

GENERATION EXPANSION PLANNING



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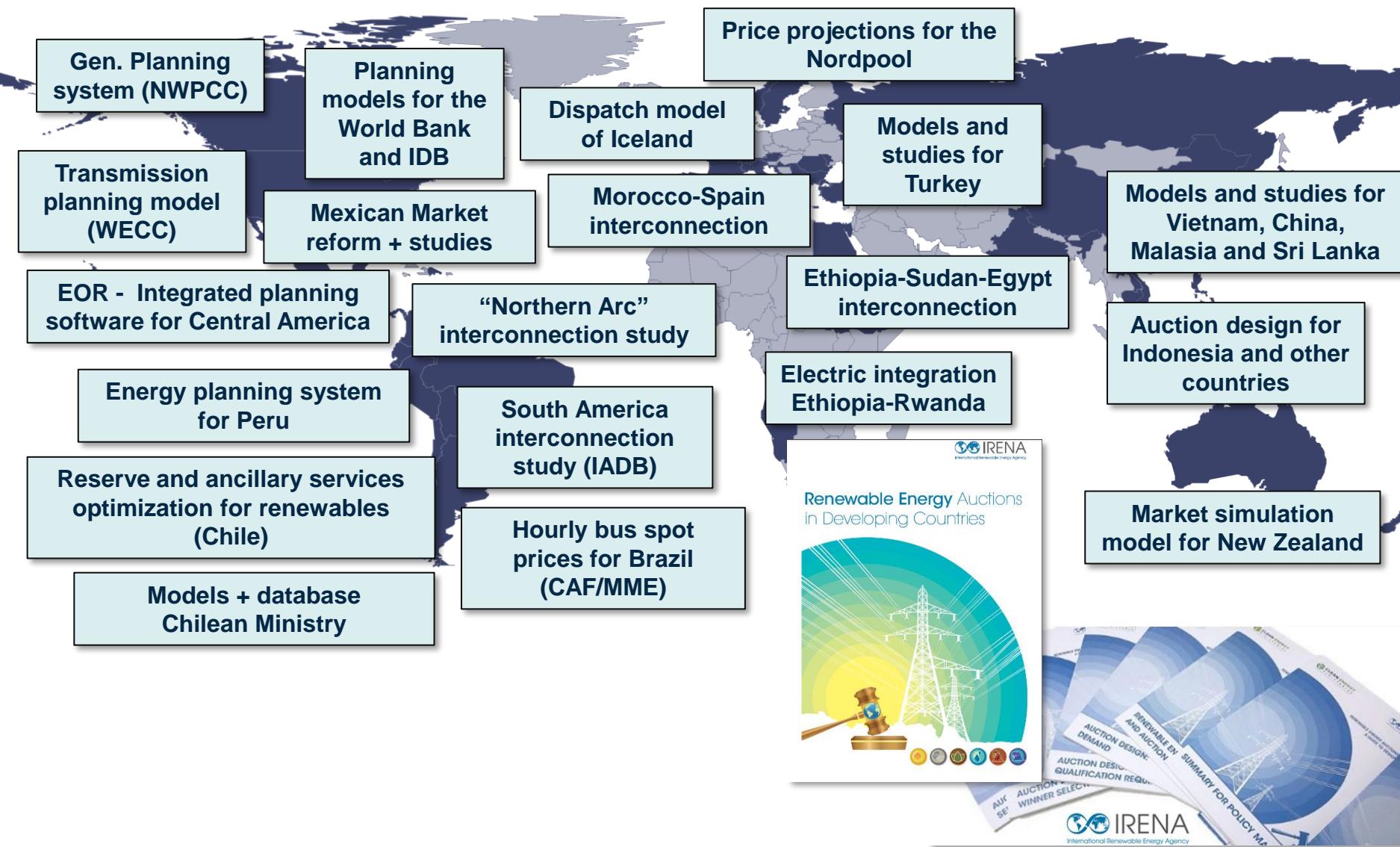
Provider of analytical solutions and consulting services (economic, regulatory, financial and technological) in electricity and gas since 1987



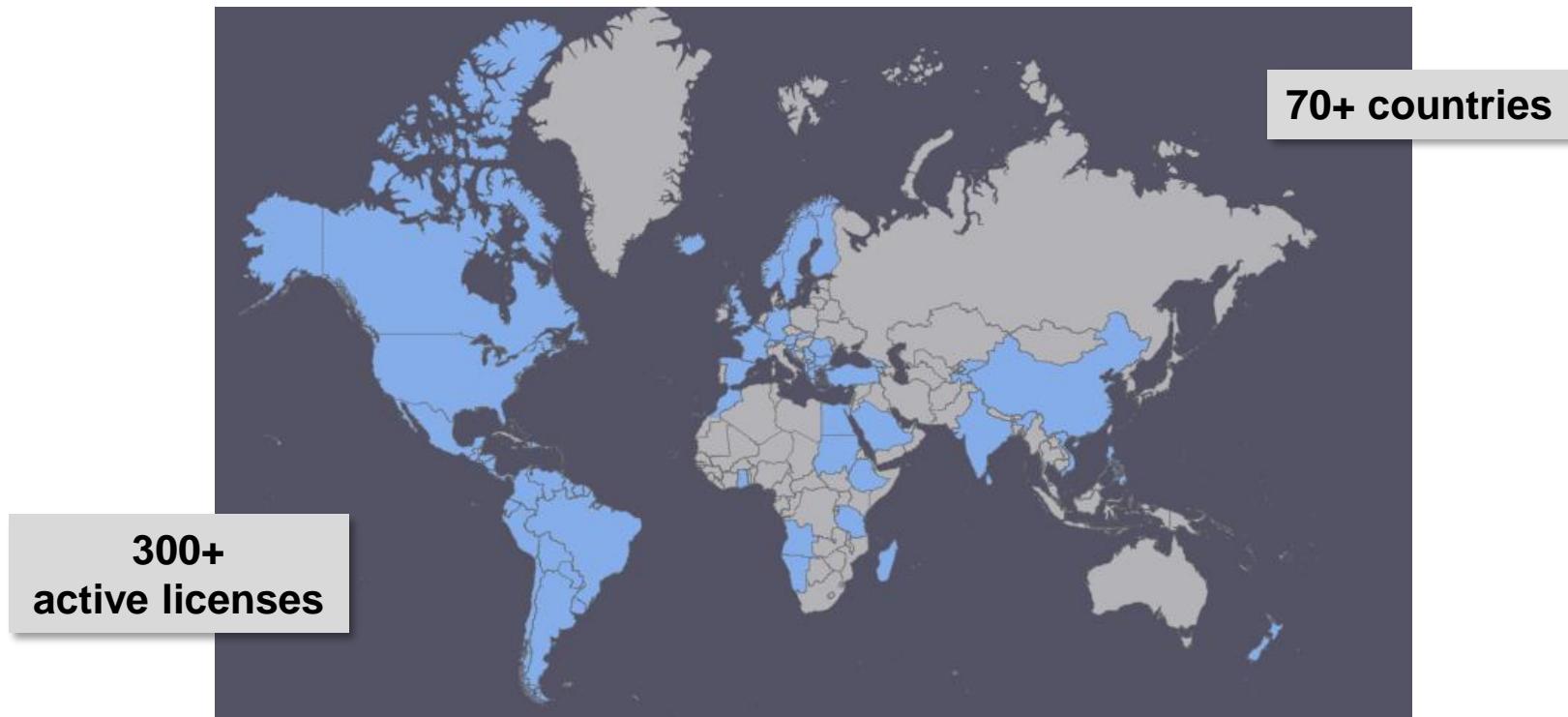
Our team has 58 experts
(17 PhDs, 31 MSc) in
engineering, optimization,
energy systems, statistics,
finance, regulation, IT and
environment analysis



We work in more than 70 countries in all continents



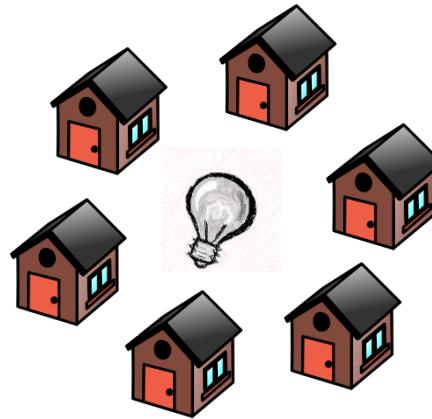
Application of analytical tools



- **Americas:** all countries in South and Central America, United States, Canada and Dominican Republic
- **Europe:** Austria, Spain, France, Scandinavia, Belgium, Turkey and the Balkans region
- **Asia:** provinces in China (including Shanghai, Sichuan, Guangdong and Shandong), India, Philippines, Singapore, Malaysia, Kirgizstan, Sri Lanka, Tajikistan and Vietnam
- **Oceania:** New Zealand
- **Africa:** Morocco, Tanzania, Namibia, Egypt, Angola, Sudan, Ethiopia and Ghana

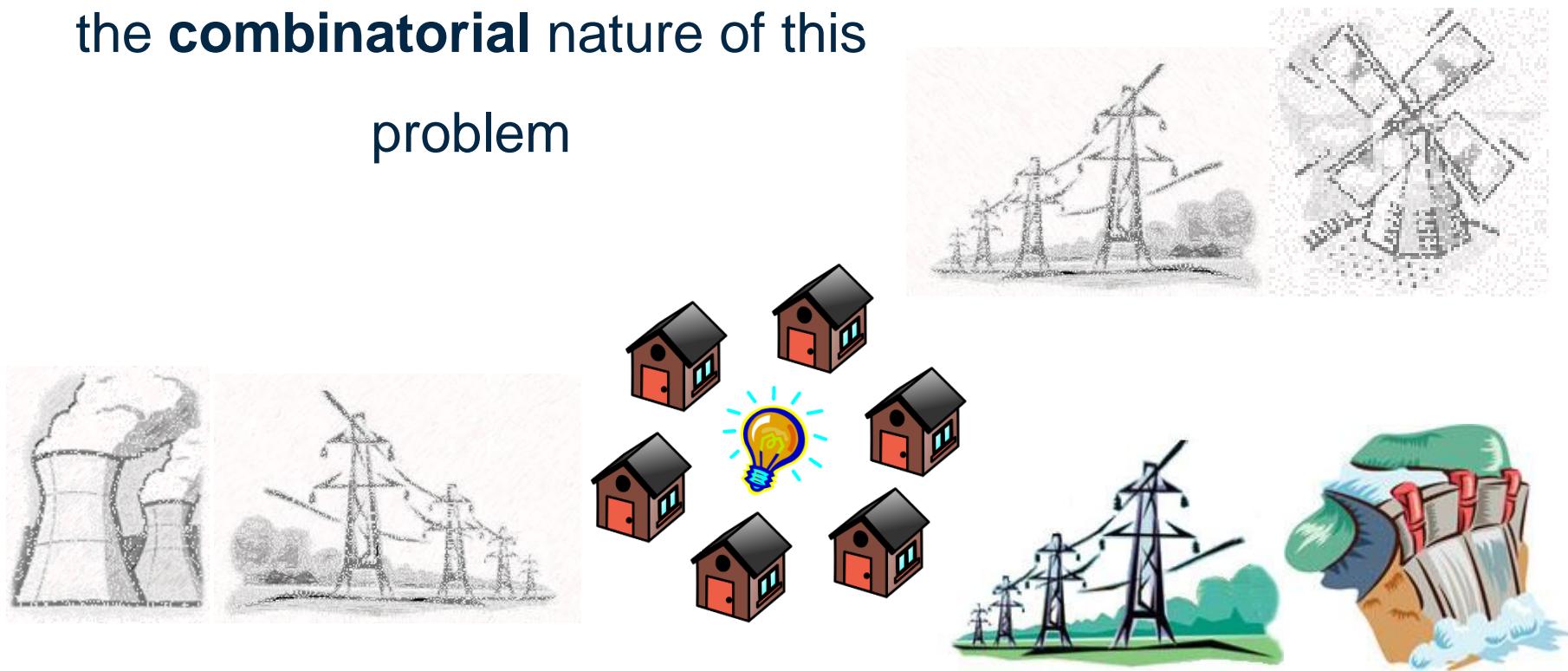
Electrical system expansion

- ▶ The origin of the expansion problem of electrical systems resides on the need for new investments in generation and transmission systems required to face the demand growth and meet planning criteria



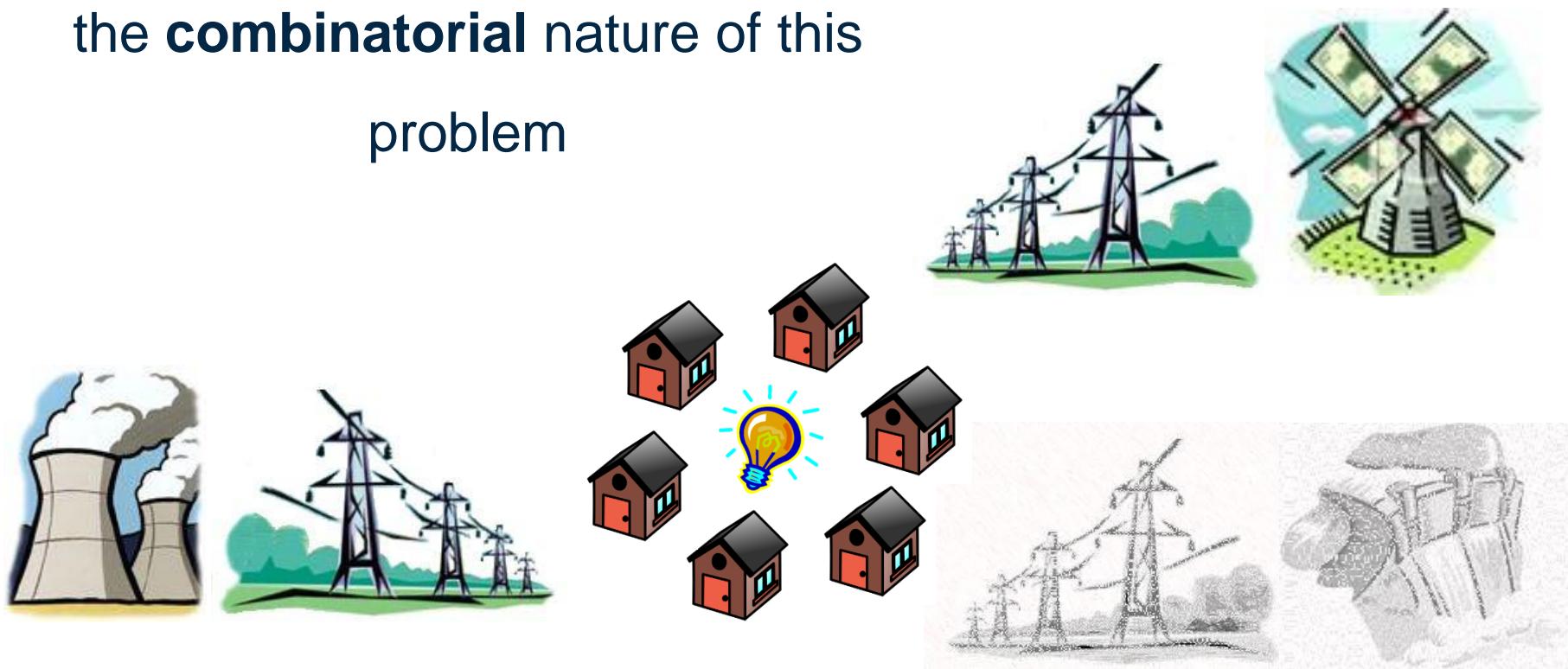
Electrical system expansion

- ▶ Selecting the “best” of a group of alternatives is what characterizes the **combinatorial** nature of this problem



Electrical system expansion

- ▶ Selecting the “best” of a group of alternatives is what characterizes the **combinatorial** nature of this problem



Electrical system expansion

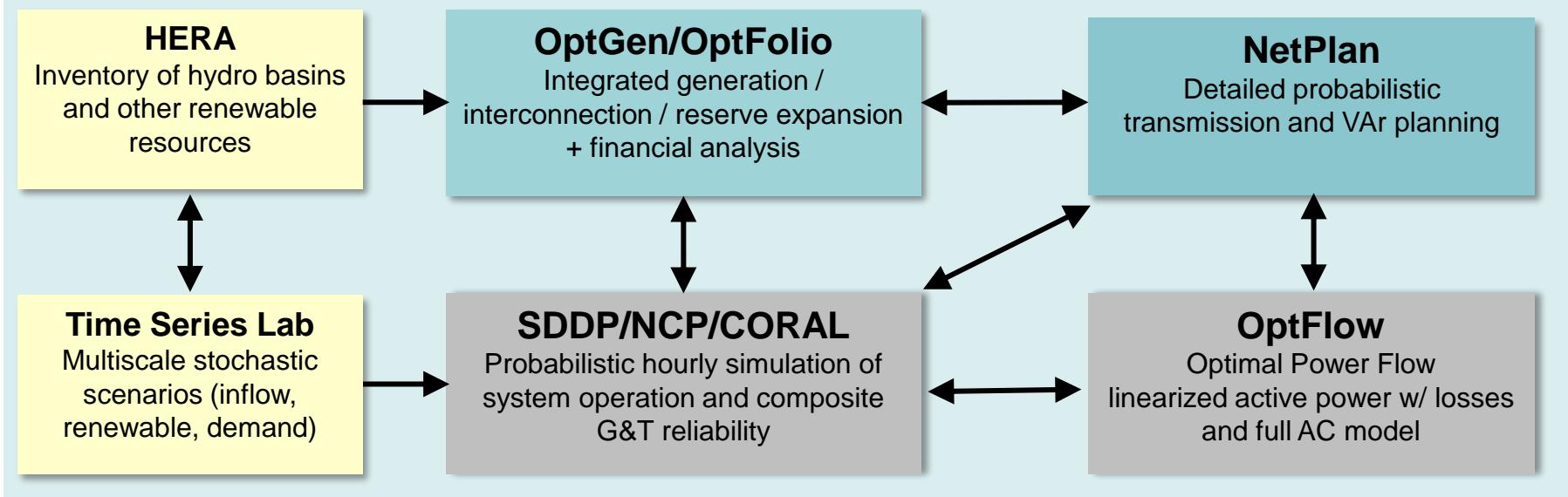
- ▶ The optimality of the expansion plan means minimizing a cost function considering: (i) investment (capital) and operation (fuel, O&M, etc.) costs of generation plants and (ii) penalties for energy not supplied, also called deficit costs
- ▶ In addition, the Generation Expansion Planning (GEP) task must meet both economic and environmental criteria, within a framework of national energy policies
- ▶ A key issue of the GEP methodology is how to deal with the **uncertainties** inherent to the planning process (load growth, renewable generation, fuel prices, etc)

PSR Planning System Components

All models represent complex power systems with thermal plants (gas, coal, nuclear), renewable generation (hydro, wind, solar etc.), CHP, transmission networks, gas pipelines and fuel storage



ePSR: Information management environment



HERA Riverbasin: main components

HERA

Inventory of hydro basins
and other renewable
resources

H1. Data preparation

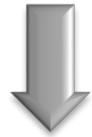
- Extraction of drainage areas
- Inflow regionalization
- Project interferences
- Candidate site selection
- Head x Area x Storage curves

H2. Engineering Design & Budget

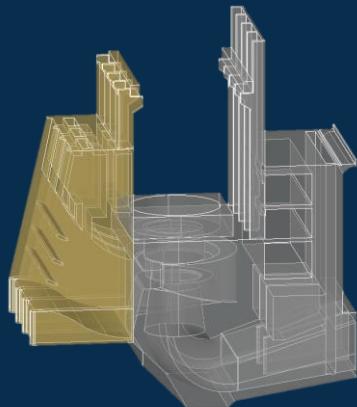
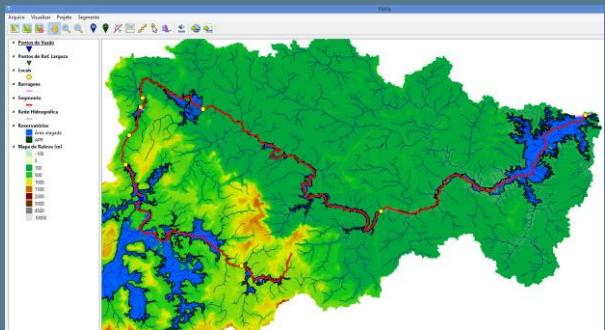
- Layout selection
- Project design
 - Budget estimate

H3. Optimization

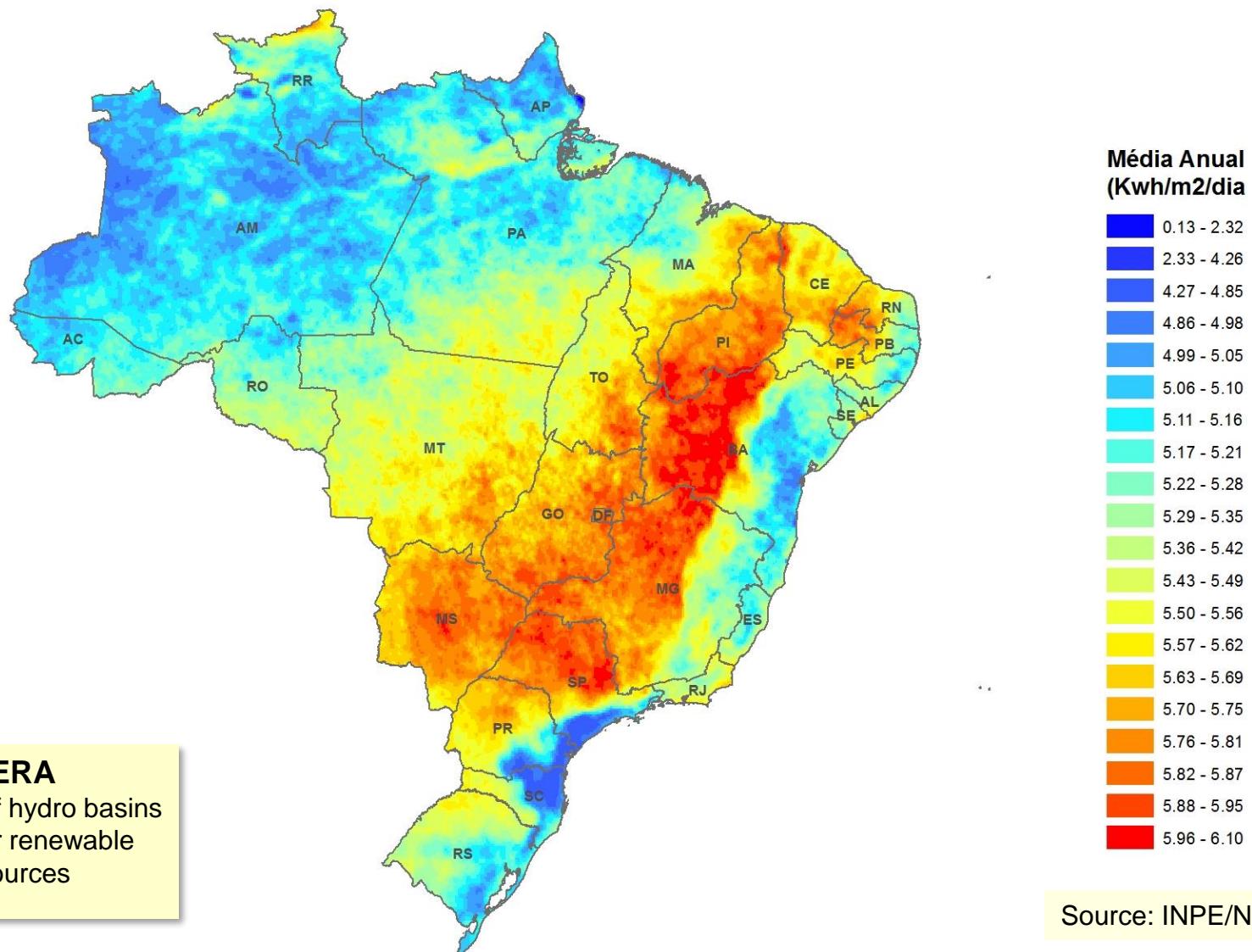
- Selection of projects that maximize the economic benefit of hydropower
- Non-linear, integer, multistage, stochastic mathematical problem



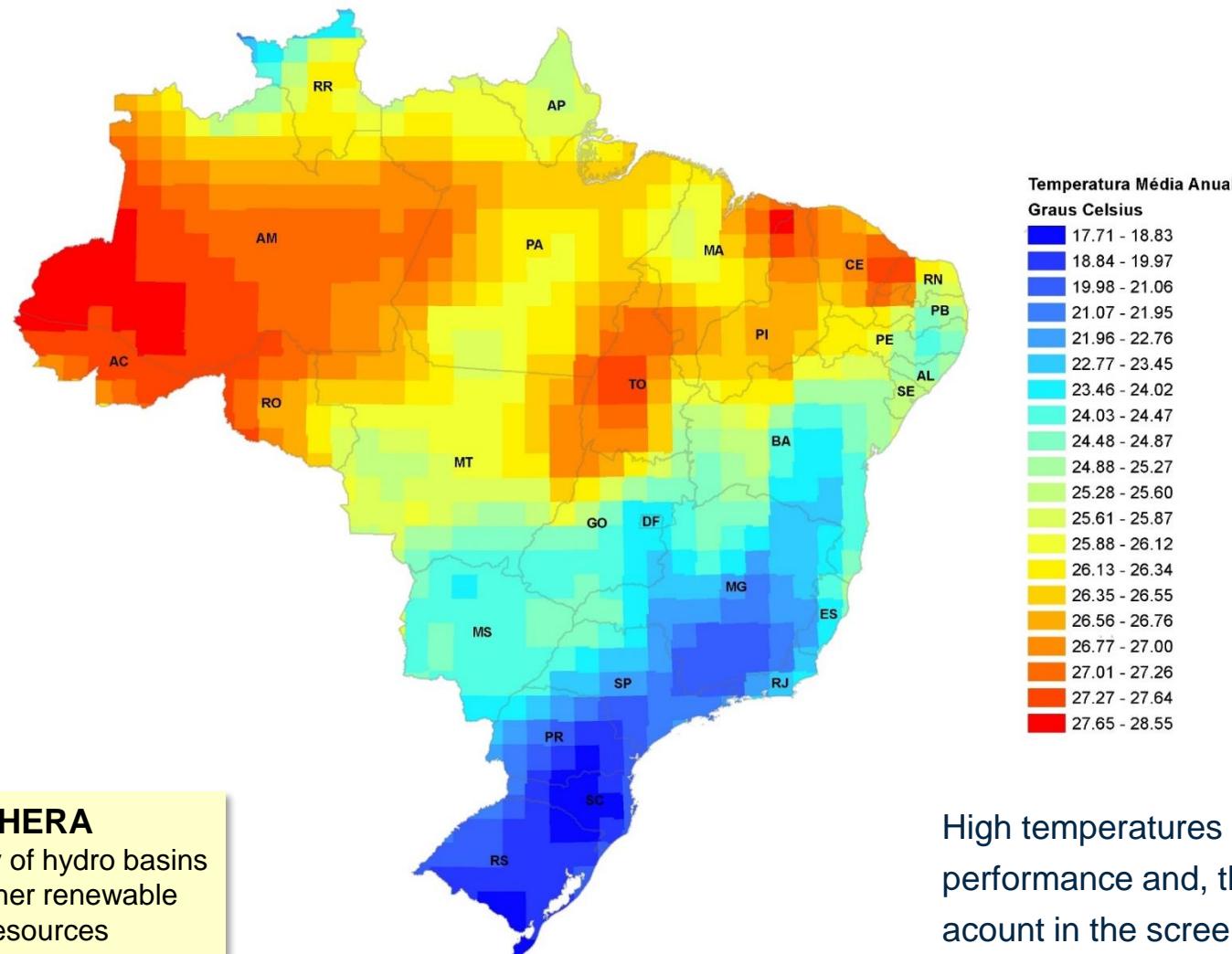
Results



HERA Solar: average annual irradiation (kWh/m²/day)



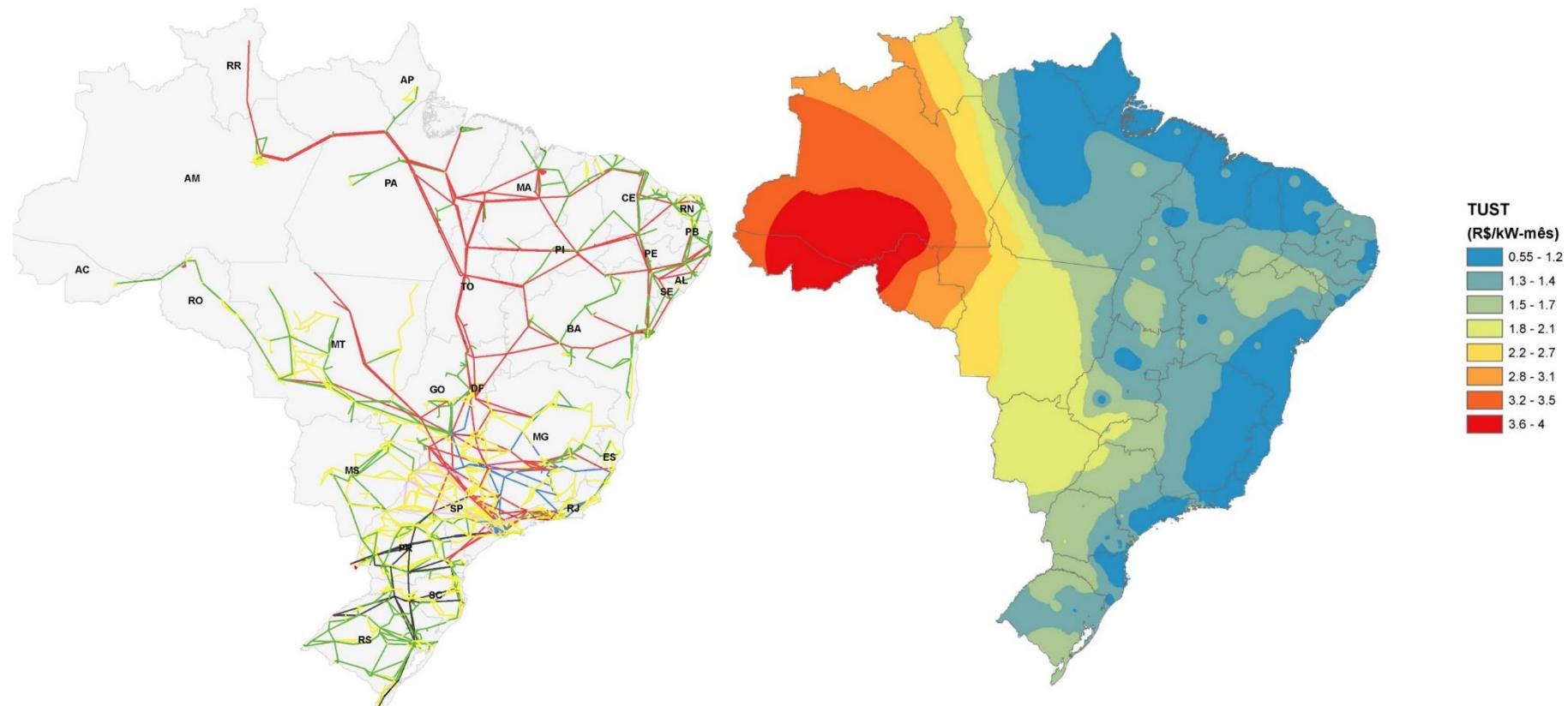
HERA Solar: Average temperature



HERA
Inventory of hydro basins
and other renewable
resources

High temperatures affect the solar cell performance and, thus, are taken into account in the screening process

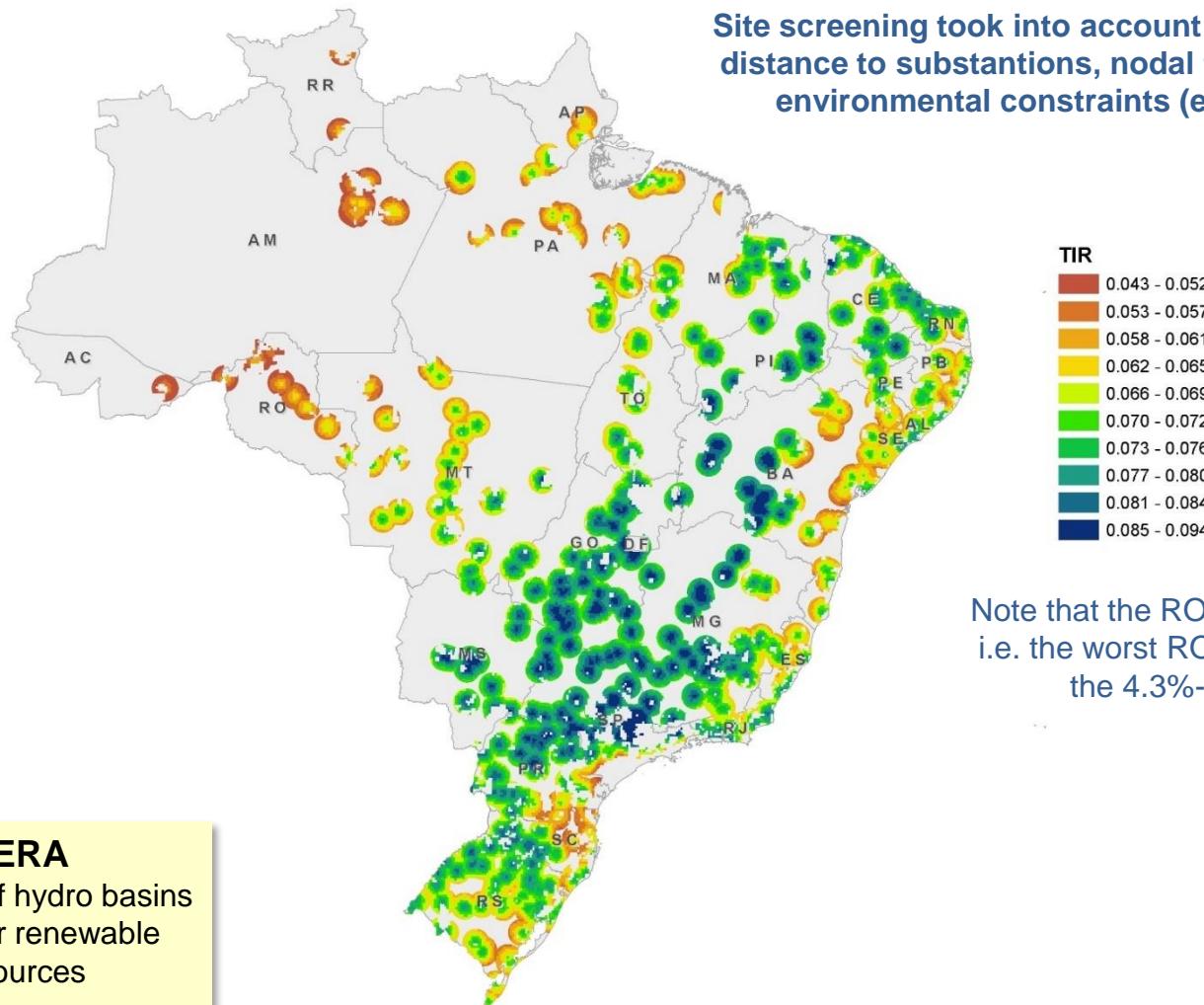
Transmission grid and nodal tariffs (TUST)



HERA

Inventory of hydro basins
and other renewable
resources

HERA Solar: project ROI for the candidate sites



Global wind data bases

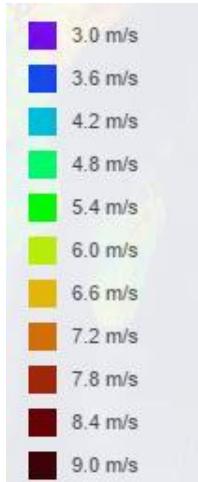
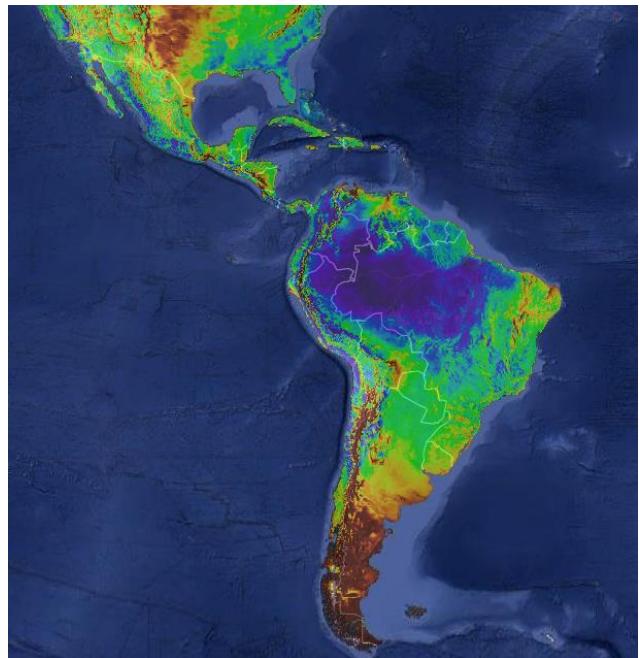
HERA

Inventory of hydro basins
and other renewable
resources



IRENA
International Renewable Energy Agency

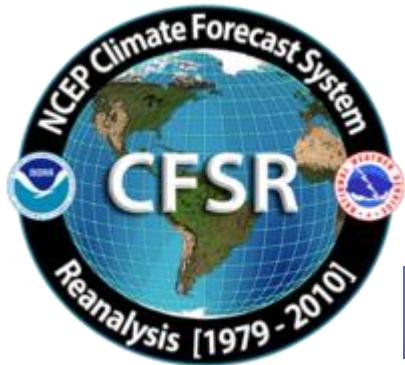
Global Atlas
FOR RENEWABLE ENERGY



HERA Wind: main components

HERA

Inventory of hydro basins
and other renewable
resources



NCAR
UCAR



Data

- Global DBs
- +30 years hourly
With reanalysis

Screening

- Siting
- Economic potential

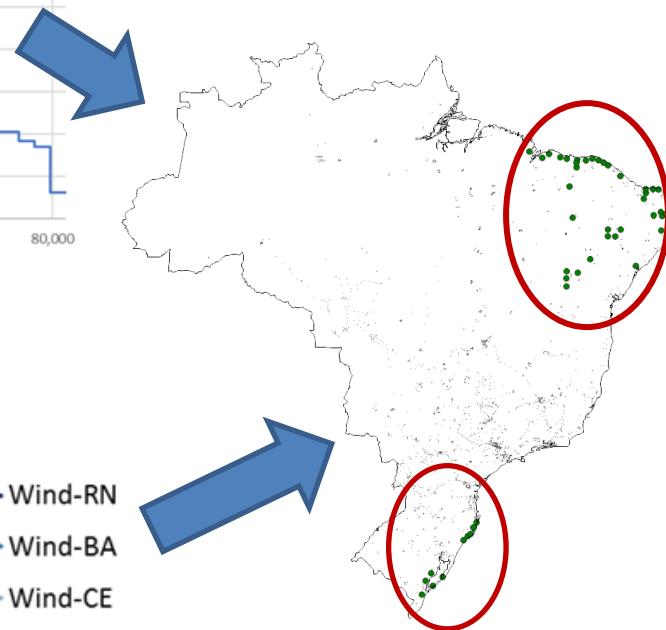
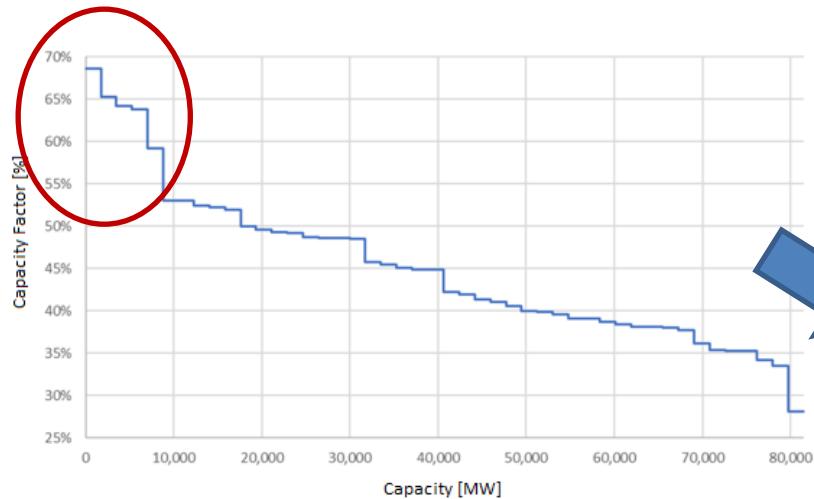
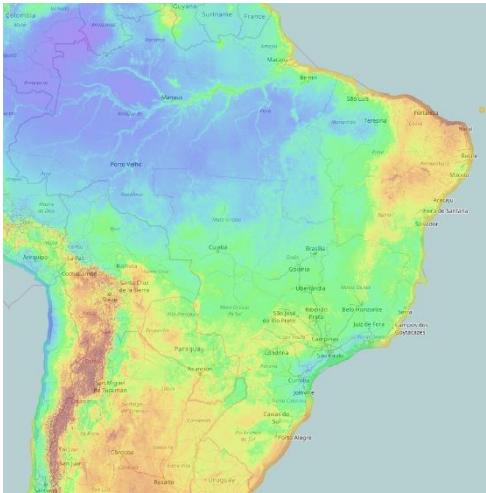
Energy production

- Generator parameters
- Wind park design

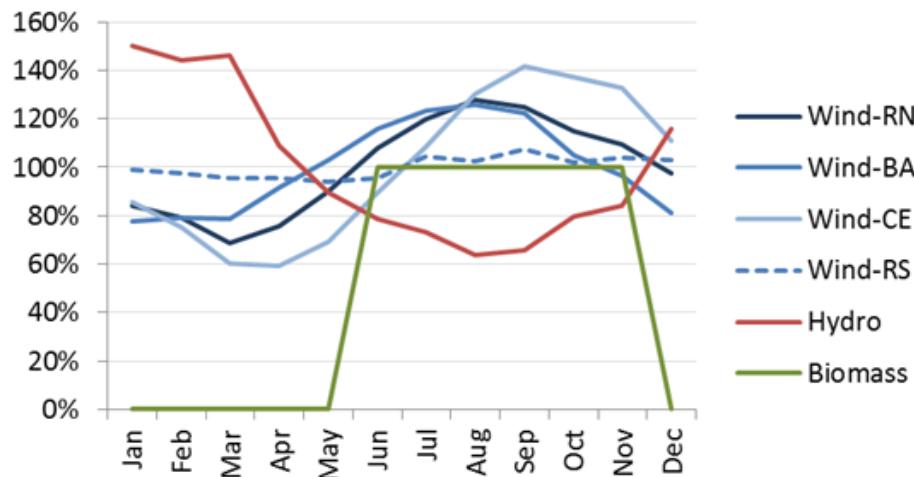
HERA Wind: main components

HERA

Inventory of hydro basins
and other renewable
resources



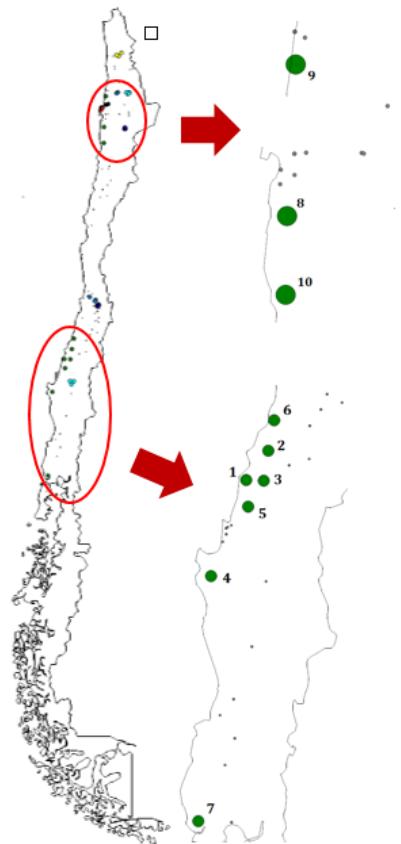
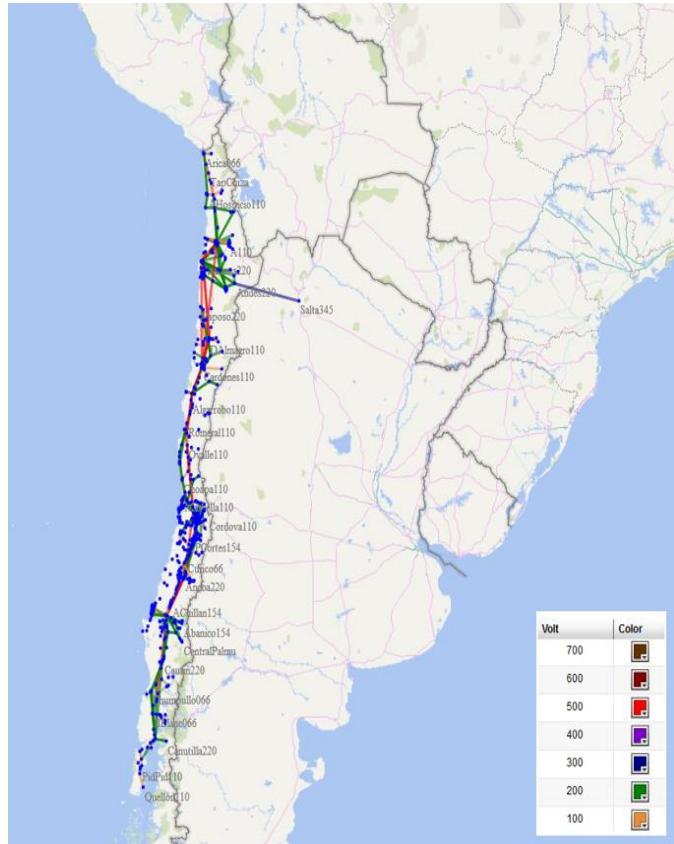
Seasonal generation patterns



Candidate ranking

- Some criteria: (i) capacity factors; (ii) distance from grid; (iii) correlation with existing wind farms etc.

Example: Chile



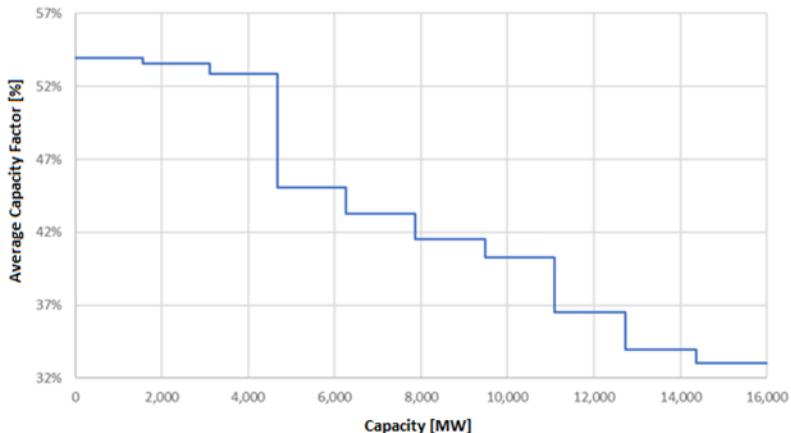
Spot	Average capacity factor
1	53.97%
2	53.57%
3	52.84%
4	45.09%
5	43.24%
6	41.51%
7	40.30%
8	36.54%
9	33.96%
10	33.01%

Candidate ranking

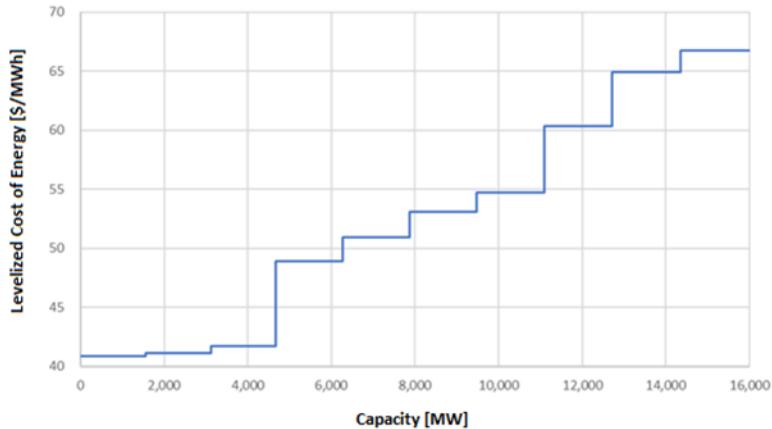
HERA

Inventory of hydro basins
and other renewable
resources

- Average Capacity Factor (p.u.):



- Levelized Cost of Energy (\$/MWh):



Classification

- Classification of candidates
- Utilization of tools to asses potential generation: SAM, HERA, etc.

Financial Assumptions

- CAPEX
- OPEX
- Financial and tributary aspects

Expansion Costs

- Combination of capacity factors and financial assumptions for pre-feasibility verification to filter projects
- Optimize system expansion based on the selected candidates

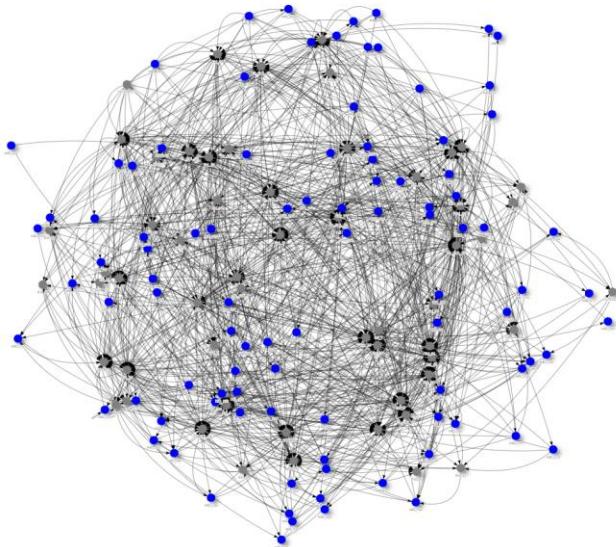
Multistage stochastic capacity expansion planning

Generation, transmission and probabilistic generation reserve

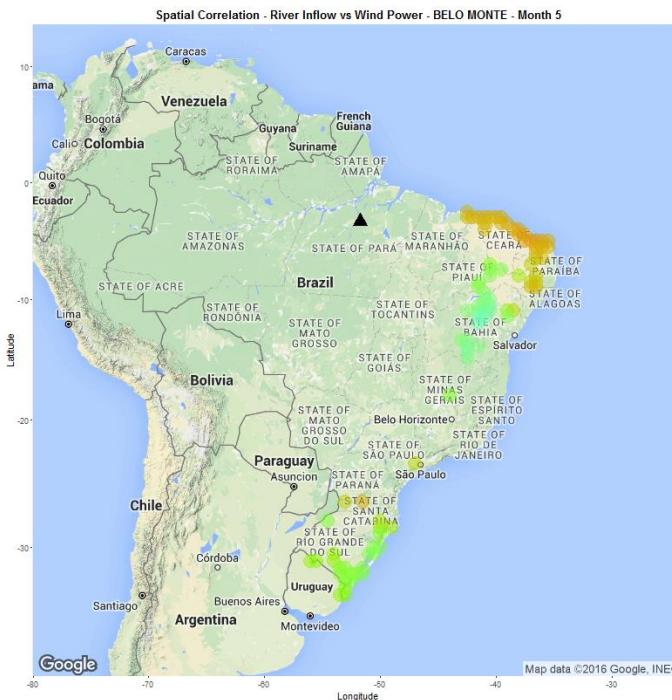
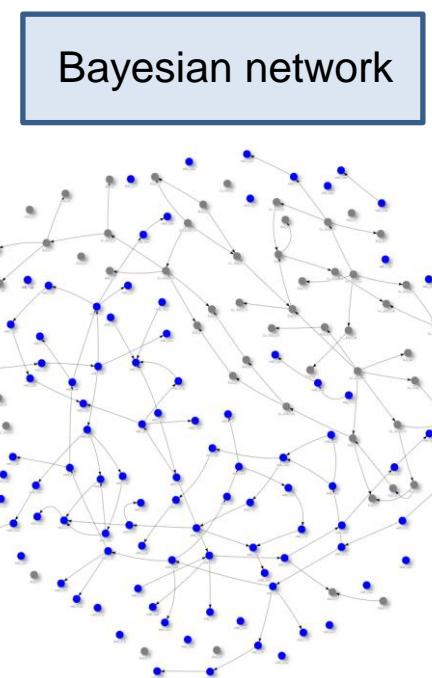
TSL: Scenario generation

Time Series Lab
Multiscale stochastic
scenarios (inflow,
renewable, demand)

- Time Series Lab (TSL) produces renewable energy scenarios conditioned to the inflows, preserving spatial and temporal correlations.



Traditional methodology



Wind & Inflows



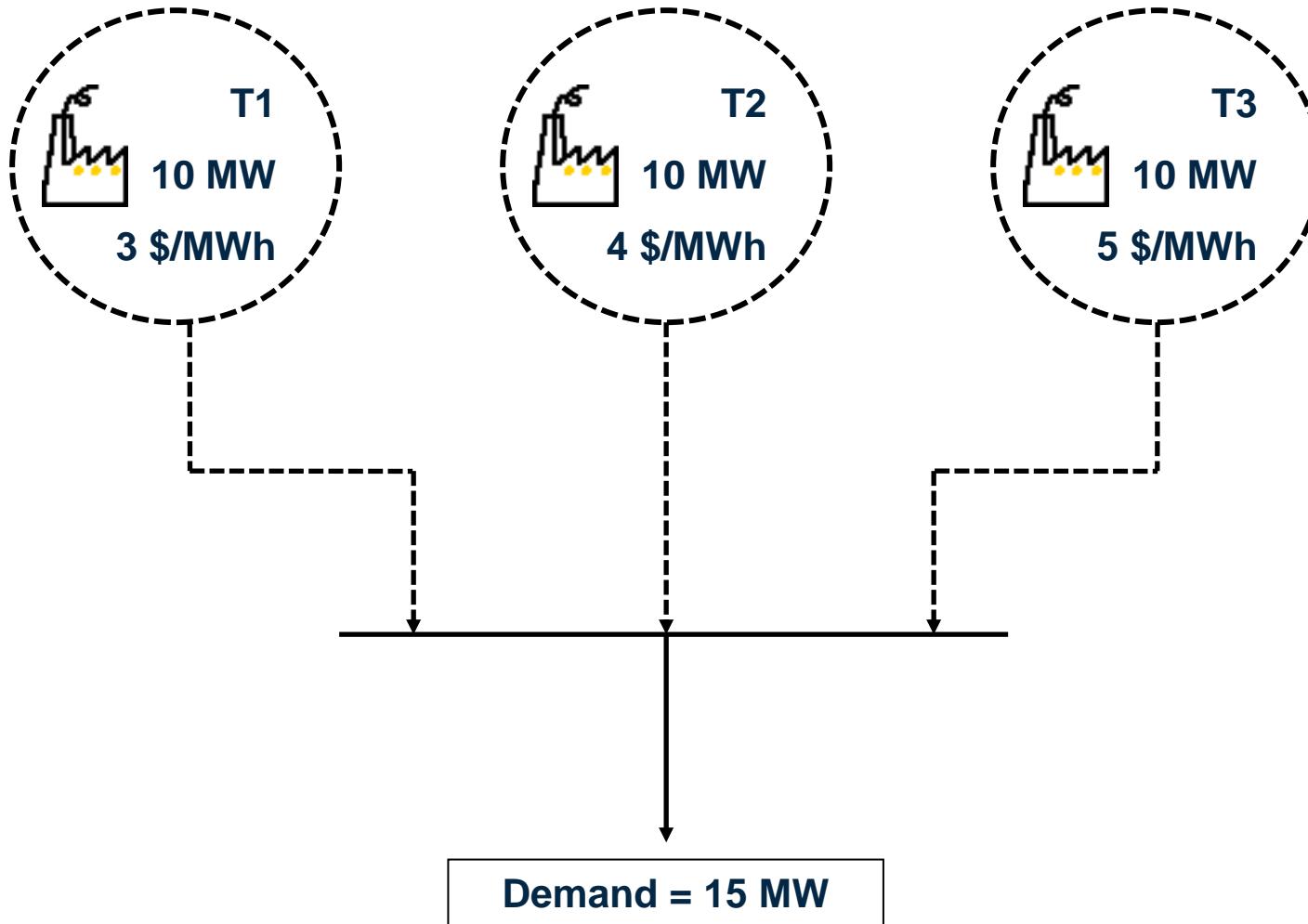
Expansion Planning Model



General overview

- ▶ OptGen is a long-term expansion planning model that determines the least-cost sizing and timing decisions for construction, retirement and reinforcement of energy and gas production and transportation capacities
- ▶ The objective is to define WHICH and WHEN projects should be constructed in order to minimize the sum of the annualized investment costs (new capacities) and the expected operating costs (fuel costs, emission costs and penalties for supply failure)
- ▶ The model takes into account several investment and operative constraints and can perform optimization under uncertainty

Example of expansion planning problem



Example of expansion planning problem

$$\text{Min } I_1 g_1^1_{\max} + I_2 g_2^2_{\max} + I_3 g_3^3_{\max} + c_1 g_1 + c_2 g_2 + c_3 g_3 + c_{\text{def}} \text{ def}$$

s.t.

$$g_1 + g_2 + g_3 + \text{def} = D$$

$$g_1 \leq g_1^1_{\max}$$

$$g_2 \leq g_2^2_{\max}$$

$$g_3 \leq g_3^3_{\max}$$

I_1, I_2, I_3 – unitary investment costs (\$/MW)

$c_1, c_2, c_3, c_{\text{def}}$ – unitary operation and deficit costs (\$/MWh)

Example of expansion planning problem

$$\text{Min } I_1 g_1^1 + I_2 g_2^2 + I_3 g_3^3 + c_1 g_1 + c_2 g_2 + c_3 g_3 + c_{\text{def}} \text{ def}$$

s.t.

$$g_1 + g_2 + g_3 + \text{def} = D$$

$$g_1 - g_1^1 \leq 0$$

$$g_2 - g_2^2 \leq 0$$

$$g_3 - g_3^3 \leq 0$$

} **Operative limits**

I_1, I_2, I_3 – unitary investment costs (\$/MW)

$c_1, c_2, c_3, c_{\text{def}}$ – unitary operation and deficit costs (\$/MWh)

Example of expansion planning problem

► For each capacity expansion decision (g'_{\max}):

► Investment cost:

- $I(g'_{\max}) = I_1 g'^1_{\max} + I_2 g'^2_{\max} + I_3 g'^3_{\max}$

► Operation cost:

- $O(g'_{\max}) = \text{Min } c_1 g_1 + c_2 g_2 + c_3 g_3$

$$\text{s.t } g_1 + g_2 + g_3 = D$$

$$g_1 \leq g'^1_{\max}$$

$$g_2 \leq g'^2_{\max}$$

$$g_3 \leq g'^3_{\max}$$

Example of expansion planning problem

$$\begin{array}{l} \text{Investment cost} \\ \text{Operation cost} \\ \hline \text{Min } 10 g_1^1_{\max} + 10 g_2^2_{\max} + 10 g_3^3_{\max} + 3 g_1 + 4 g_2 + 5 g_3 + 50 \text{ def} \\ \text{s.t.} \\ g_1 + g_2 + g_3 + \text{def} = 15 \\ g_1 - g_1^1_{\max} \leq 0 \\ g_2 - g_2^2_{\max} \leq 0 \\ g_3 - g_3^3_{\max} \leq 0 \end{array}$$

Operative limits

Generators maximum capacity : 10 MW

Enumerating solutions

► Investment cost

$$I(0) = 10 \cdot 0 + 10 \cdot 0 + 10 \cdot 0$$

► Operation cost

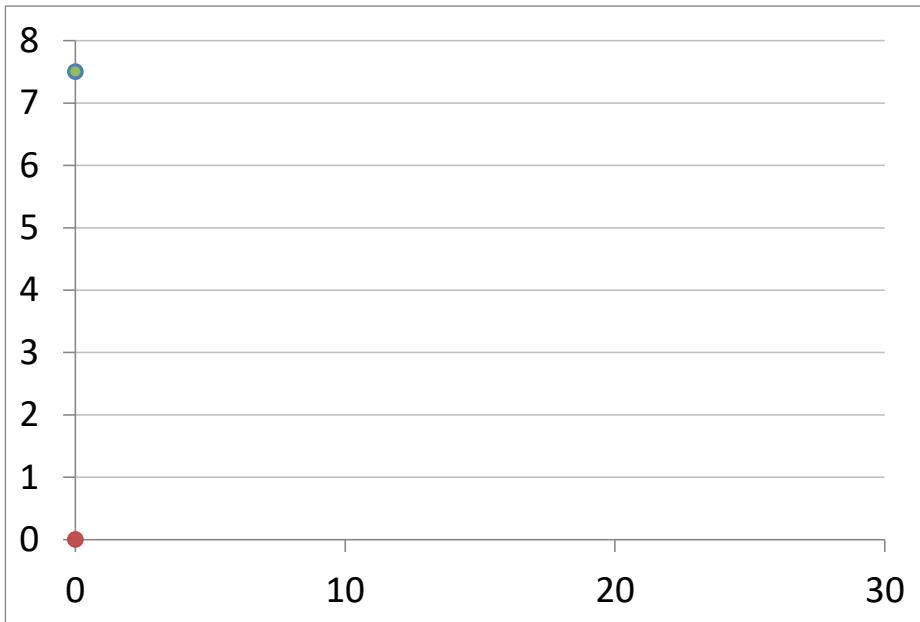
$$O(0) = \text{Min } 3 g_1 + 4 g_2 + 5 g_3 + 50 \text{ def}$$

$$\text{s/t } g_1 + g_2 + g_3 + \text{def} = 15$$

$$g_1 \leq 0$$

$$g_2 \leq 0$$

$$g_3 \leq 0$$



$$I(0) = 0 \text{ k\$}$$

$$O(0) = 750 \text{ k\$}$$

750 k\$

Enumerating solutions

► Investment cost

$$I(10) = 10 \cdot 10 + 10 \cdot 0 + 10 \cdot 0$$

► Operation cost

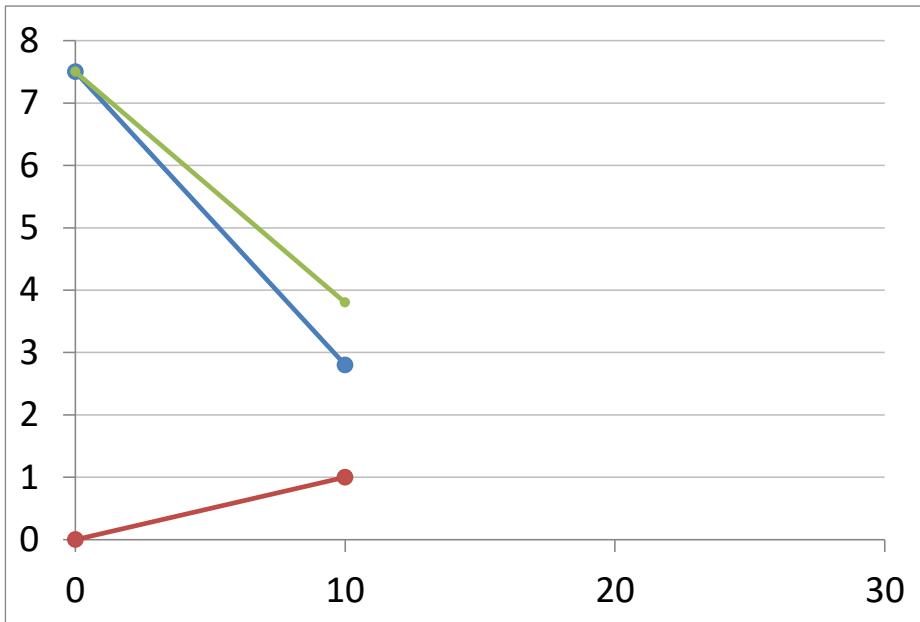
$$O(10) = \text{Min } 3 g_1 + 4 g_2 + 5 g_3 + 50 \text{ def}$$

$$\text{s/t } g_1 + g_2 + g_3 + \text{def} = 15$$

$$g_1 \leq 10$$

$$g_2 \leq 0$$

$$g_3 \leq 0$$



$$I(0) = 0 \text{ k\$}$$

$$I(10) = 100 \text{ k\$}$$

$$O(0) = 750 \text{ k\$}$$

$$O(10) = 280 \text{ k\$}$$

$$750 \text{ k\$}$$

$$380 \text{ k\$}$$

Enumerating solutions

► Investment cost

$$I(20) = 10 \cdot 10 + 10 \cdot 10 + 10 \cdot 0$$

► Operation cost

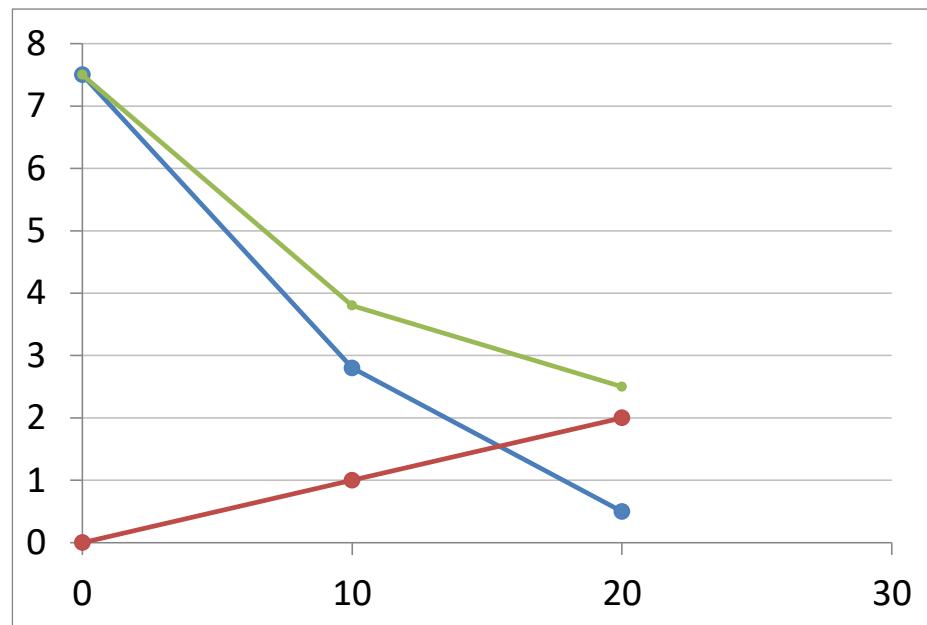
$$O(20) = \text{Min } 3 g_1 + 4 g_2 + 5 g_3 + 50 \text{ def}$$

$$\text{s/t } g_1 + g_2 + g_3 + \text{def} = 15$$

$$g_1 \leq 10$$

$$g_2 \leq 10$$

$$g_3 \leq 0$$



$$I(0) = 0 \text{ k\$}$$

$$I(10) = 100 \text{ k\$}$$

$$I(20) = 200 \text{ k\$}$$

$$O(0) = 750 \text{ k\$}$$

$$O(10) = 280 \text{ k\$}$$

$$O(20) = 50 \text{ k\$}$$

$$750 \text{ k\$}$$

$$380 \text{ k\$}$$

$$250 \text{ k\$}$$

Enumerating solutions

► Investment cost

$$I(30) = 10 \cdot 10 + 10 \cdot 10 + 10 \cdot 10$$

► Operation cost

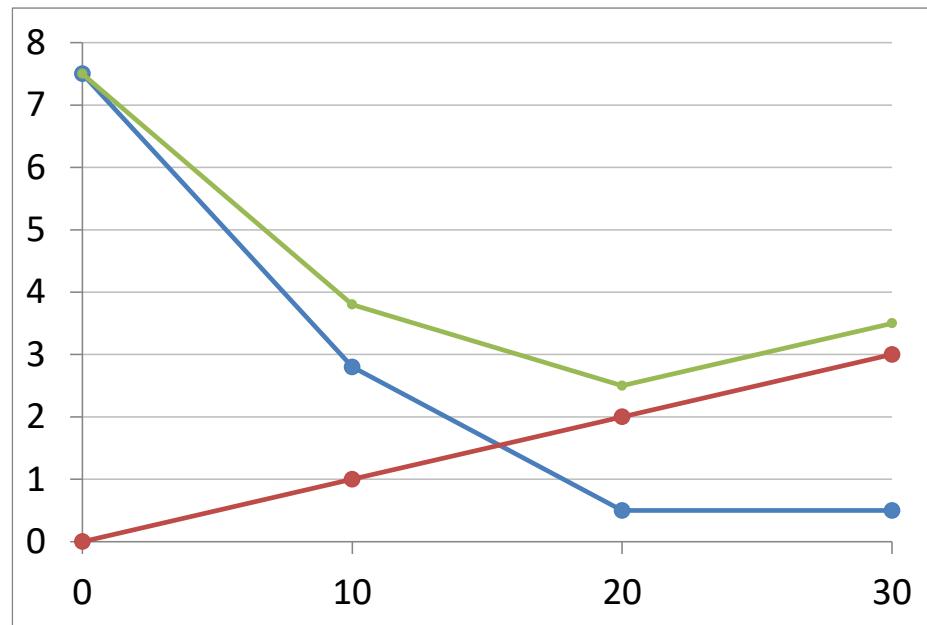
$$O(30) = \text{Min } 3 g_1 + 4 g_2 + 5 g_3 + 50 \text{ def}$$

$$\text{s/t } g_1 + g_2 + g_3 + \text{def} = 15$$

$$g_1 \leq 10$$

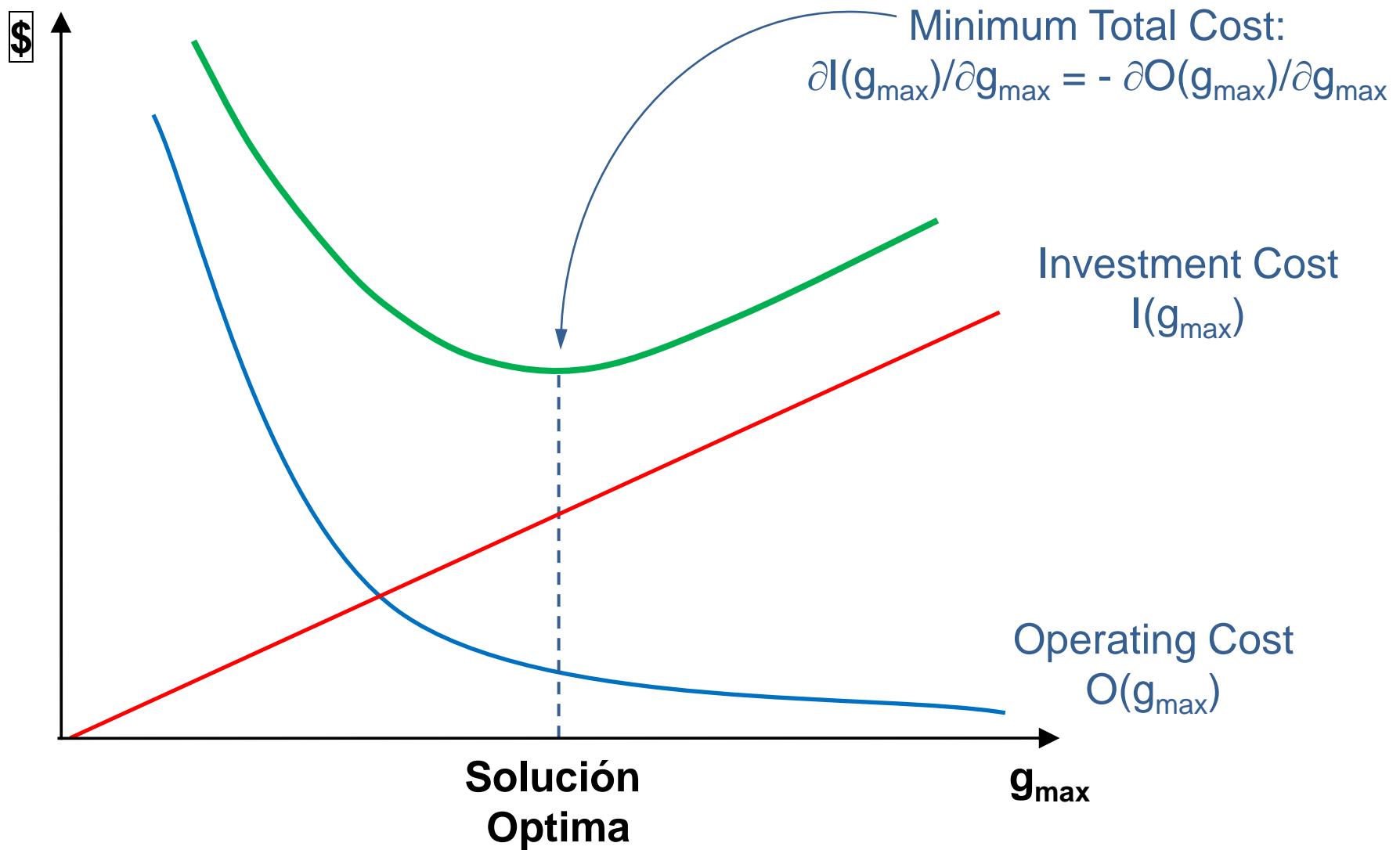
$$g_2 \leq 10$$

$$g_3 \leq 10$$



$I(0) = 0 \text{ k\$}$	$I(10) = 100 \text{ k\$}$	$I(20) = 200 \text{ k\$}$	$I(30) = 300 \text{ k\$}$
$O(0) = 750 \text{ k\$}$	$O(10) = 280 \text{ k\$}$	$O(20) = 50 \text{ k\$}$	$O(30) = 50 \text{ k\$}$
750 k\\$	380 k\\$	250 k\\$	350 k\\$

The GEP Task – Solution method



The GEP Task – Plants and system modeling

► Candidate projects

- Production components: Hydro, Thermal and Renewable plants
- Interconnection links and transmission circuits (lines, transformers, etc.)
- Gas pipelines, production nodes, regasification stations

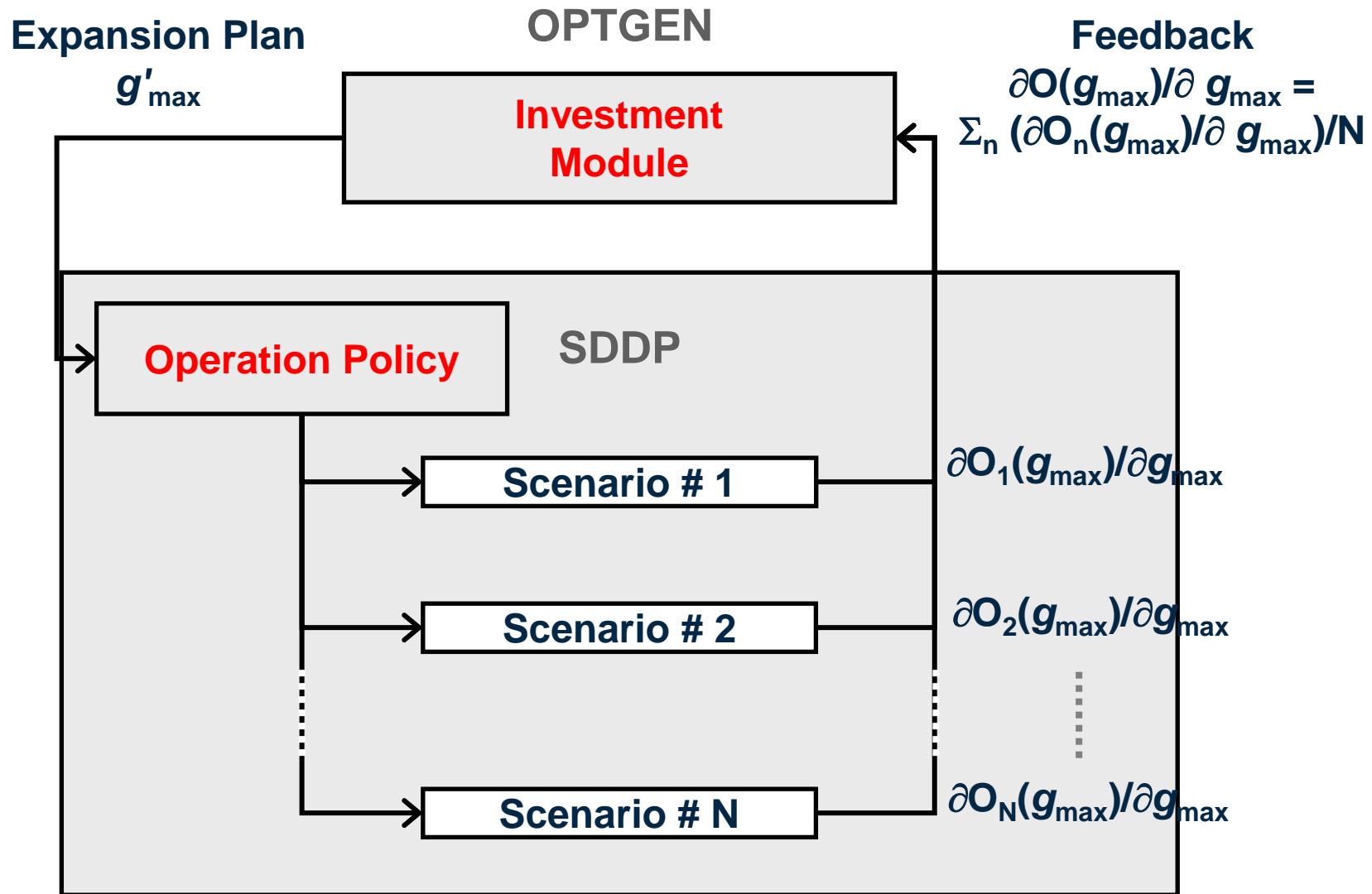
► Additional input data (for investment decision)

- Investment costs
- Investment timeframe windows
- Relational constraints (association, precedence, exclusivity)
- Budgetary constraints
- Firm energy and capacity constraints

The GEP Task – Plants and system modeling

- ▶ The least-cost GEP is achieved by optimizing the trade-off between investment costs to build new projects and the expected value of operative costs obtained from the stochastic hydrothermal dispatch model, which allows a detailed representation of the electric-gas system's operation under uncertainty
- ▶ SDDP is used as the operation planning module

Optgen + SDDP as operation module

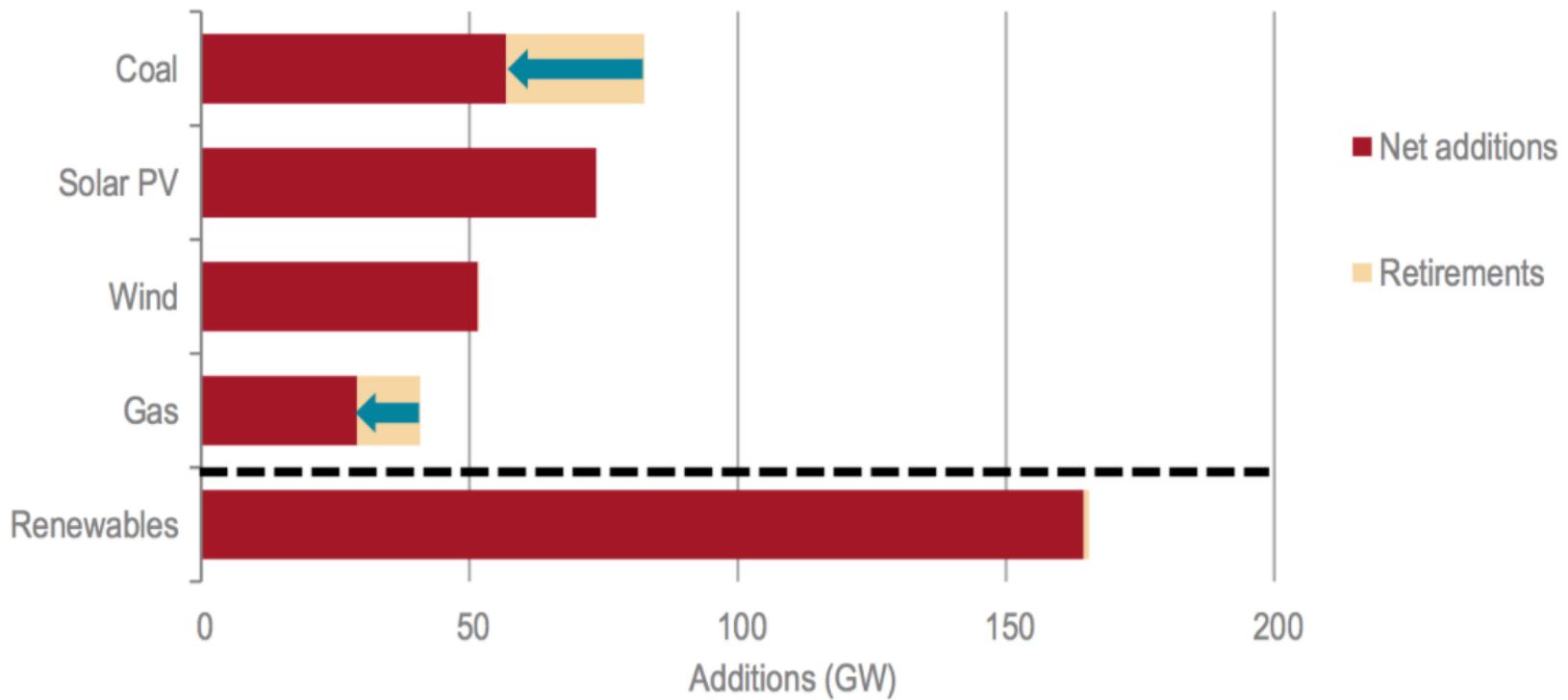




Expansion Planning – Current Scenario

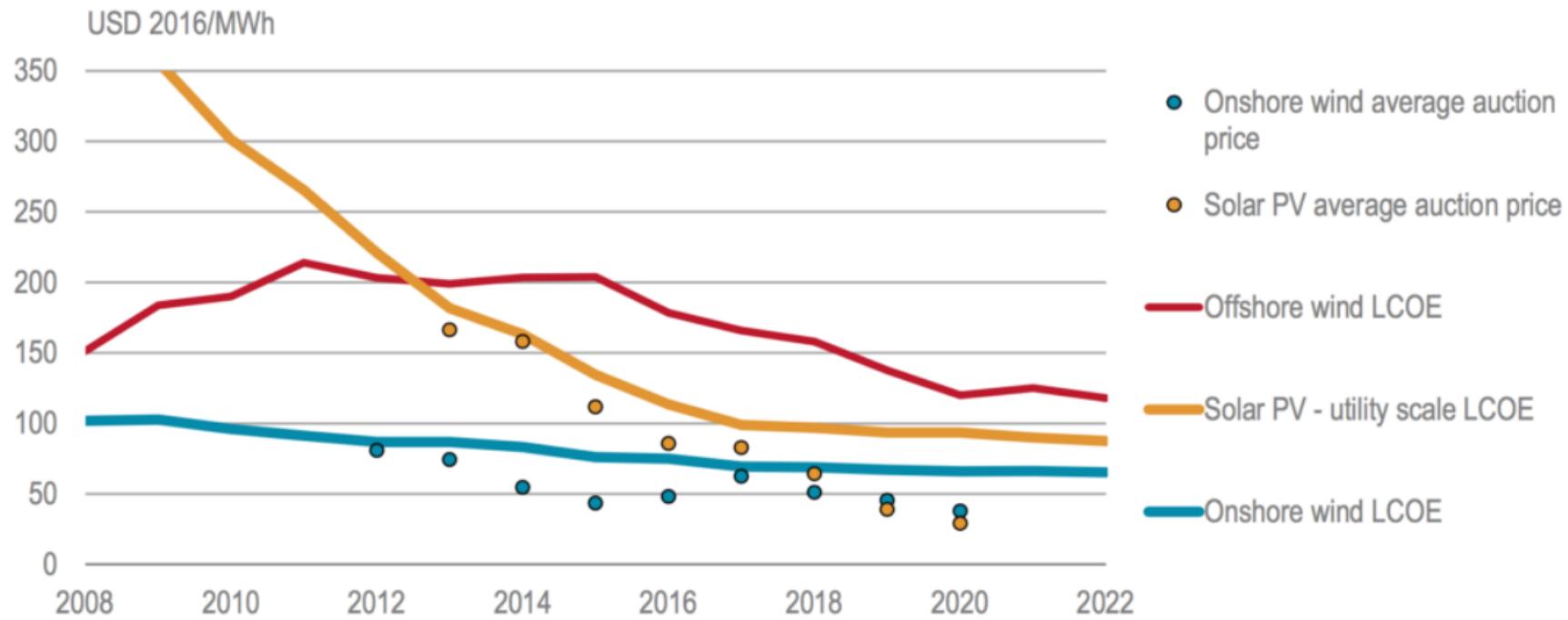


Expansion planning – Current scenario



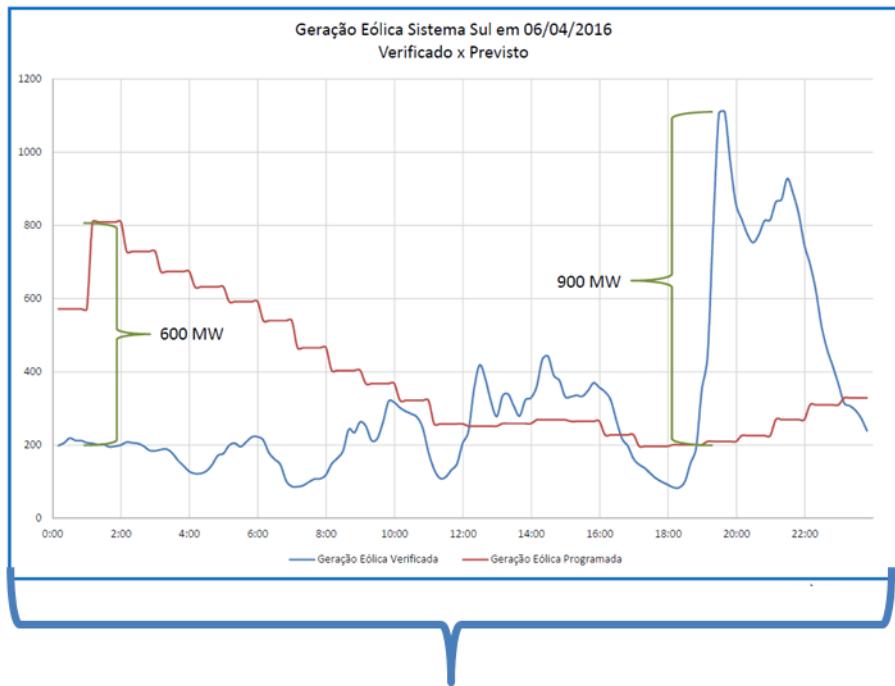
Electricity capacity additions by fuel 2016. Source: Renewables 2017 Pre-launch Media Webinar.

Expansion planning – Current scenario



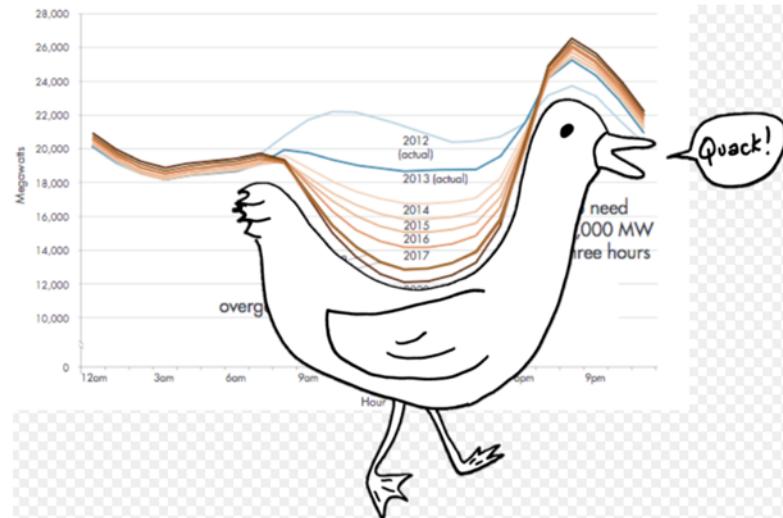
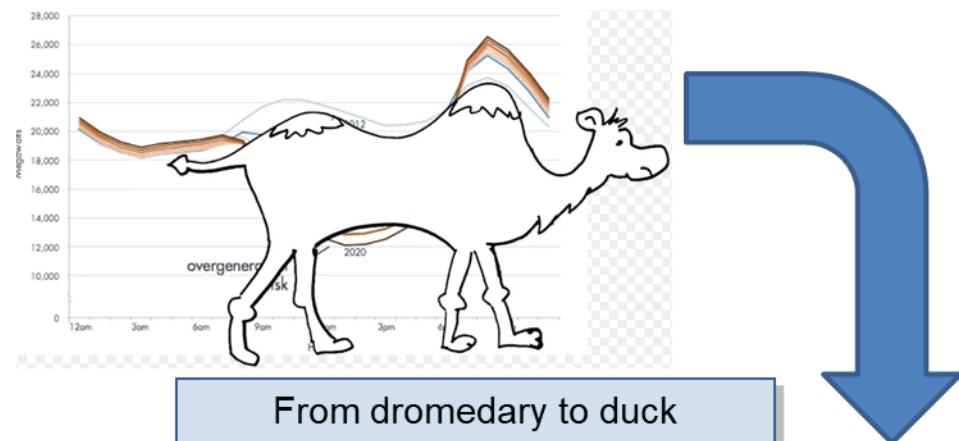
Global average levelised cost of energy (LCOE) and auction results for projects by commissioning date. Source: Renewables 2017, IEA.

High Renewable Penetration - Challenges



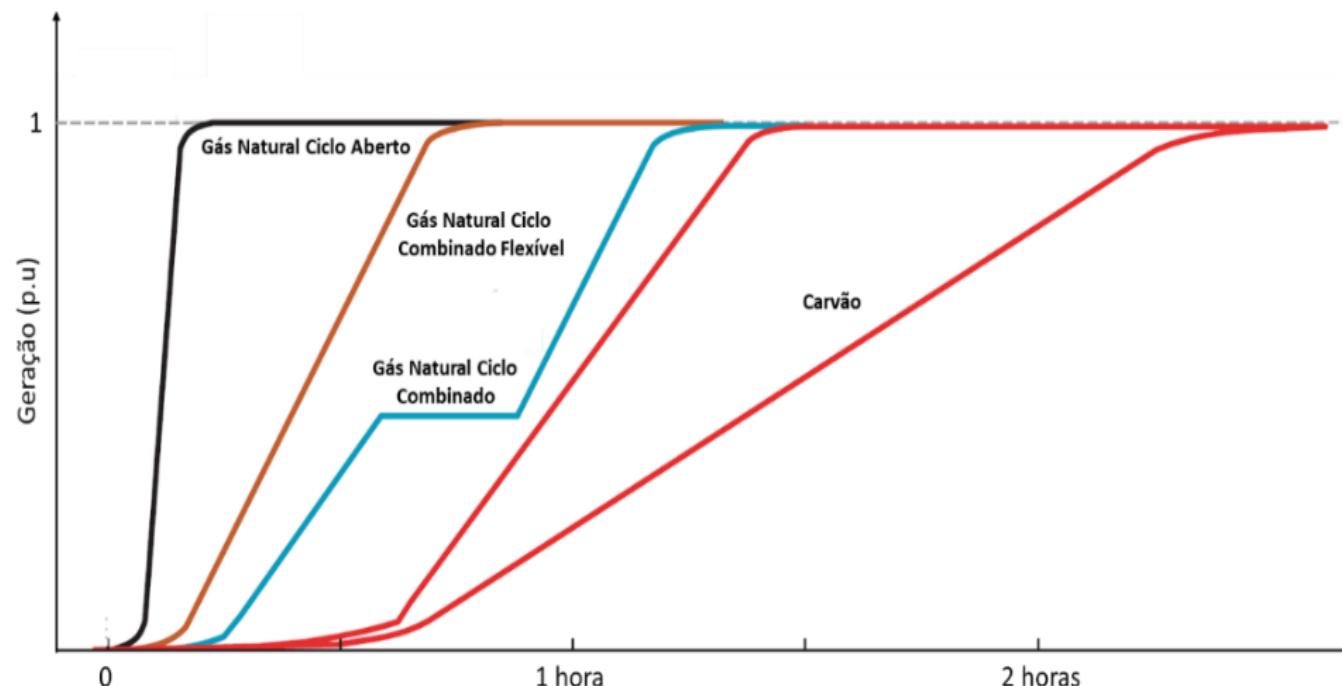
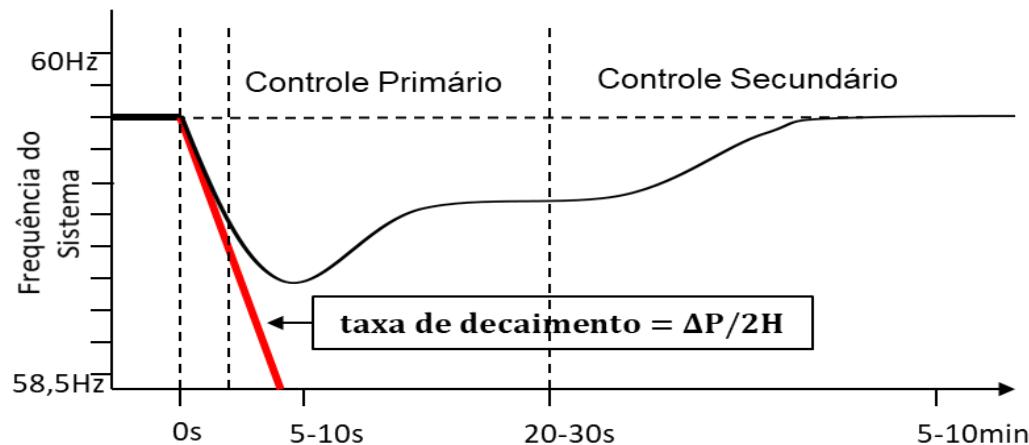
1000 MW ramp in 1 hour

900 MW difference between
scheduled and verified



- **Operating Reserve:** needed to guarantee security of supply

High Renewable Penetration - Challenges





Case Study: The Expansion Planning of the Mexican System



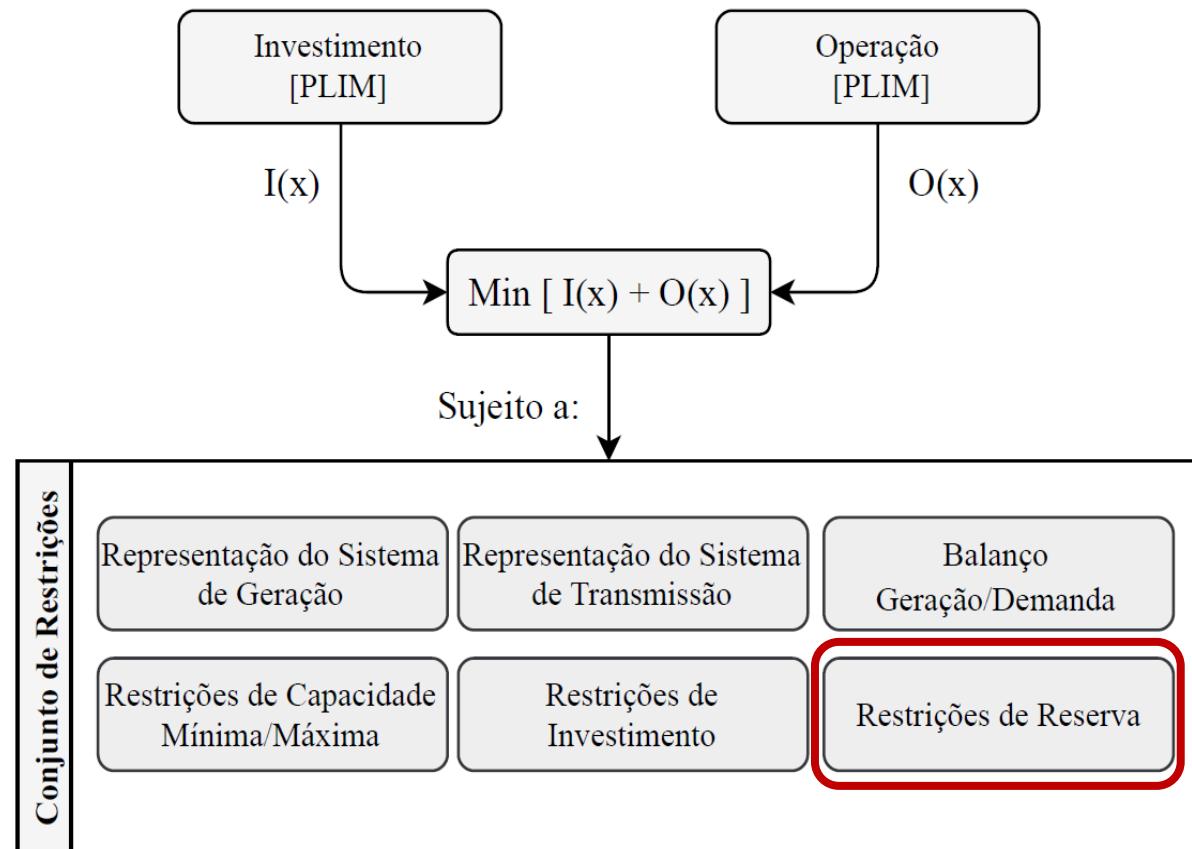
The Expansion Planning of the Mexican System



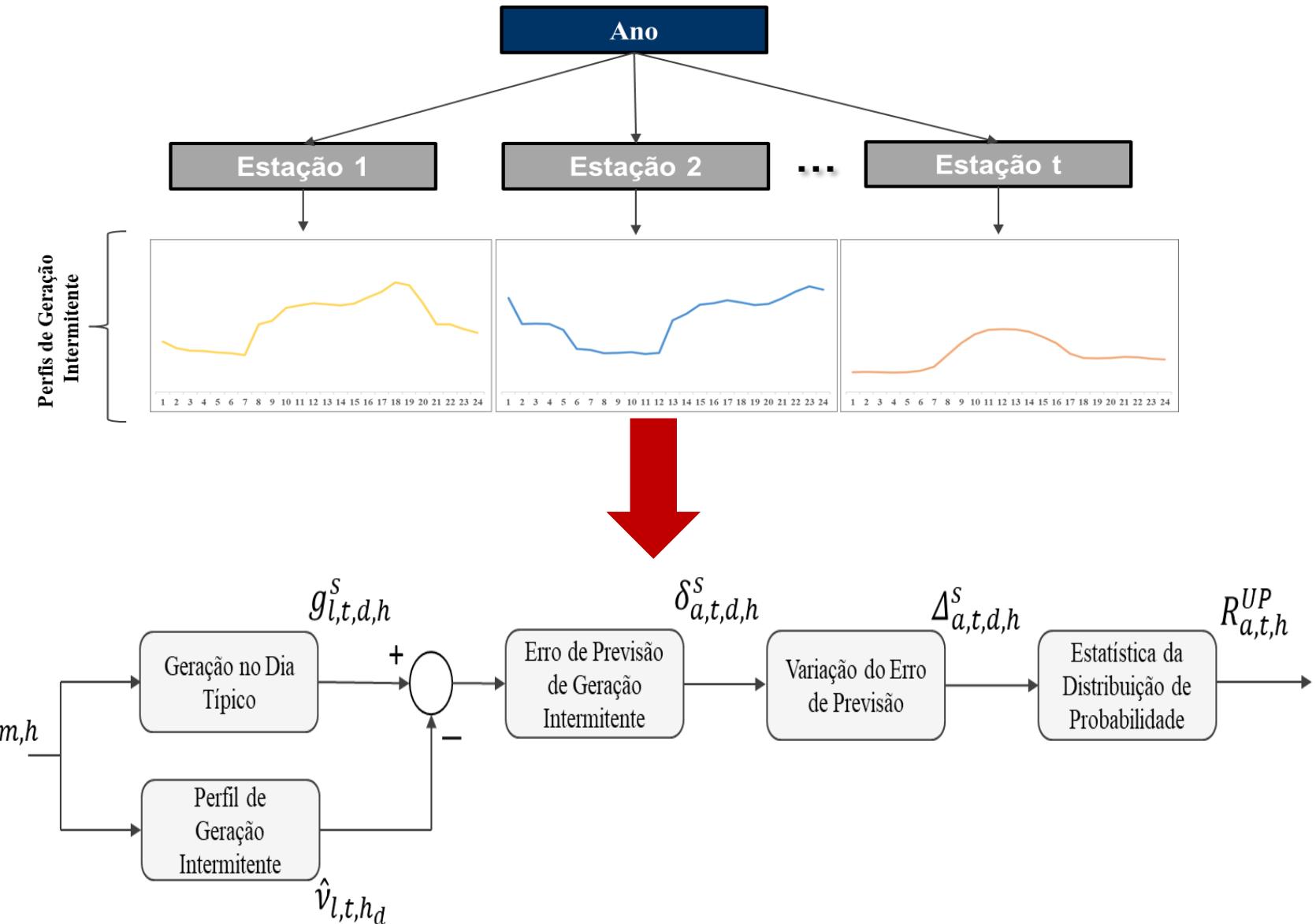
Universidade Federal
do Rio de Janeiro
Escola Politécnica

Modelo de Expansão da Geração Considerando Requisito de Reserva Probabilística Dinâmica

Weslly de Sousa Morais

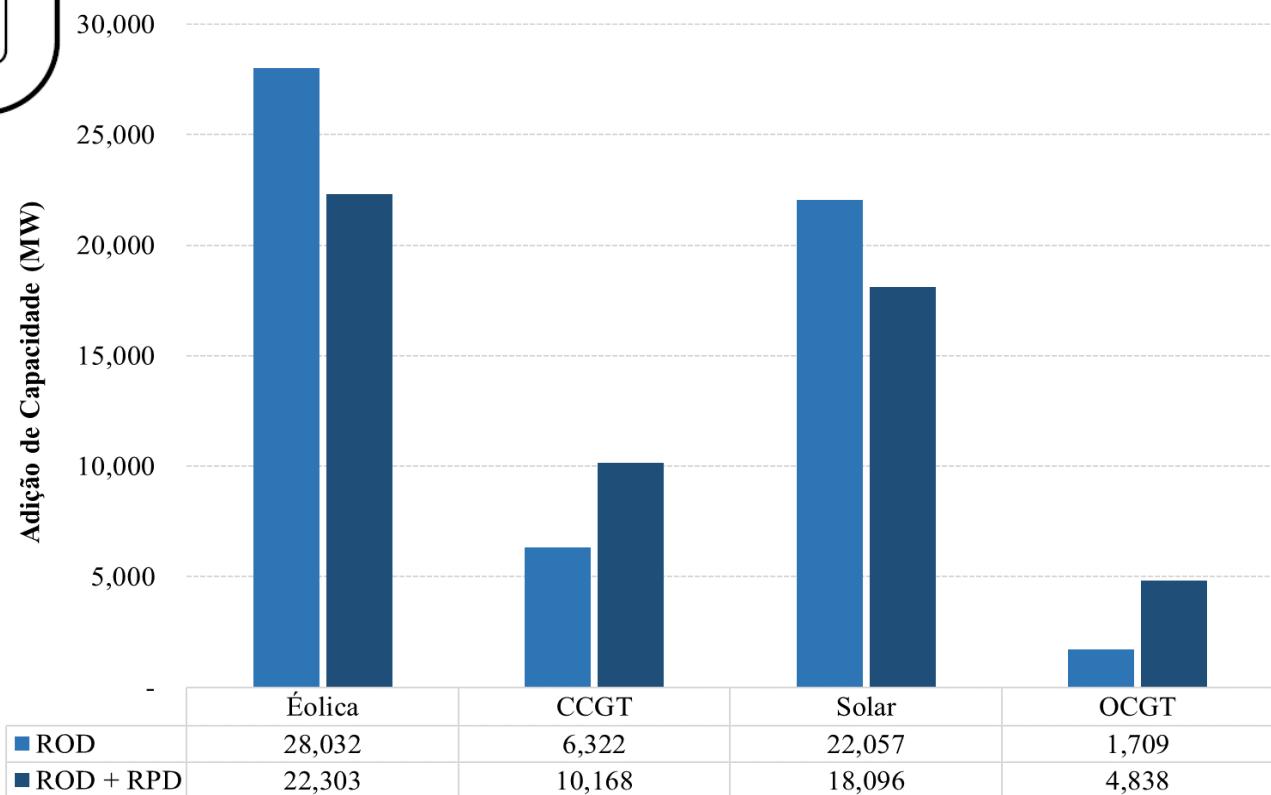
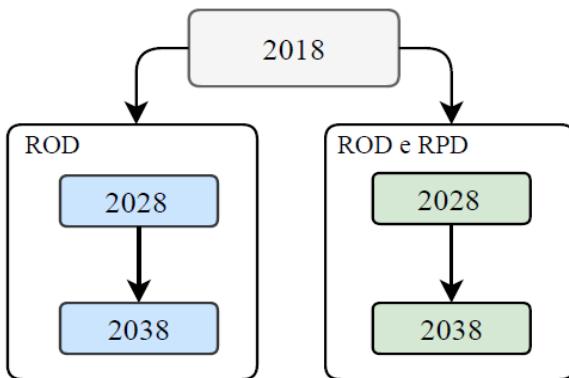


The Expansion Planning of the Mexican System



The Expansion Planning of the Mexican System

Estudo de Caso 1

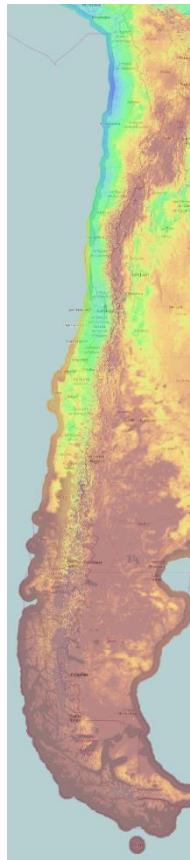


Case Study: The Expansion Planning of the Chilean System

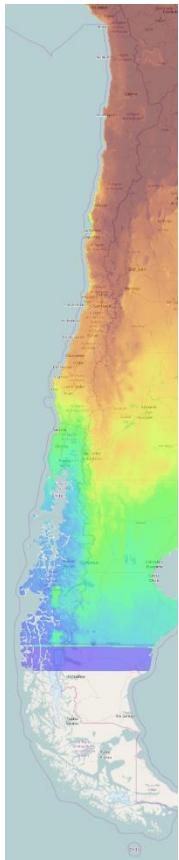


The Expansion Planning of the Chilean System

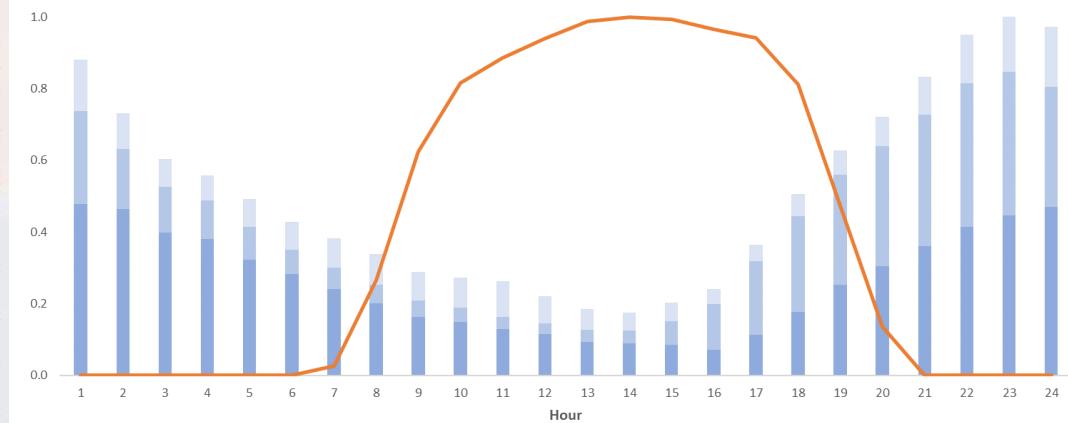
Wind



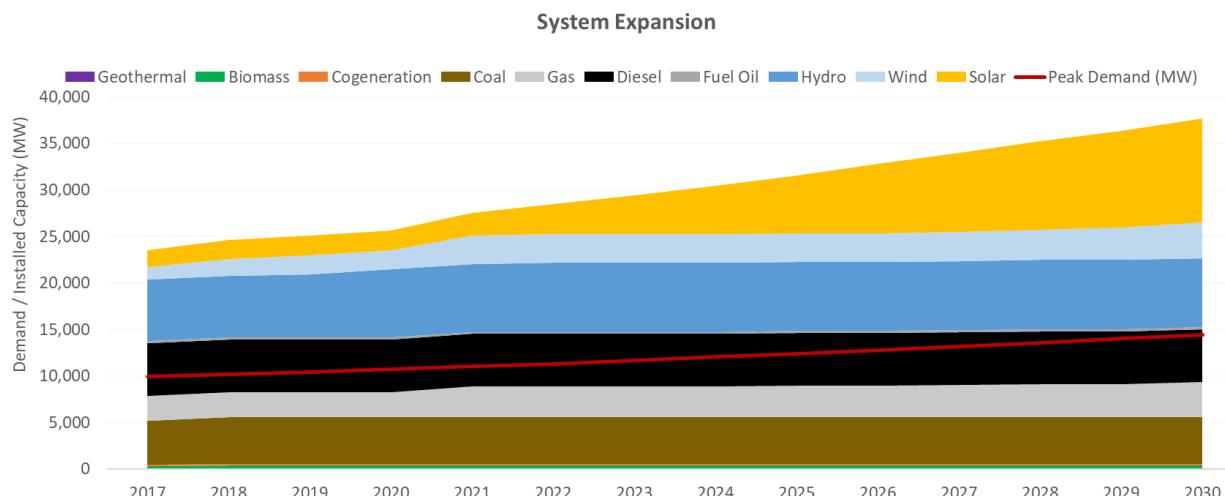
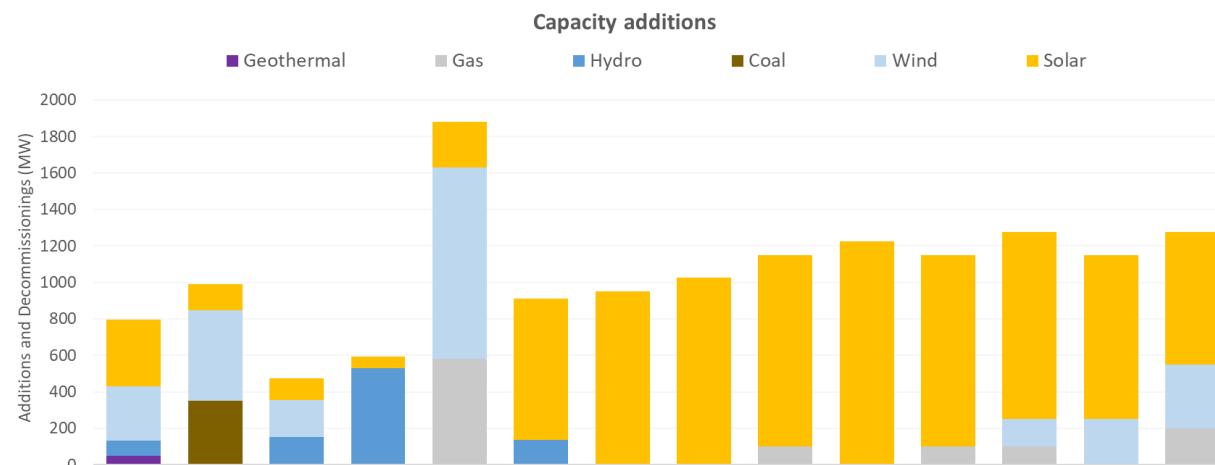
Solar



Reina Cururos Vientos Solar

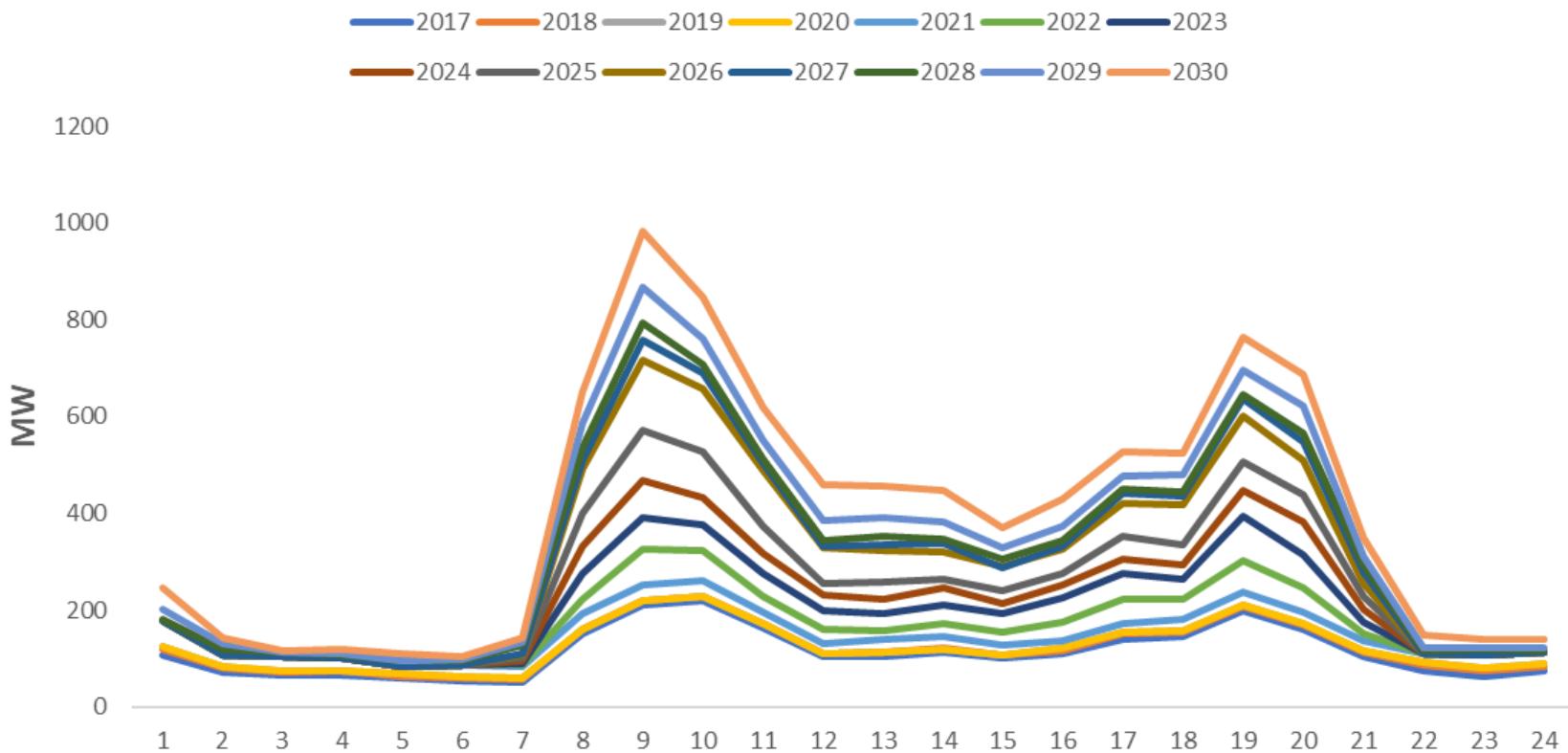


The Expansion Planning of the Chilean System



The Expansion Planning of the Chilean System

Example R_{VRE}^* in Chile:

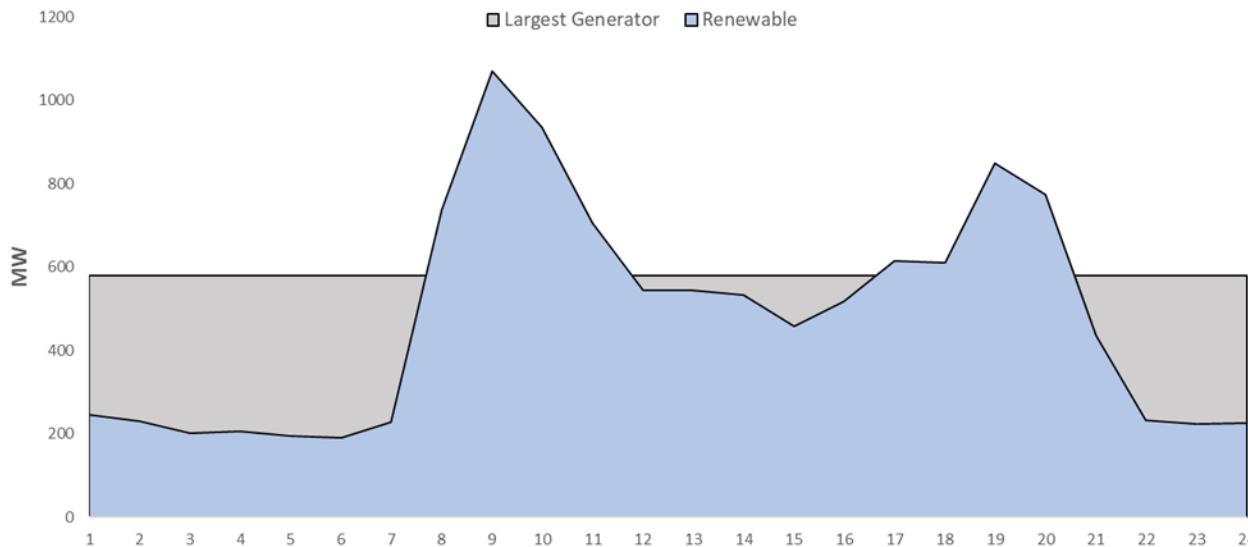


The Expansion Planning of the Chilean System

- Finally, the final reserve requirement of the system will be:

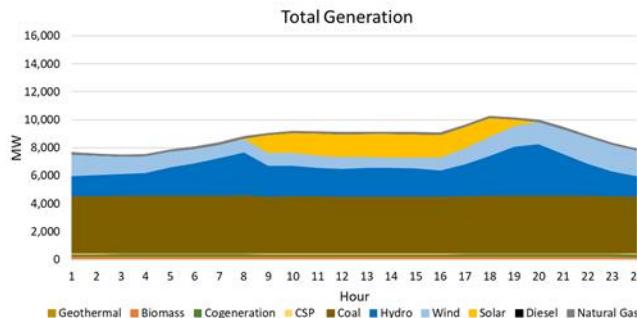
$$R = \text{Demand} + \max\{\bar{G}, R_{VRE}^*\}$$

Example: \bar{G} and R_{VRE}^* in Chile (2030):

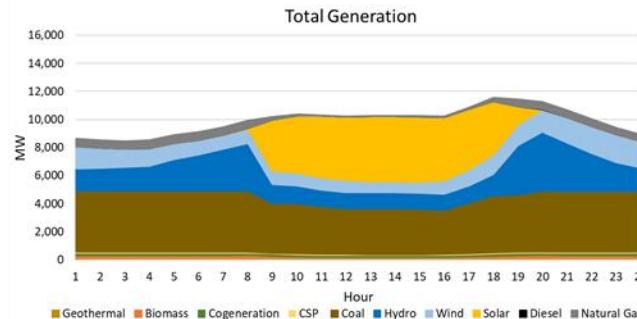


The Expansion Planning of the Chilean System

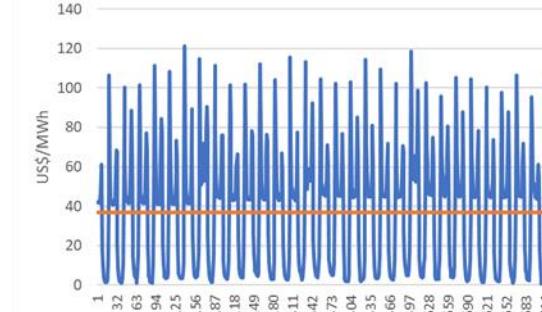
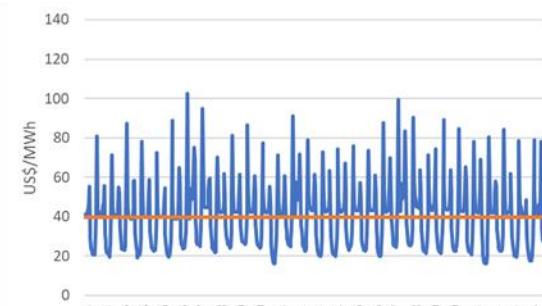
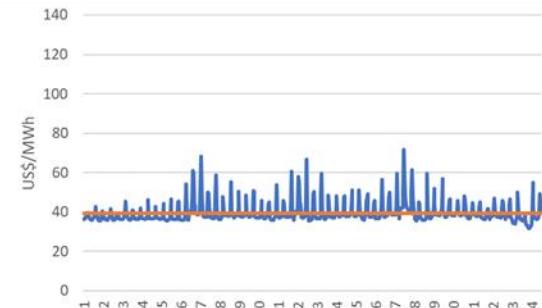
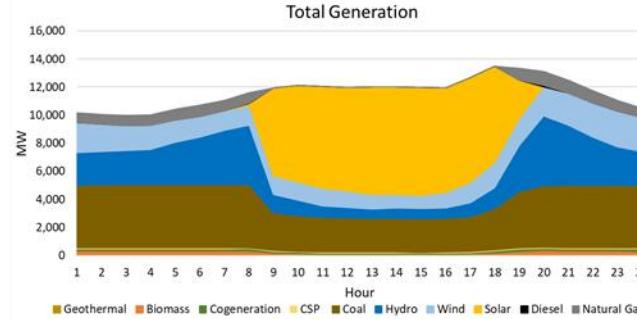
2021



2025



2030

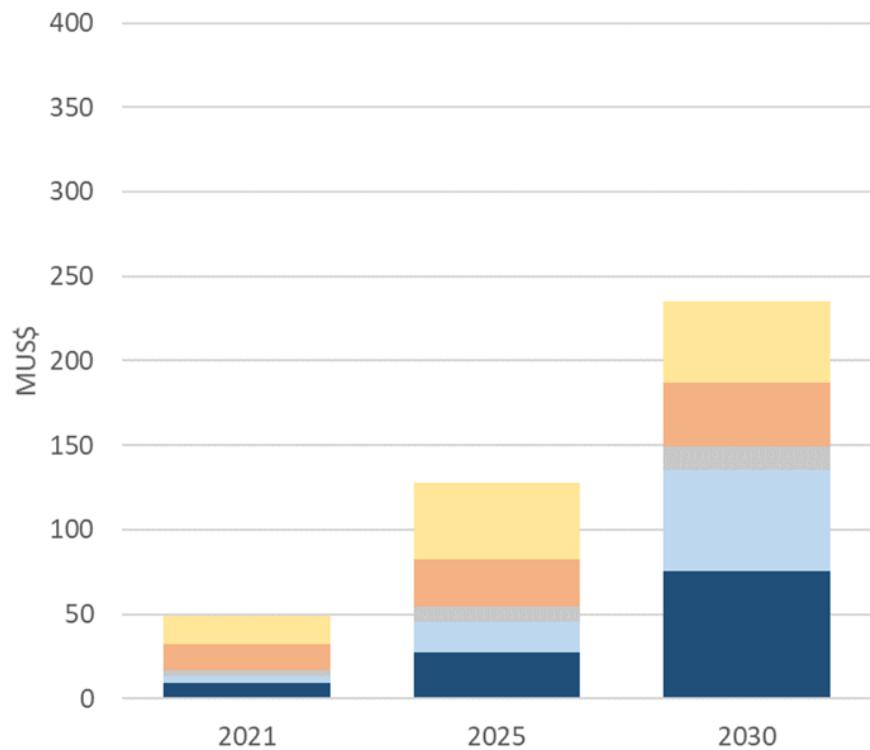


The Expansion Planning of the Chilean System

► A small recap → The high penetration of intermittent renewables lead to new operational challenges, which stand out:

- Over-supply situations;
- Fast upward and downward ramps;
- Increasing thermal cycling;

Example of the Flexibility Cost Calculation:

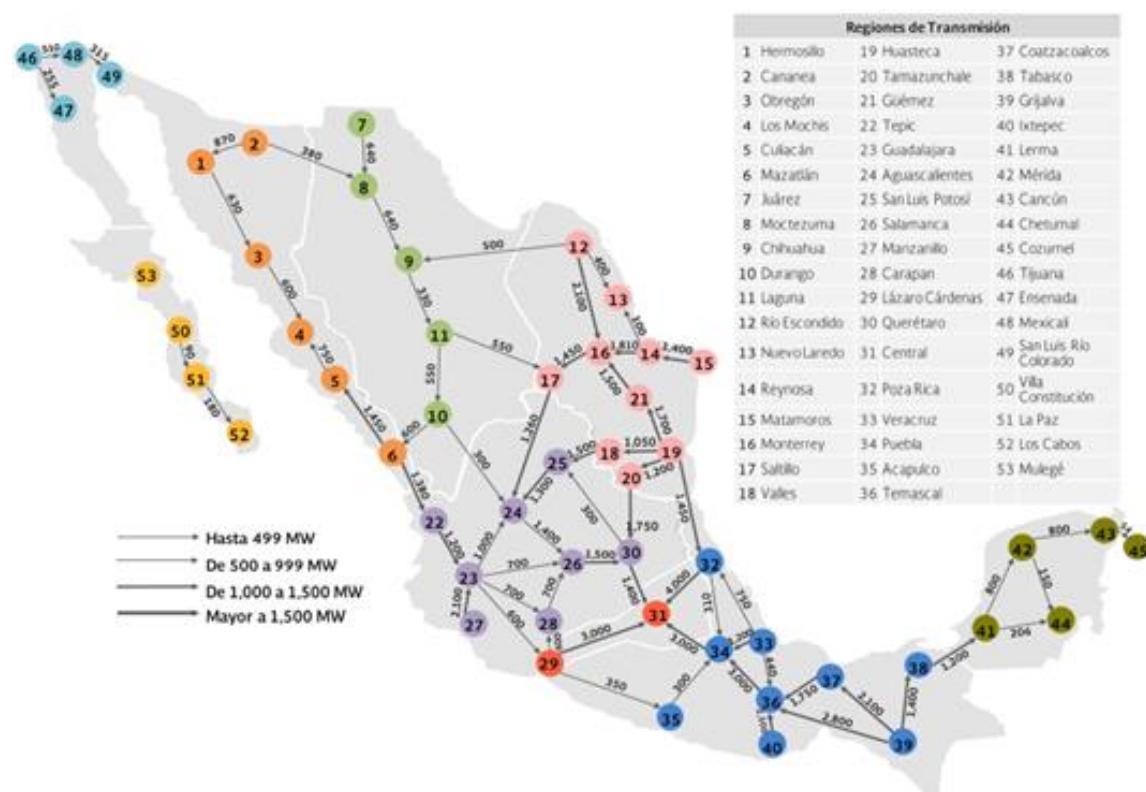


Generation + Interconnections

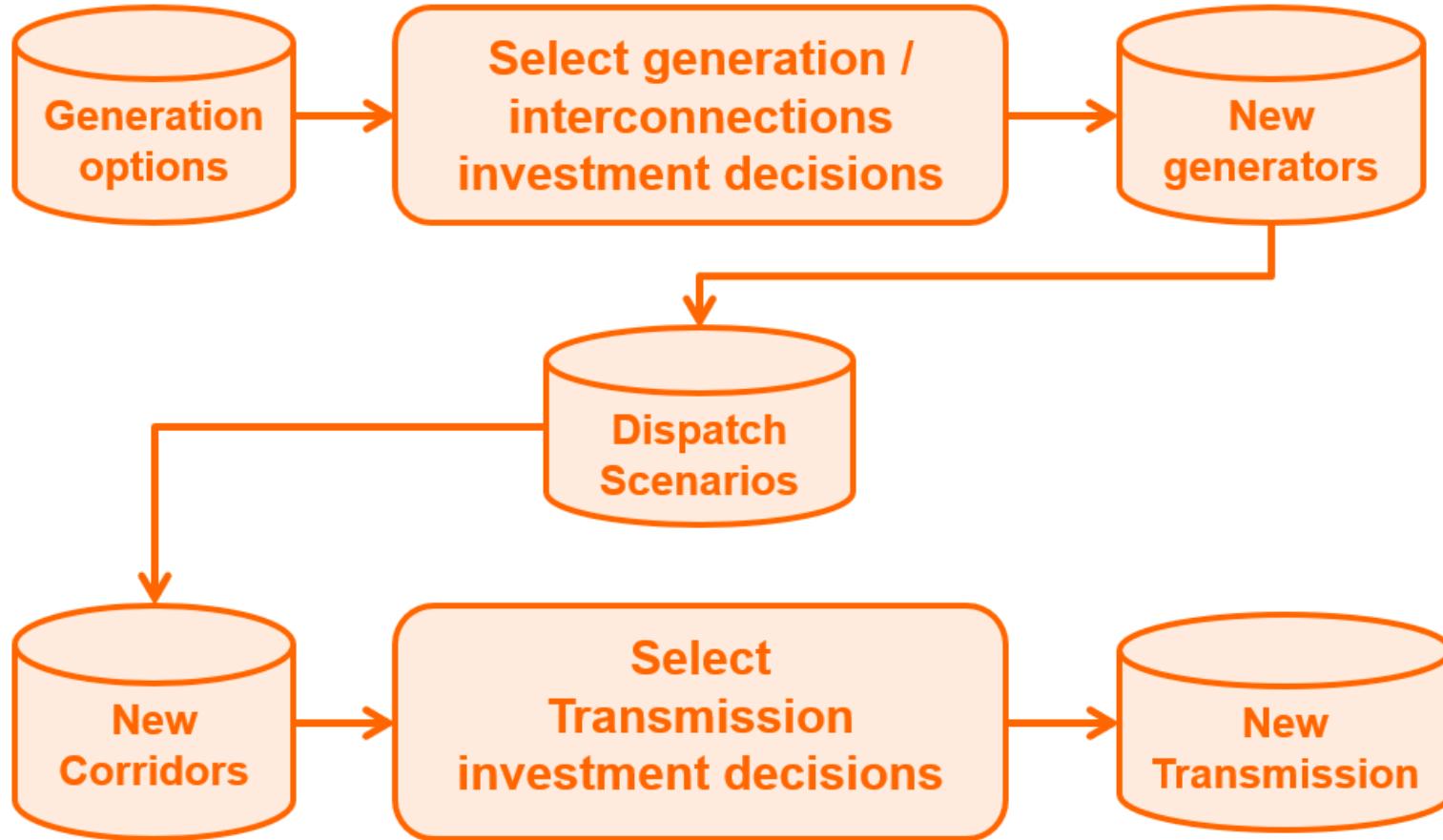
- Hierarchical planning of the transmission network:

Phase 1: Integrated expansion of generation and major transmission links

Phase 2: Detailed Network Expansion (lower voltages)



Hierarchical G→T Planning Overview



Example: Central America



Transmission System

Num. of Buses:	1980
< 69 kV	1291
69 kV	283
115 kV	74
138 kV	151
230 kV	179
400 kV	2

Num of Circuits:	2075
Interconnections	13
Lines	920
Transformers	1142

PSR



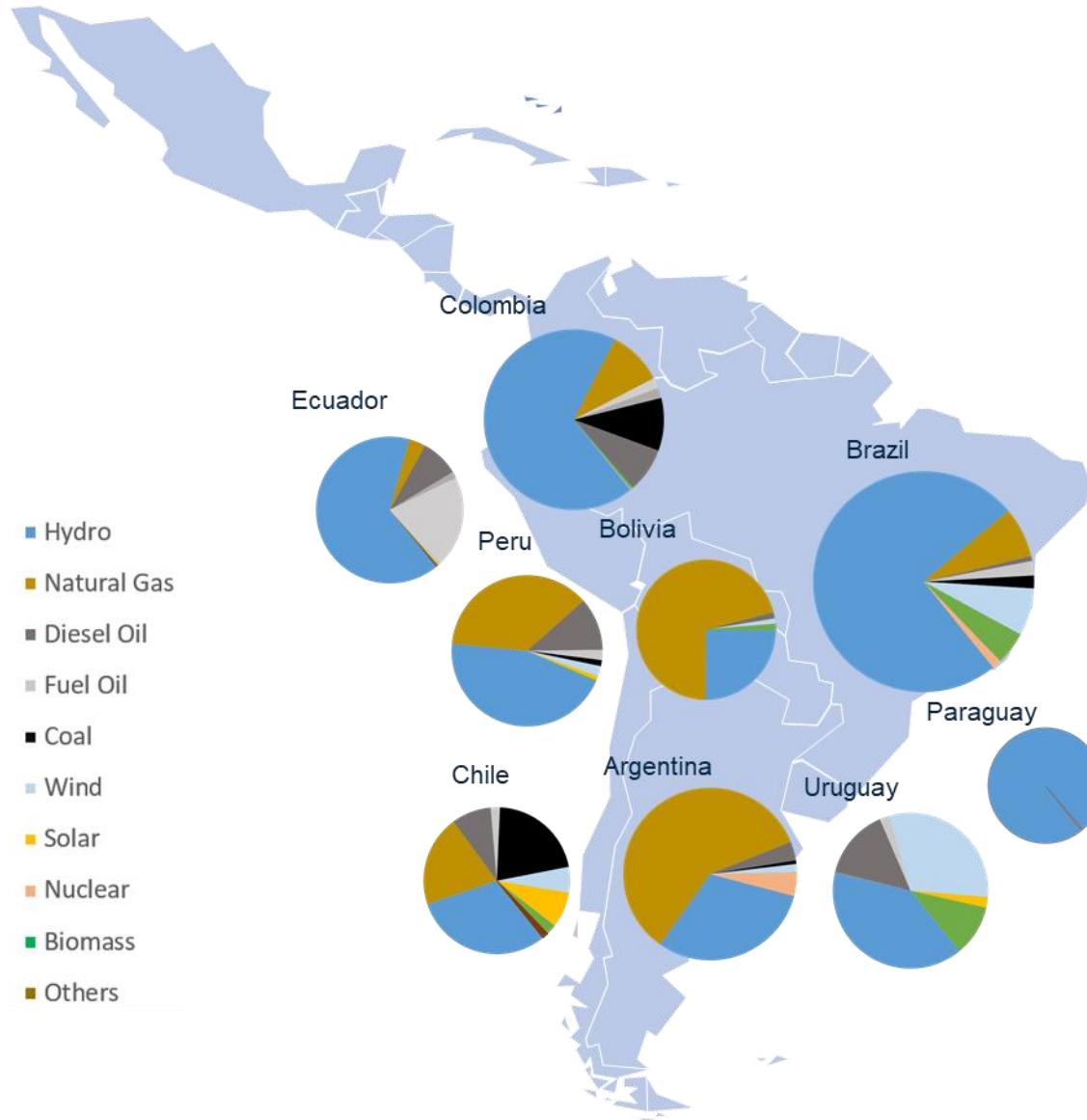
Energy Integration Assessment



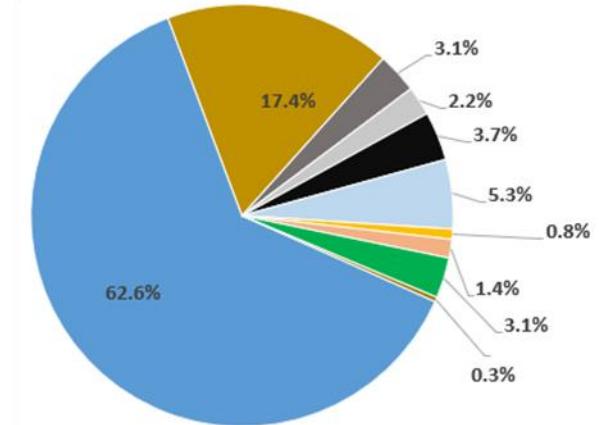
Energy Integration Assessment

- ▶ Study sponsored by the IADB ➔ evaluate the benefits of interconnecting 9 South America countries (Argentina, Bolivia, Ecuador, Peru, Brazil, Uruguay, Paraguay, Chile and Colombia)
- ▶ Detailed representation of each system:
 - Existing System
 - Demand/Fuel prices forecast
 - List of Candidates (Thermal, Hydro, Solar and Wind)
 - G&T expansion planning until 2036
- ▶ Hourly operating simulations of the interconnected regions
- ▶ Benefit evaluation metrics:
 - Reduction of operating costs
 - Reduction of CO2 emissions
 - Increase in firm capacity
 - Reduction of secondary reserve requirements
- ▶ Benefit-cost ratio calculation

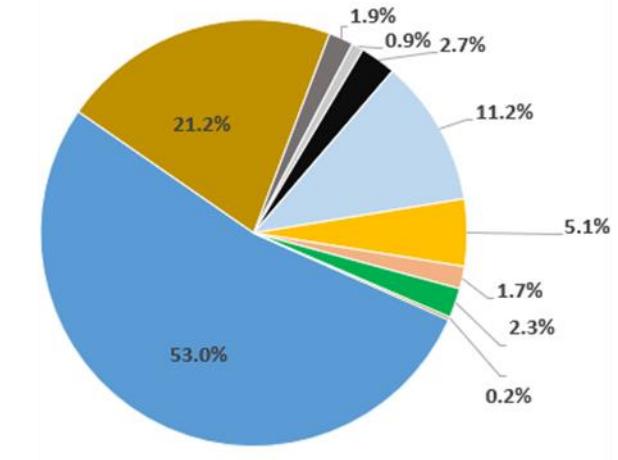
Installed Capacity – South America



2016



2036



Results

- Benefit of adding 800 MW in the Peru-Chile Interconnection:

Metric	Unit	Horizon	Without Interconnection	With Interconnection	Benefit
Operating Cost	MUS\$	2017-2036	86,559.00	86,163.00	396
CO ₂ emissions	Mton	2017-2036	2,771.00	2,714.00	57
Firm Capacity	MWavg	2036	93,307.00	93,451.00	144
Secondary Reserve	MW	2036	10,932.73	9,495.17	15%



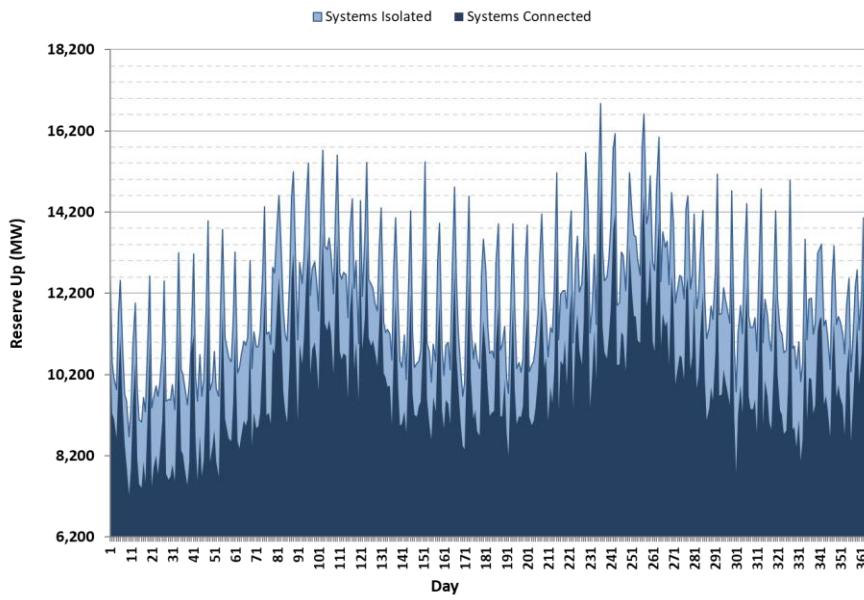
Investment Cost = 92 MUS\$

$$\text{Benefit-cost ratio} = \frac{396 \text{ MUS\$}}{92 \text{ MUS\$}} = 4.3$$

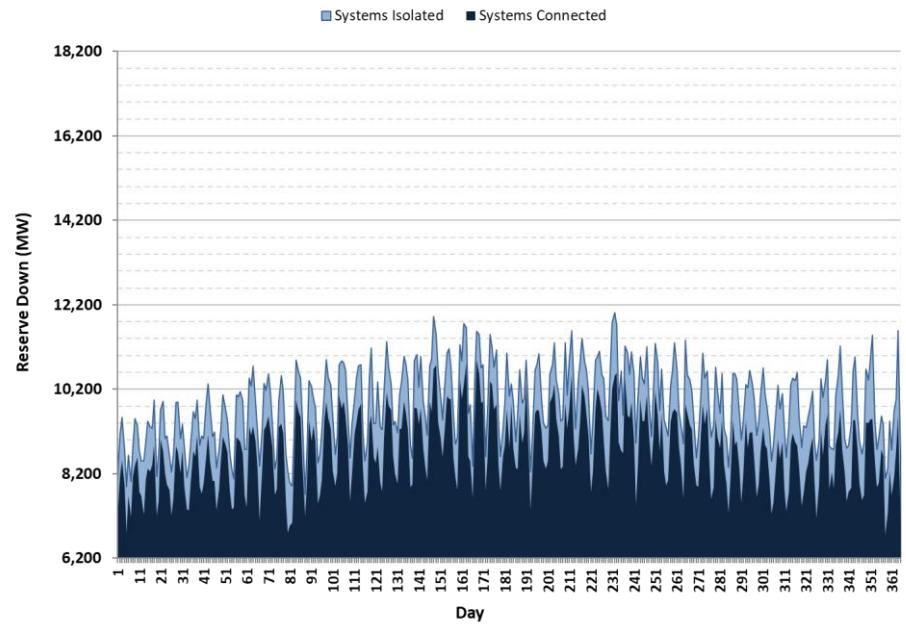
Results

- ▶ Reduction of secondary reserve requirements:

Upwards:

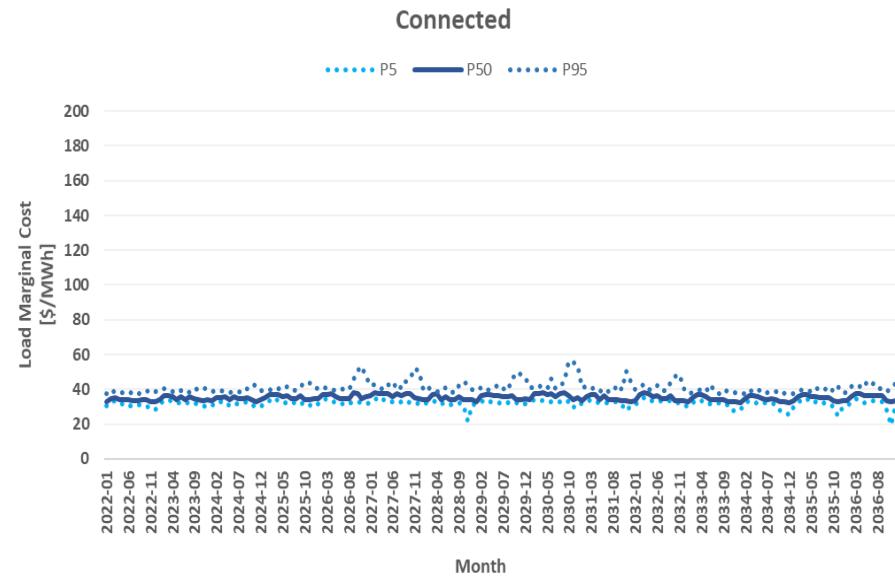
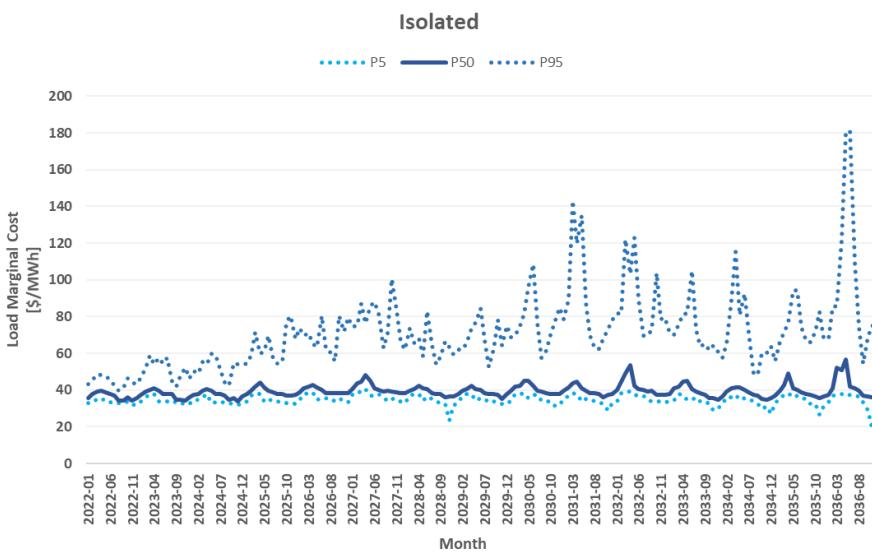


Downwards:



Other Results

- ▶ Another result that deserves attention is the dispersion of the load marginal costs:





Follow us!

The screenshot shows the homepage of the PSR website (www.psr-inc.com/pt/). The main content area features a banner for the XIV International Conference on Stochastic Programming (ICSP 2016) held in Búzios, Brazil, from June 25 to July 1, 2016. Below the banner, there are four sections: MODELAGEM DE SISTEMAS ENERGÉTICOS, FERRAMENTAS DE SUPORTE FINANCEIRO, ANÁLISE DE MERCADOS DE ENERGIA, and RECURSOS HÍDRICOS E MEIO AMBIENTE. Each section includes a small image and a brief description. At the bottom, there are news items and event details. A large red arrow points from the top center towards the right sidebar, which is titled 'PRODUÇÃO CIENTÍFICA'. The sidebar lists years from 2016 down to 2000, with 'Artigos e papers' and 'Teses e dissertações' sections for each year.

PRODUÇÃO CIENTÍFICA

Apresentações ►

Artigos e papers ▾

2016

2015

2014

2013

2012

2011

2010

2009

2008

2007

2006

2005

2004

2003

2002

2001

2000

Teses e dissertações ►

NOTÍCIAS

Energy Report de Julho está disponível

PSR participa da XIV Conferência Internacional sobre Programação ...

Energy Report de Junho está disponível

PSR participa do Conselho Empresarial de Energia Elétrica do Sistema ...

Publicação 04.08.2016

Evento 11.07.2016

Publicação 06.07.2016

Evento 05.07.2016

MODELAGEM DE SISTEMAS ENERGÉTICOS

Esta suite de ferramentas é adaptada para a representação sob ...

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QUESTIONS?





Obrigado!!

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