Study Example

- ▶ 13 years horizon
- ▶ 54 scenarios
- ▶ 300 thermal plants (100 projects)
- ▶ 650 wind and solar plants (500 projects)
- ▶ 100 hydro plants
- ▶ 12 transmission lines / 6 buses (simplified network)
- ▶ ~**5.6 MM constraints** per year
- ▶ ~**7.8 MM variables (3 MM integer)** per year

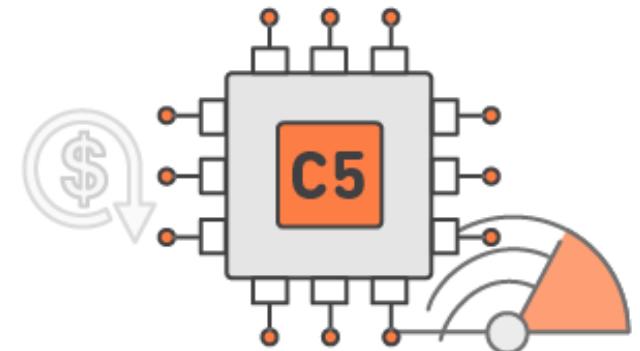


**Generadoras de Chile**

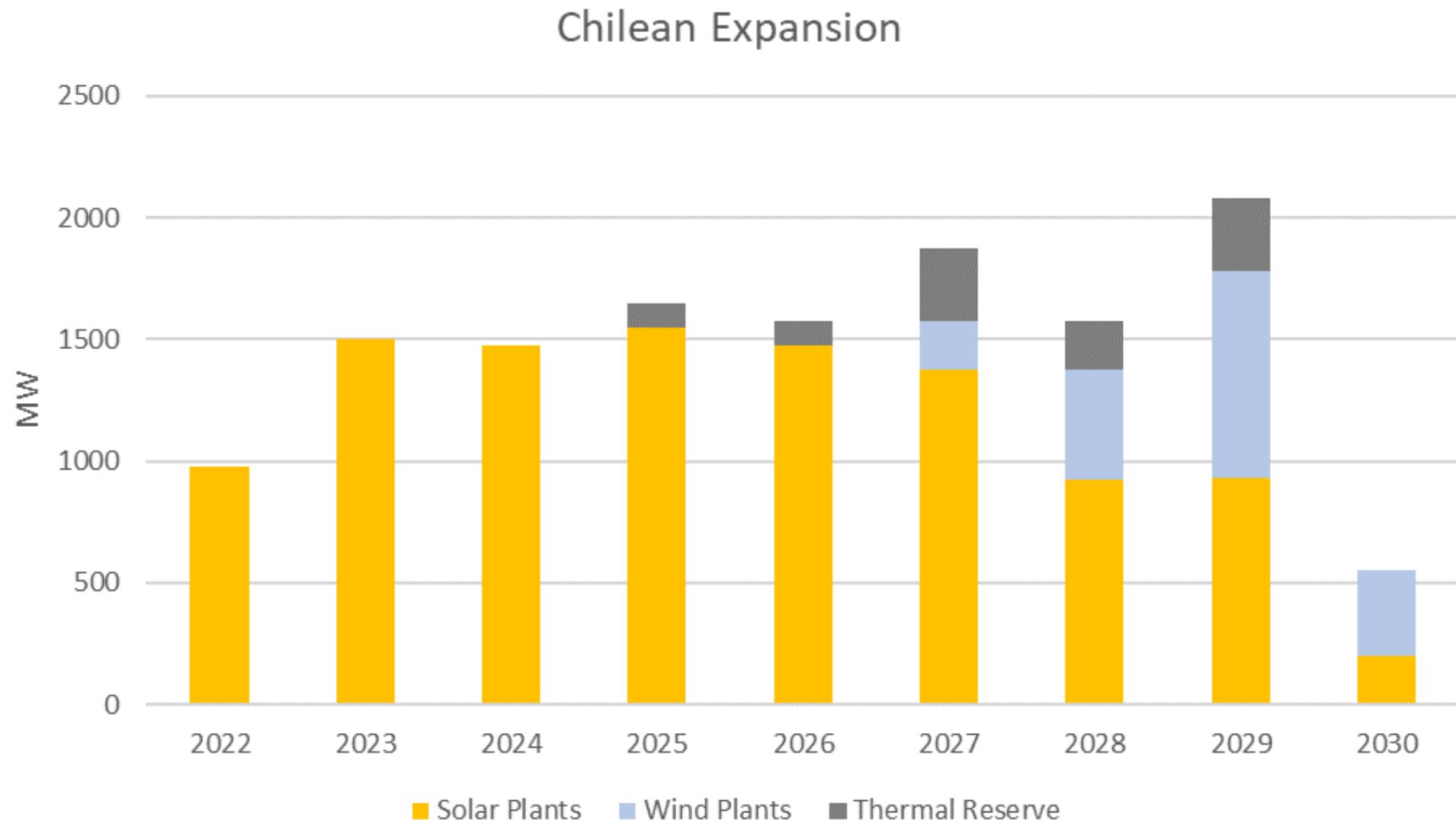


## Solving the Model

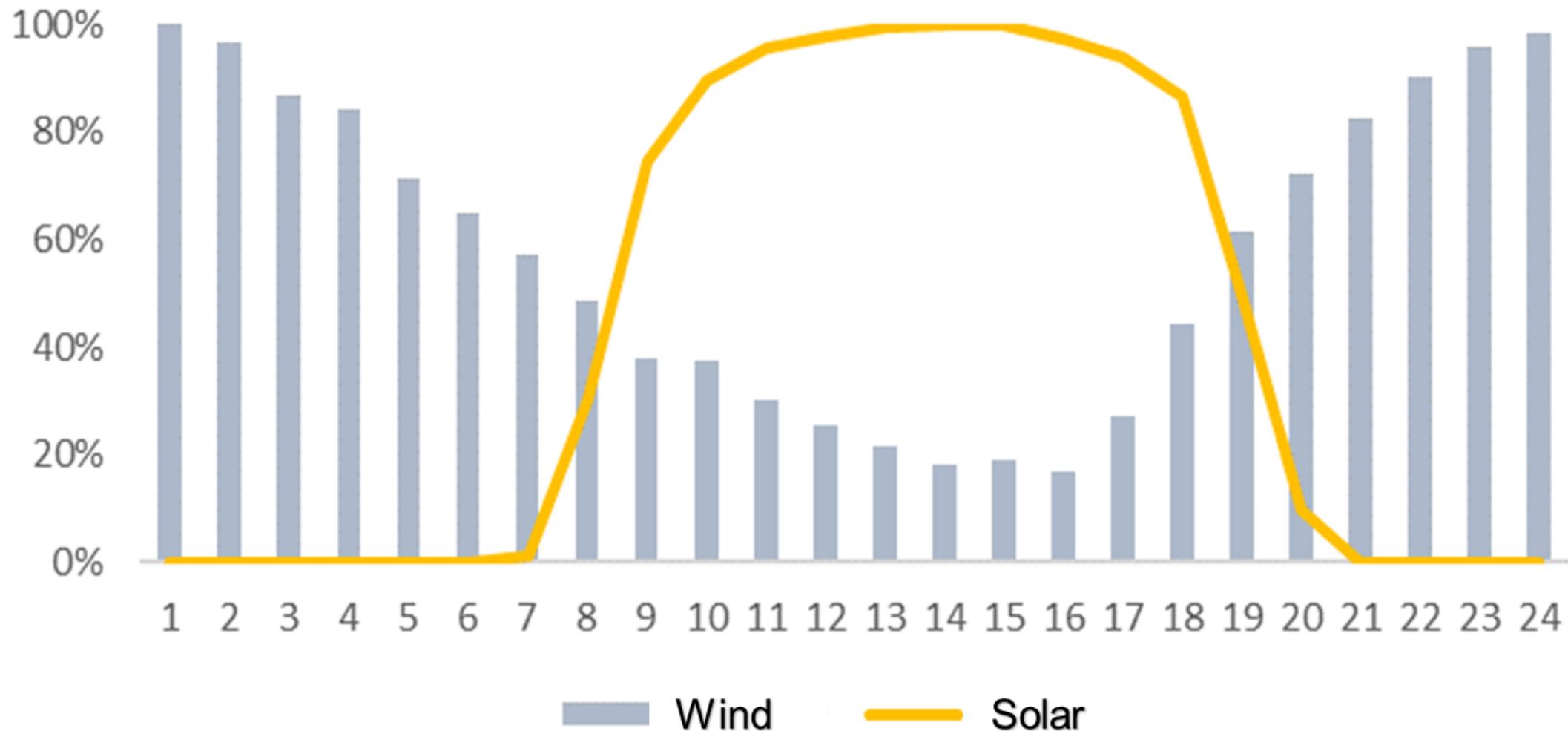
- ▶ FICO **Xpress** 8.5 solver
- ▶ c5.9xlarge amazon instance - 3.0 GHz Intel Xeon Platinum processors - **36 vCPU** - 72 GB RAM
- ▶ Xpress control parameters were **tuned** by Xpress lead developer (Michael Perregaard)
- ▶ Solve time: ~**240 minutes** per year



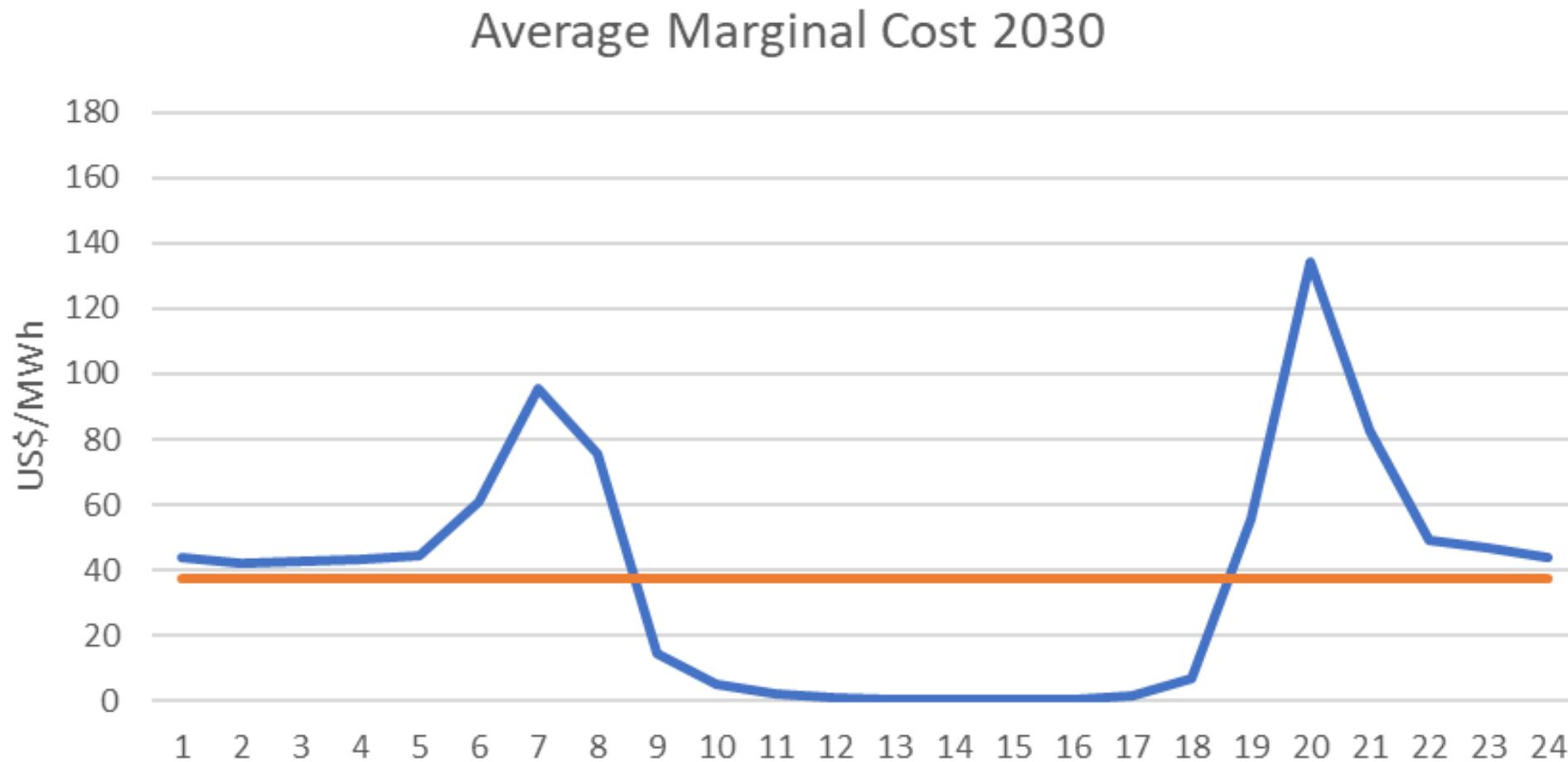
## Results - Incremental Expansion



## Results - Wind and Solar complementarity



## Results - Marginal Costs



## Brazilian System Study Example

- ▶ 1 year horizon
- ▶ 10 scenarios
- ▶ 600 thermal plants (400 projects)
- ▶ 100 wind and solar plants (30 projects)
- ▶ 200 hydro plants
- ▶ 10 battery projects
- ▶ 50 transmission lines / 30 buses (simplified network)
- ▶ **~5 MM constraints** per year
- ▶ **~4 MM variables (1 MM integer)** per year

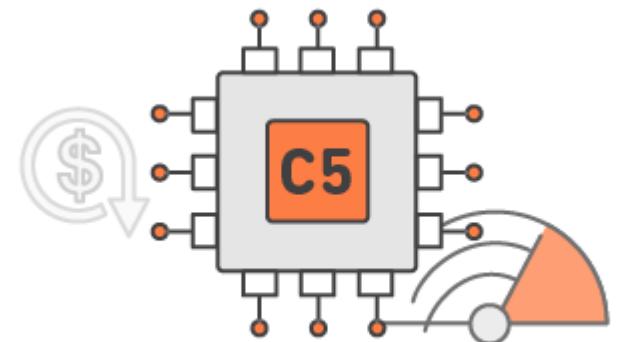


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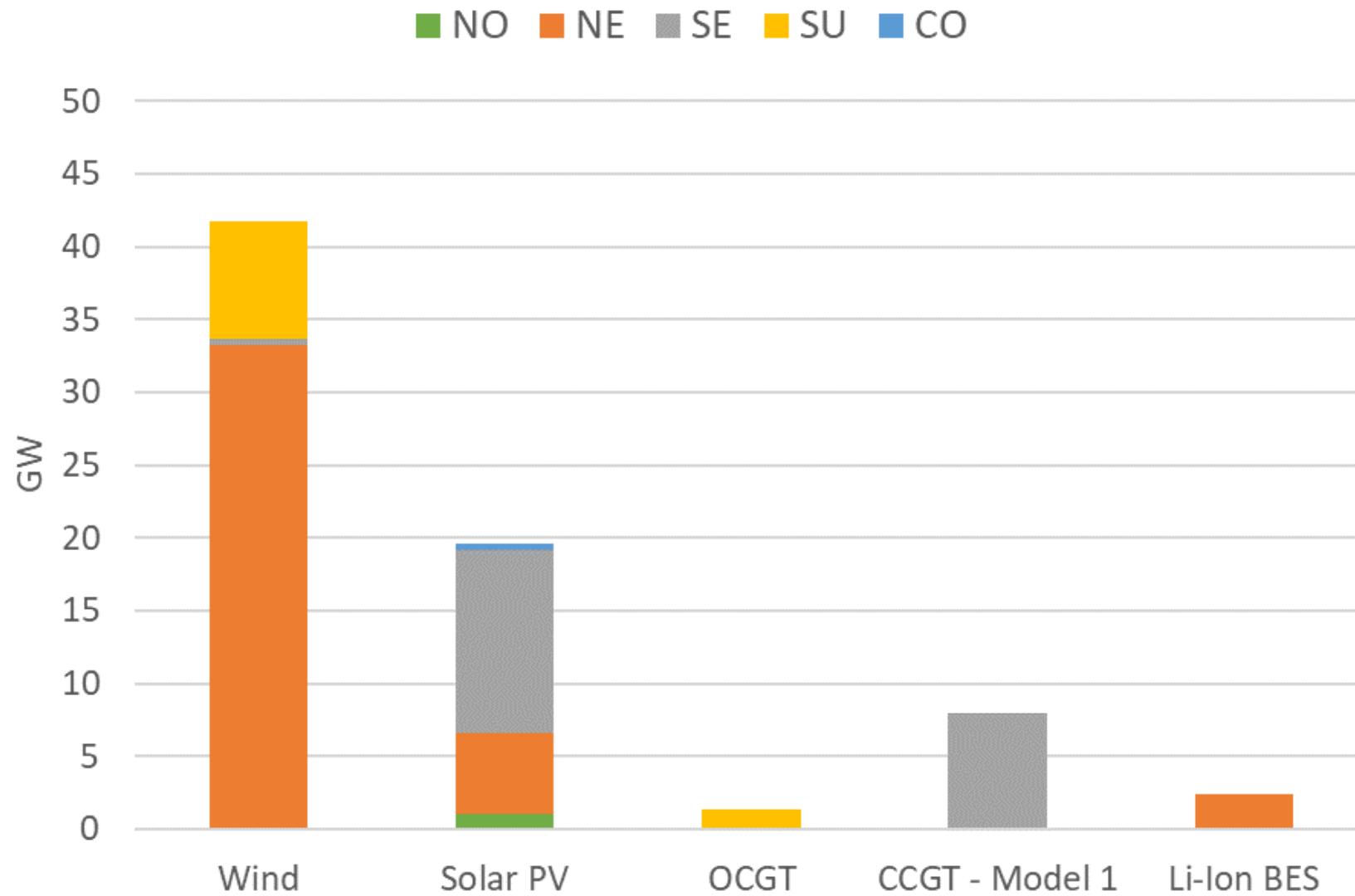


## Solving the Model

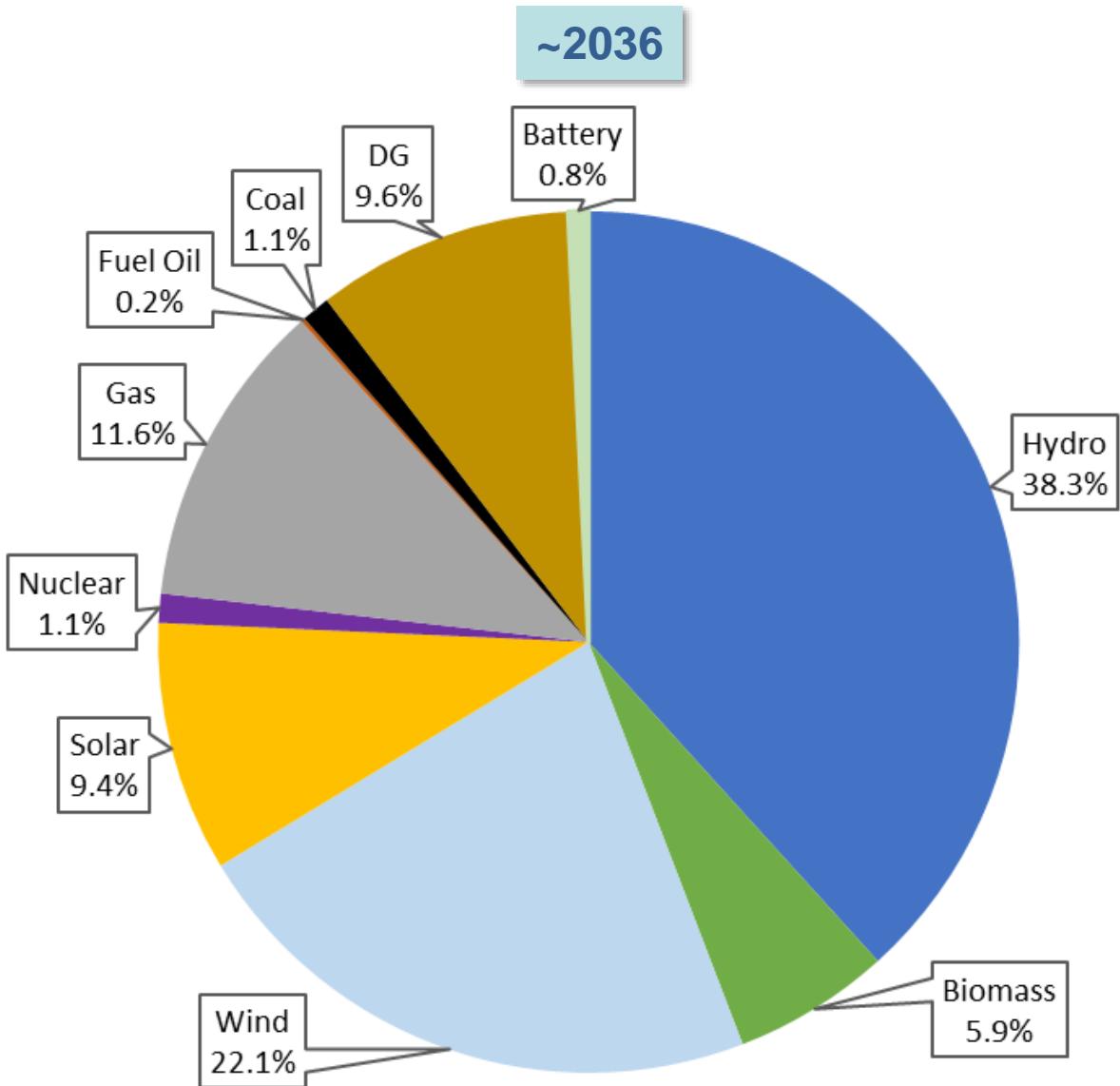
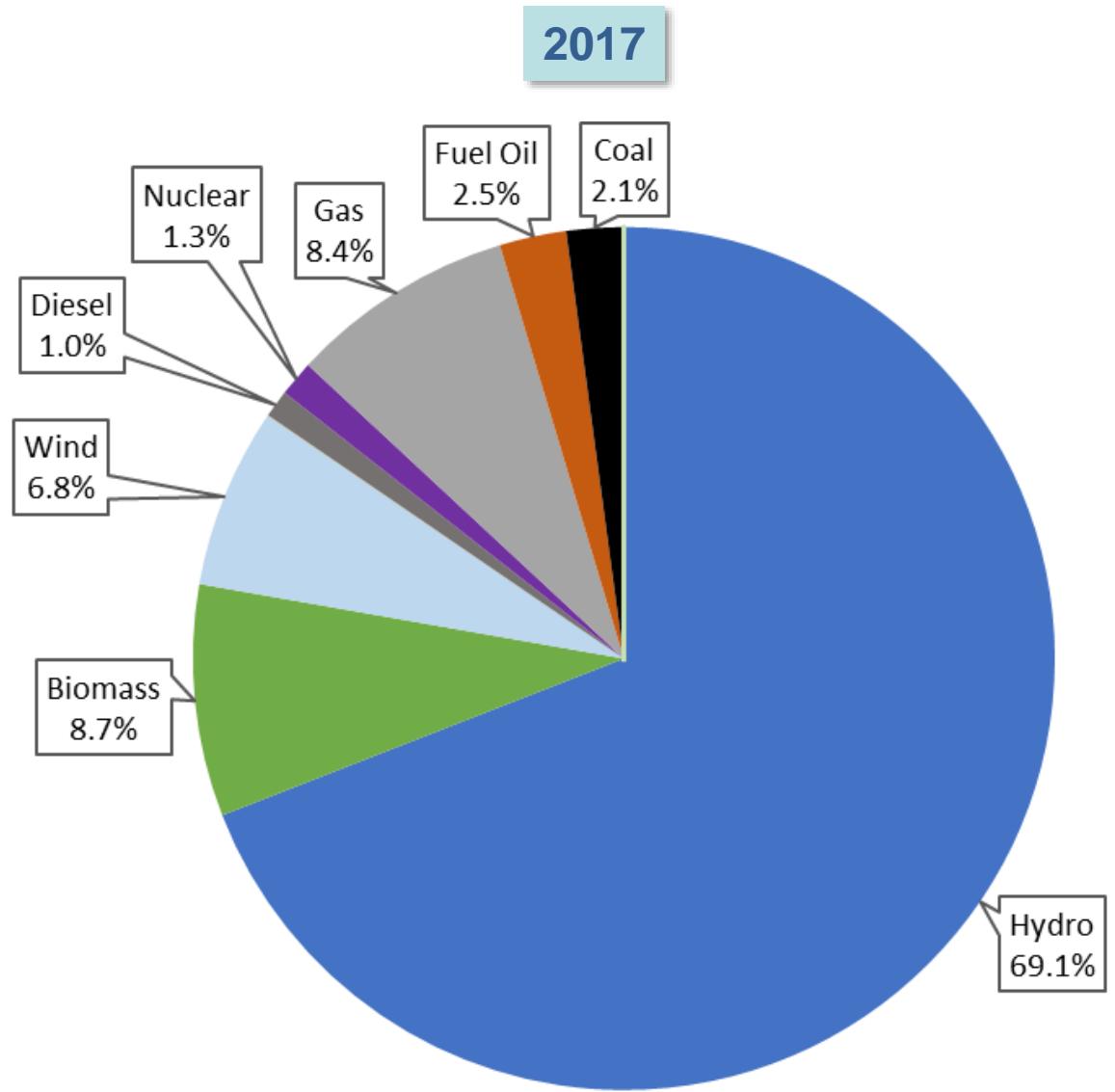
- ▶ FICO **Xpress** 8.5 solver
- ▶ c5.9xlarge amazon instance - 3.0 GHz Intel Xeon Platinum processors - **36 vCPU** - 72 GB RAM
- ▶ Xpress control parameters were **tuned** by Xpress lead developer (Michael Perregaard)
- ▶ Solve time: ~**70 minutes**

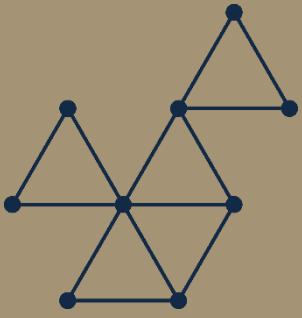


## Incremental Expansion



## Installed Capacity





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**Thanks!**

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