PSR

GENERATION EXPANSION PLANNING

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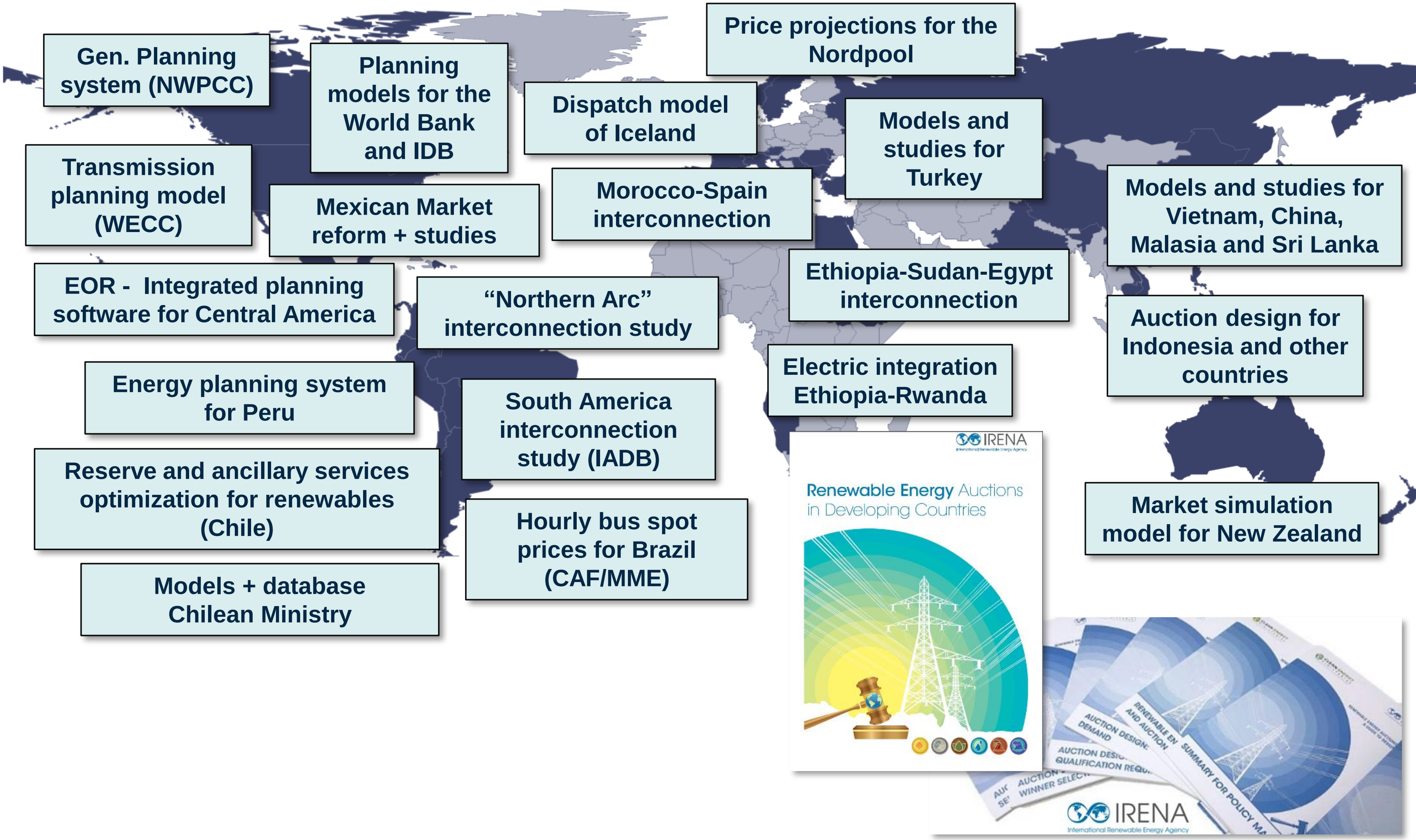
PSR

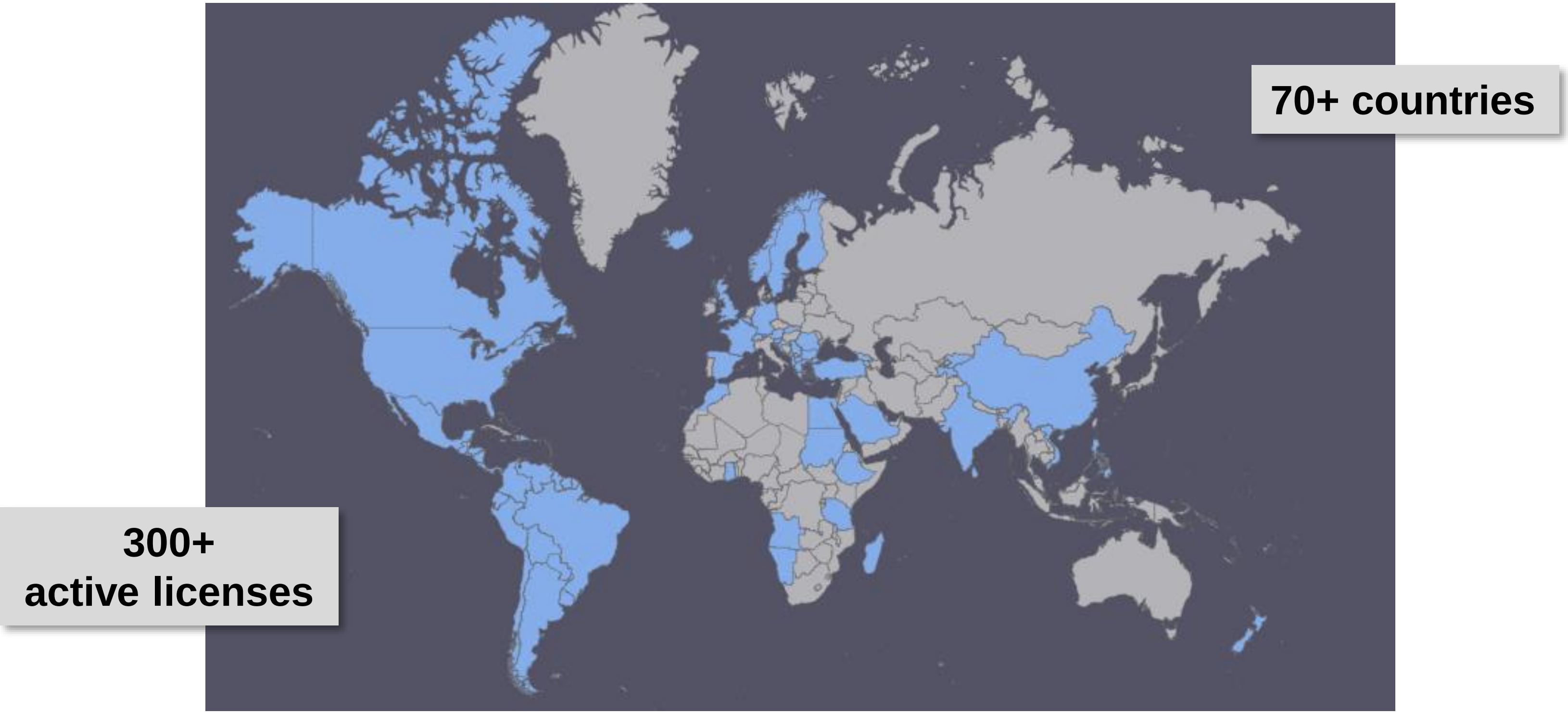
Provider of analytical solutions and consulting services (economic, regulatory, financial and technological) in electricity and gas since 1987

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



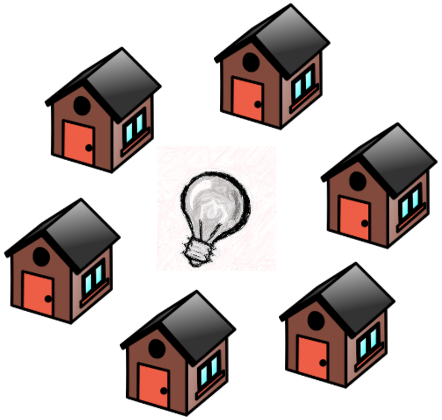
Application of analytical tools



- **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

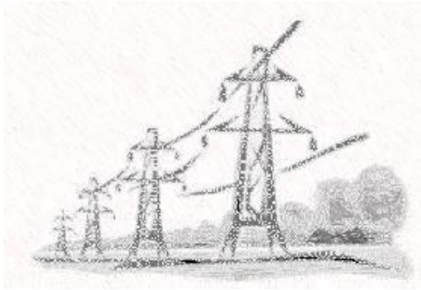
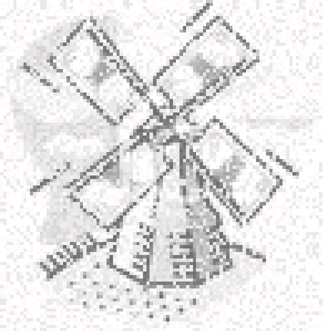
Electrical system expansion

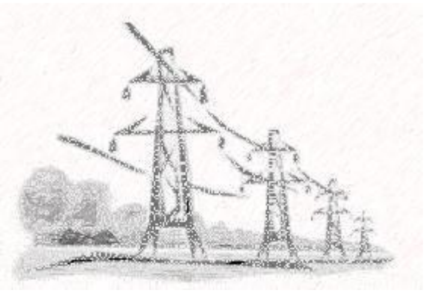
- The origin of the expansion problem of electrical systems resides on the need for new investments in generation and transmission systems required to face the demand growth and meet planning criteria



Electrical system expansion

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




Electrical system expansion

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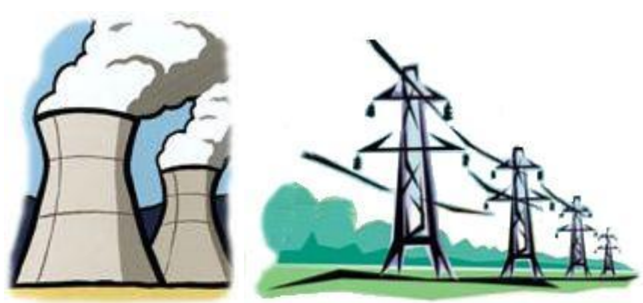
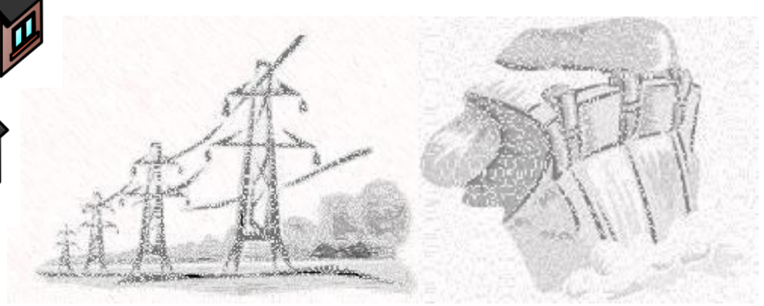




Electrical system expansion

- 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

PSR Cloud

ePSR: Information management environment

HERA
Inventory of hydro basins and other renewable resources

OptGen/OptFolio
Integrated generation / interconnection / reserve expansion + financial analysis

NetPlan
Detailed probabilistic transmission and VAr planning

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

SDDP/NCP/CORAL
Probabilistic hourly simulation of system operation and composite G&T reliability

OptFlow
Optimal Power Flow linearized active power w/ losses and full AC model

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

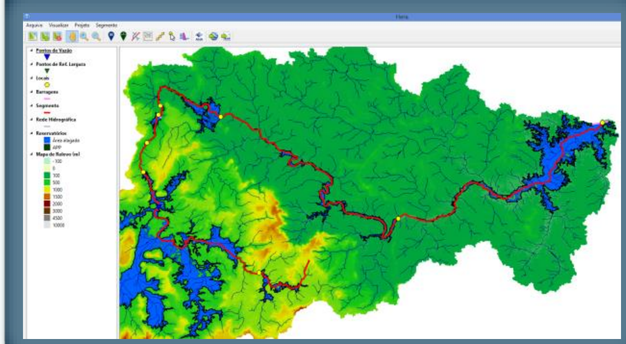
Layout selection

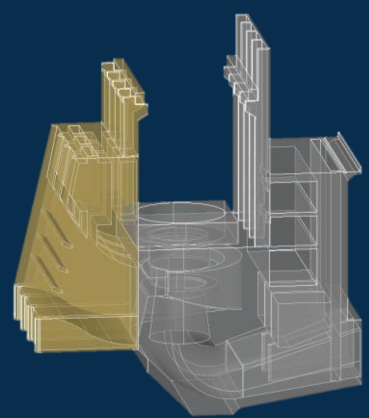
- Project design
- Budget estimate

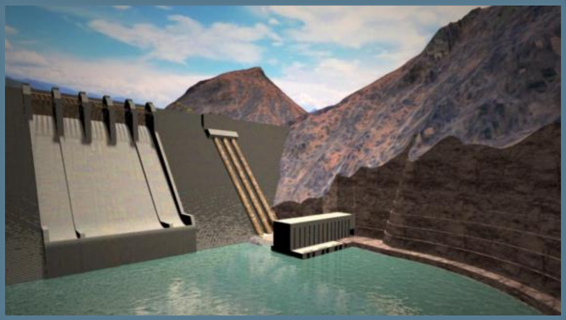
H3. Optimization

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

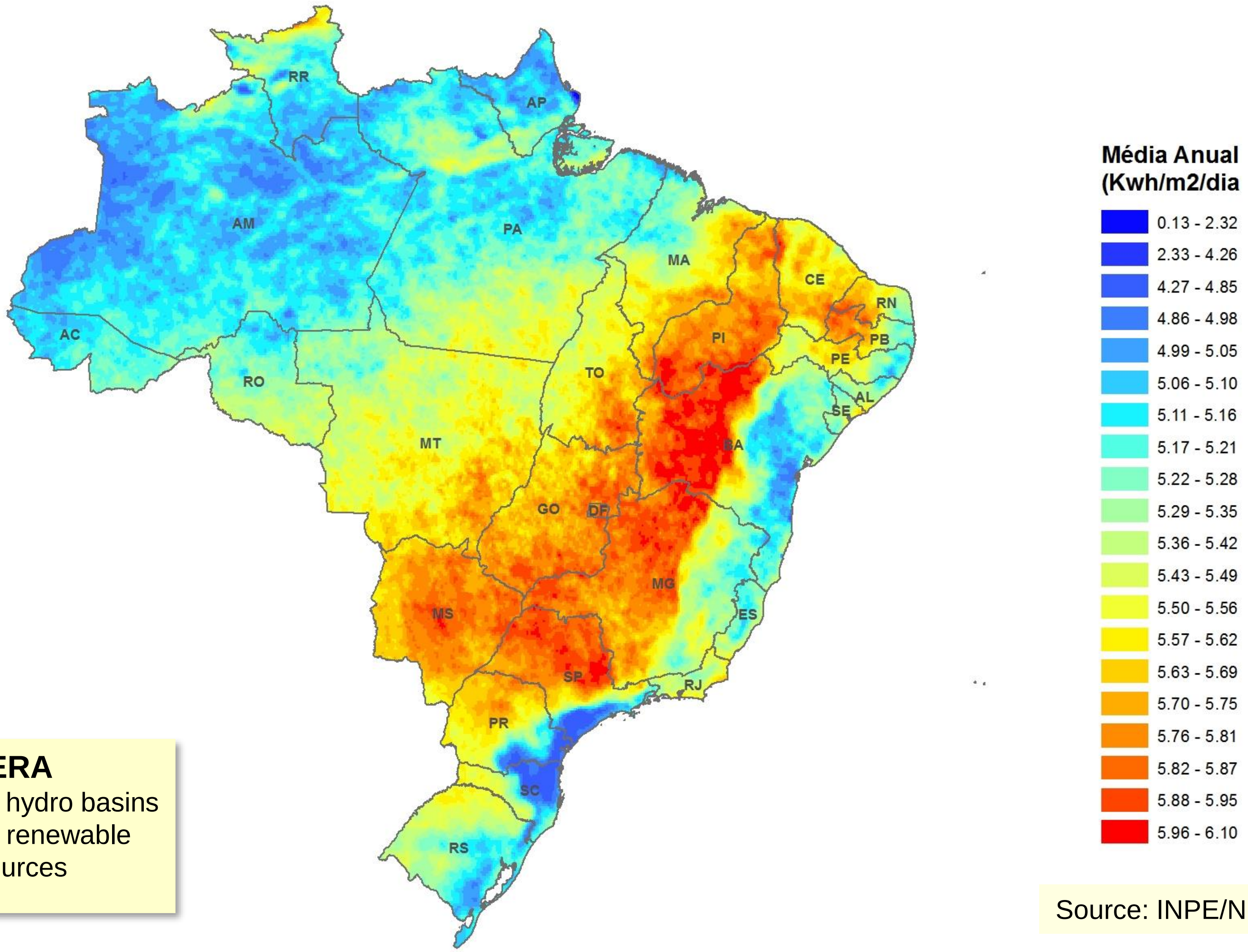
Results







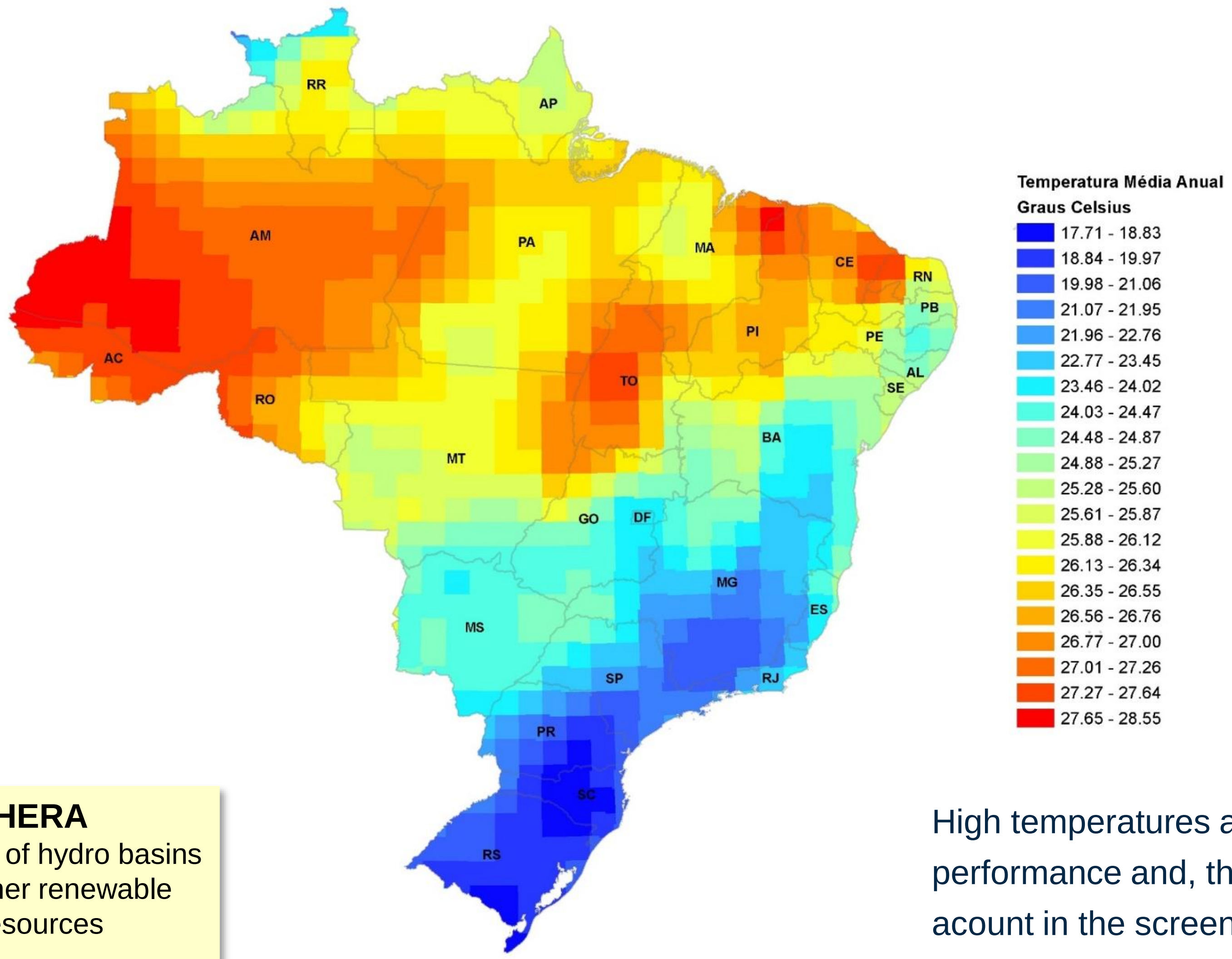
HERA Solar: average annual irradiation (kWh/m^2/day)



Source: INPE/NREL

HERA
Inventory of hydro basins and other renewable resources

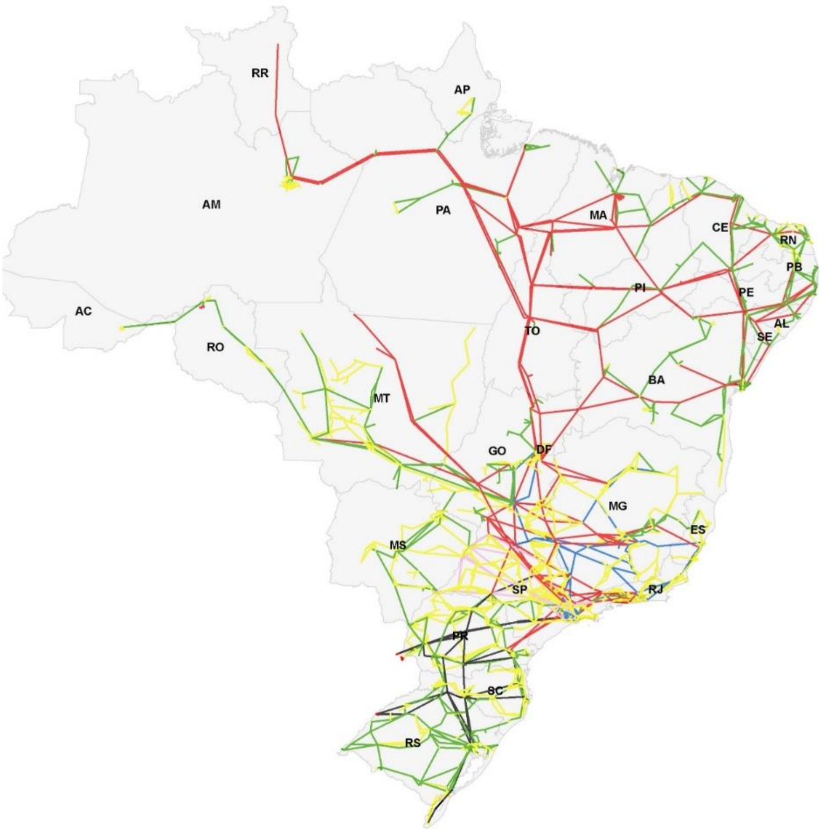
HERA Solar: Average temperature

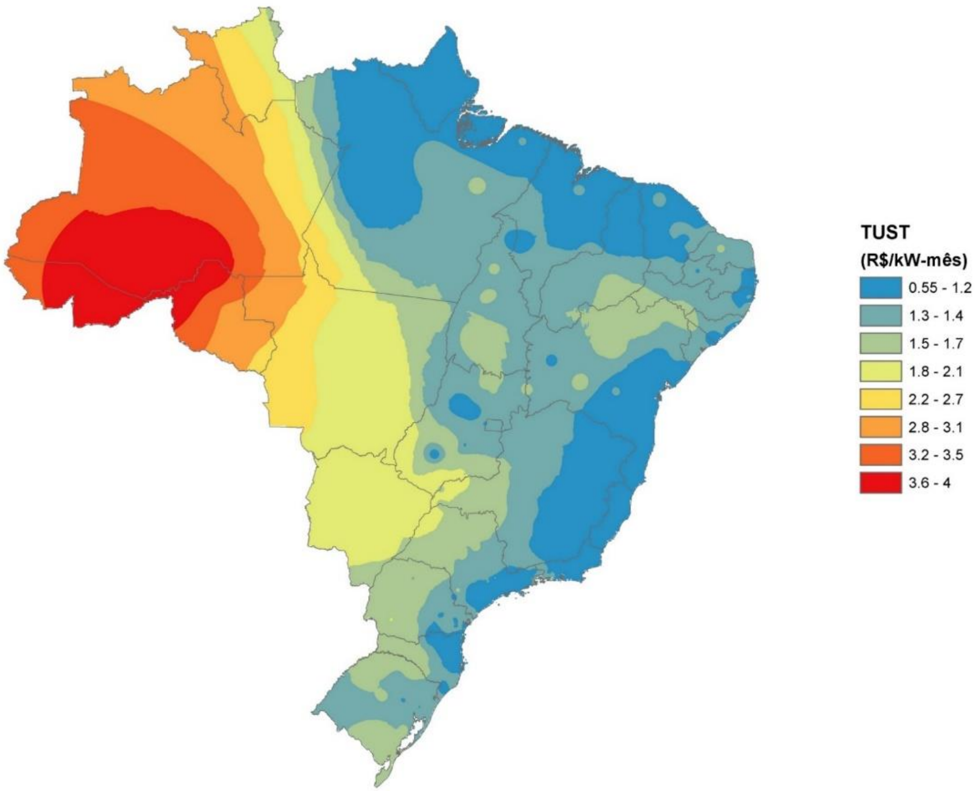


HERA
Inventory of hydro basins and other renewable resources

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

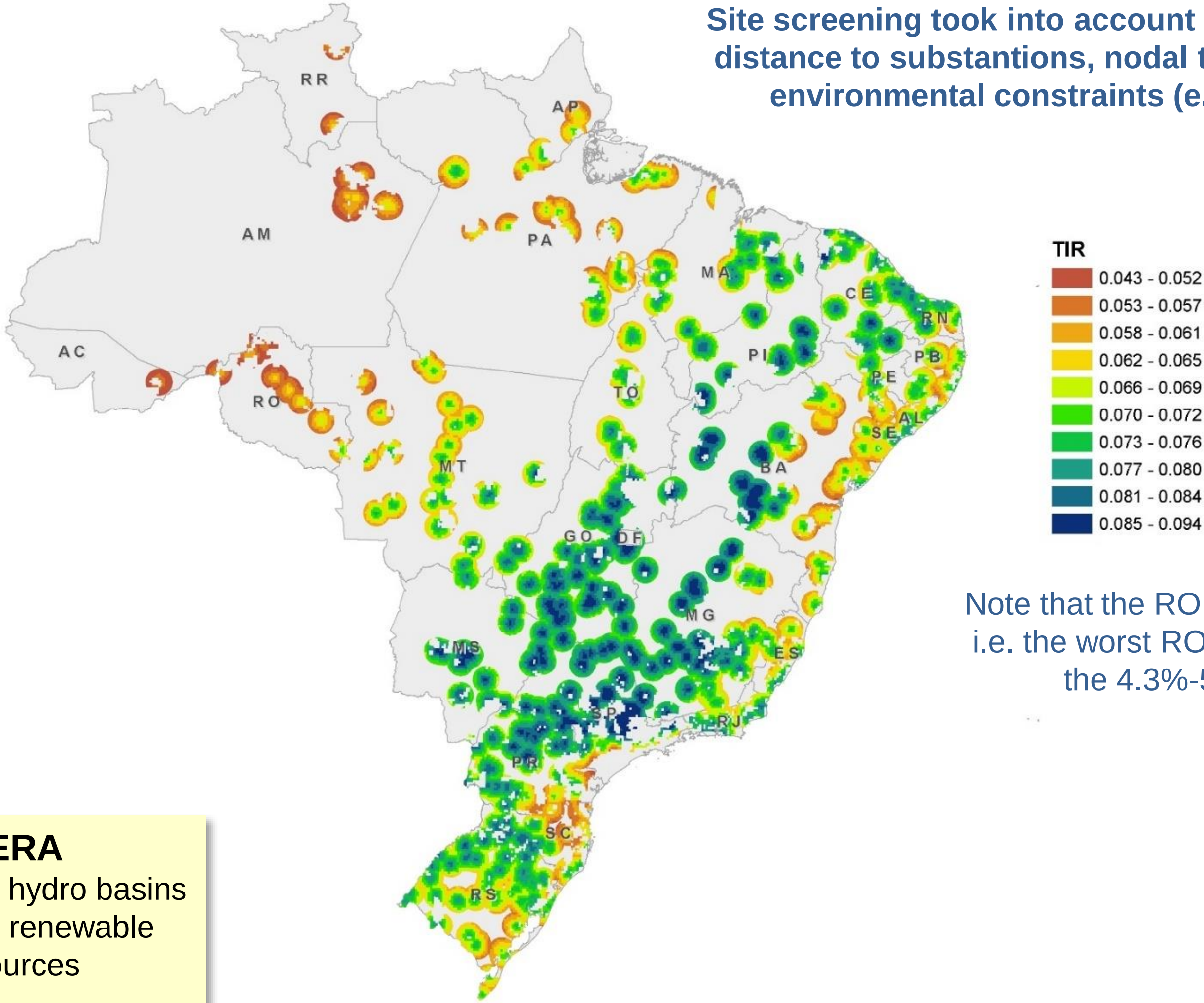
Transmission grid and nodal tariffs (TUST)





HERA
Inventory of hydro basins and other renewable resources

HERA Solar: project ROI for the candidate sites



Site screening took into account insolation, temperature, distance to substantions, nodal transmission tariffs and environmental constraints (e.g. protected zones)

Note that the ROI values are in p.u. i.e. the worst ROI above (red) is in the 4.3%-5.2% range

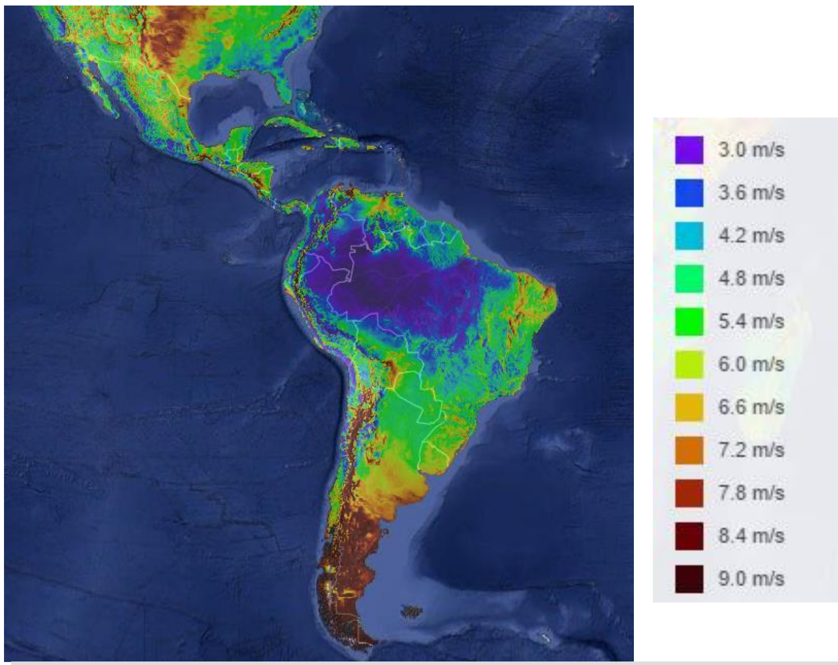
HERA
Inventory of hydro basins and other renewable resources

Global wind data bases

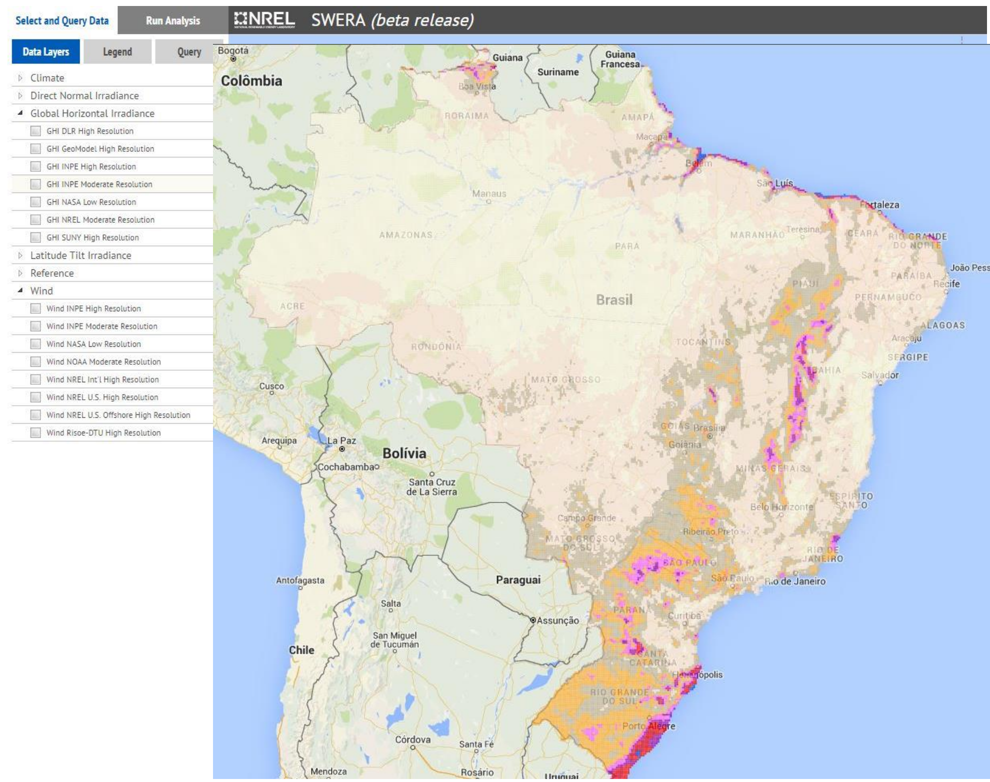
HERA
Inventory of hydro basins and other renewable resources

IRENA
International Renewable Energy Agency

Global Atlas
FOR RENEWABLE ENERGY



SANDER PARTNER REN21 JRC EUROPEAN COMMISSION National Research Council of Italy NOVELTIS ESMAP NREL GeoModel SOLAR



HERA Wind: main components

HERA
Inventory of hydro basins and other renewable resources

Data

- Global DBs
- +30 years hourly
  With reanalysis

Screening

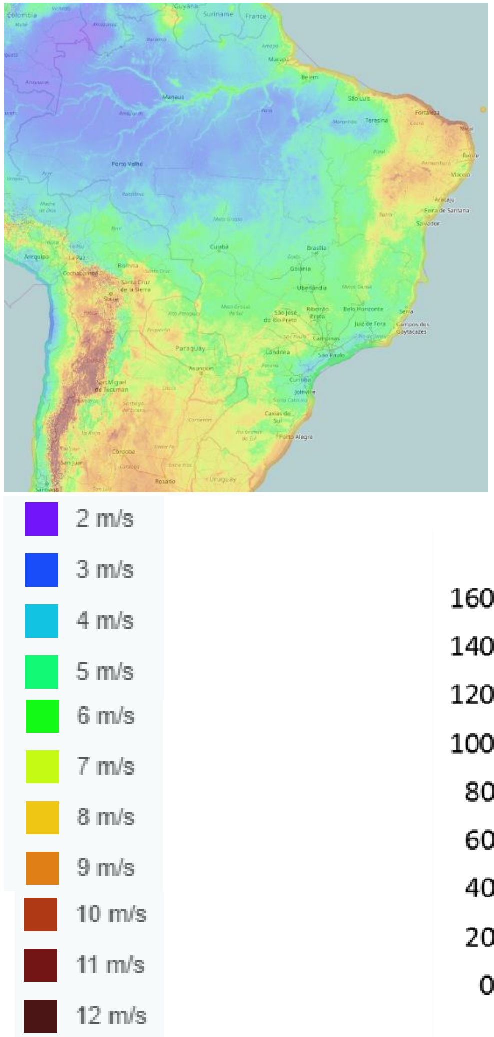
- Siting
- Economic potential

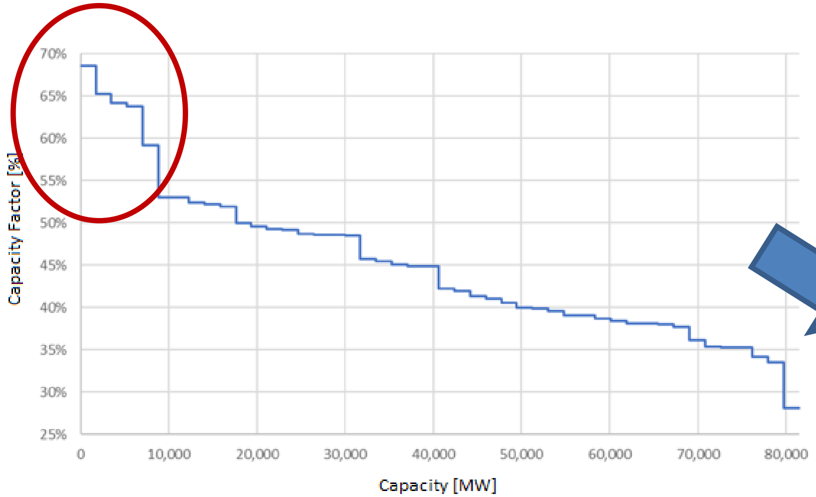
Energy production

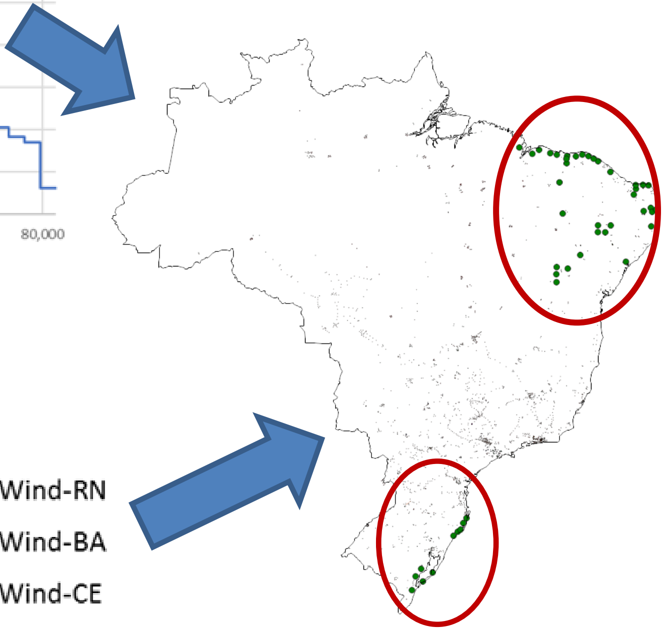
- Generator parameters
- Wind park design

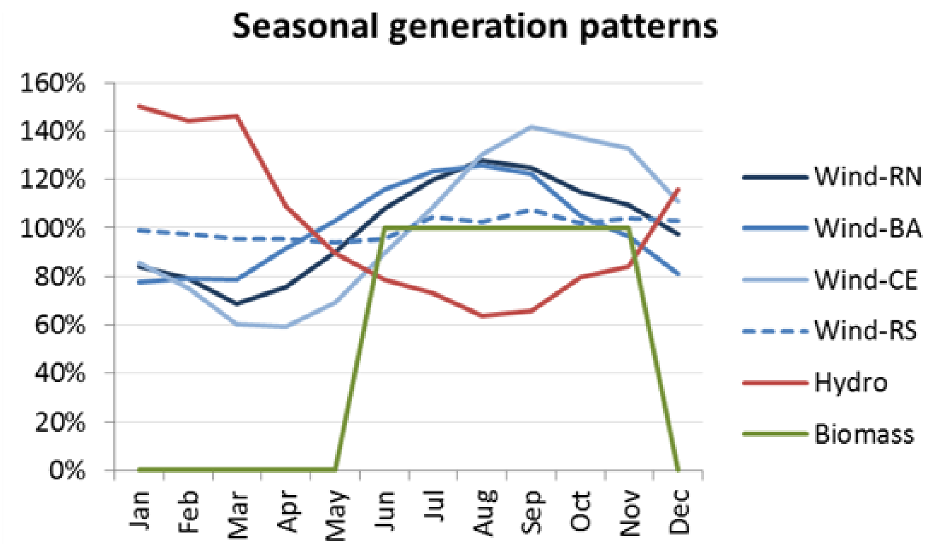
HERA Wind: main components

HERA
Inventory of hydro basins and other renewable resources







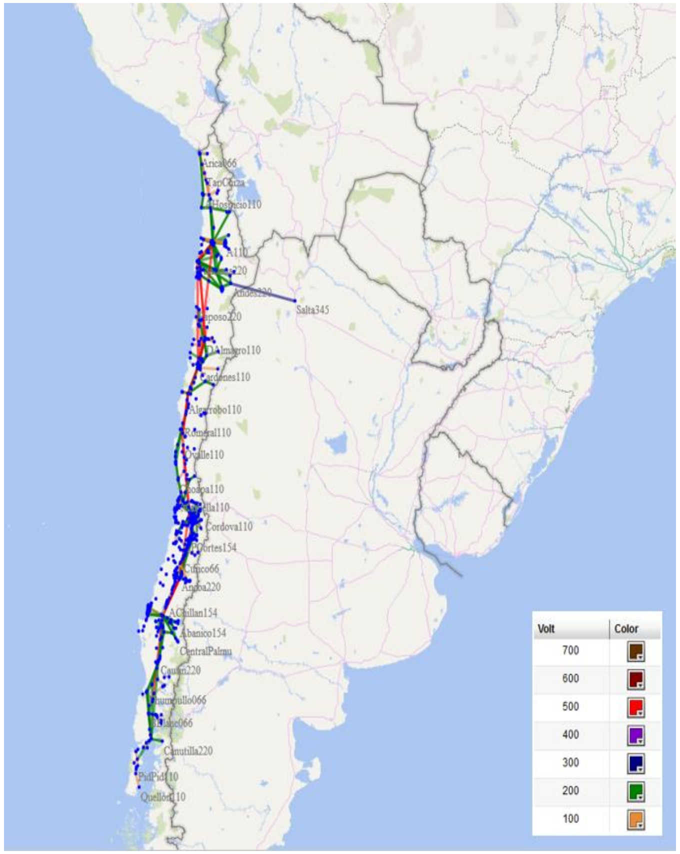


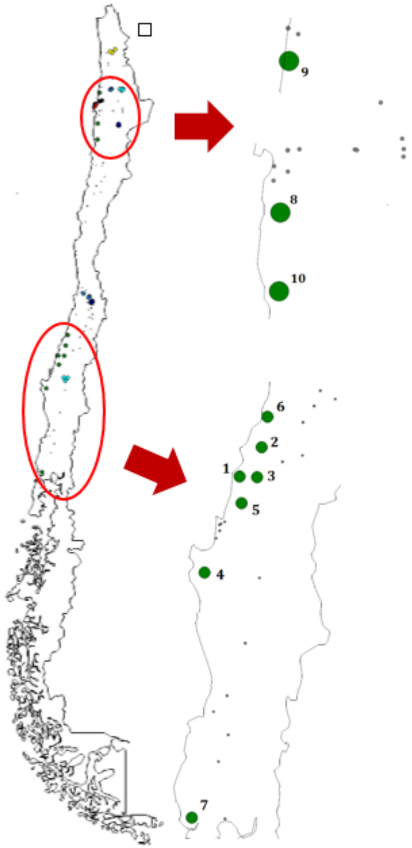
Candidate ranking

HERA
Inventory of hydro basins and other renewable resources

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

Example: Chile



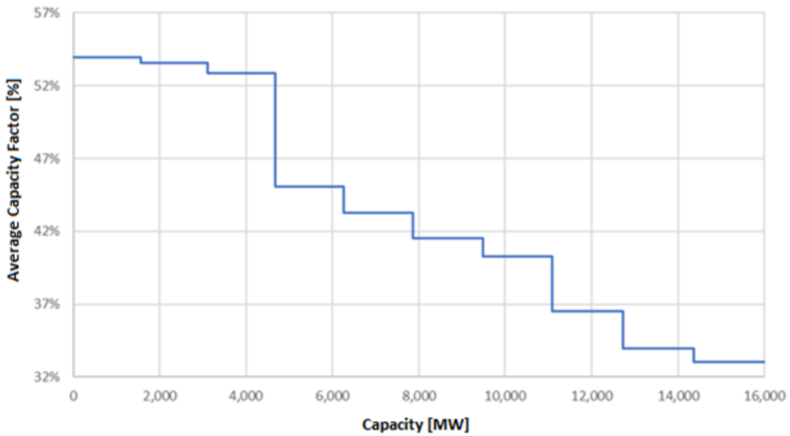


Spot	Average capacity factor
1	53.97%
2	53.57%
3	52.84%
4	45.09%
5	43.24%
6	41.51%
7	40.30%
8	36.54%
9	33.96%
10	33.01%

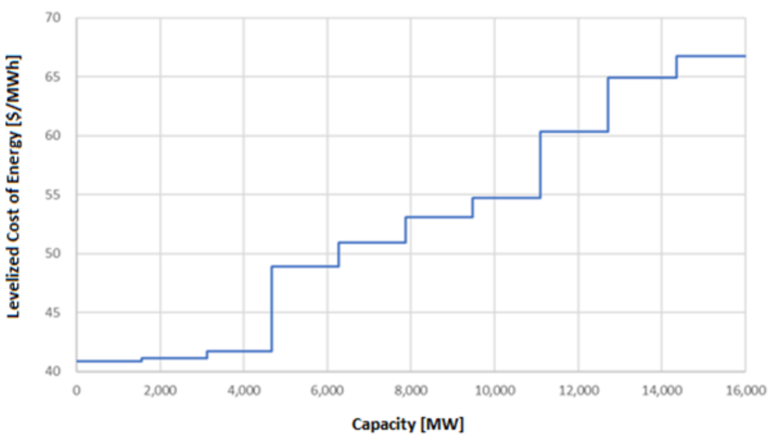
Candidate ranking

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.

Finantial Assumptions
- CAPEX
- OPEX
- Financial and tributary aspects

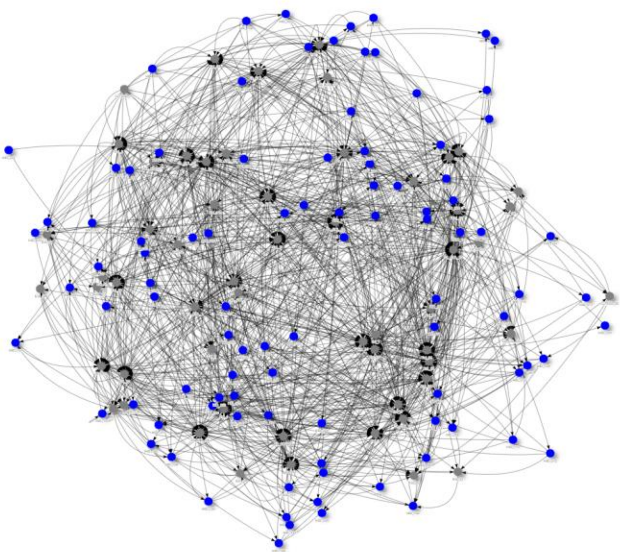
Expansion Costs
- Combination of capacity factors and financial assumptions for pre-feasibility verification to filter projects
- Optimize system expansion based on the selected candidates

Multistage stochastic capacity expansion planning
Generation, transmission and probabilistic generation reserve

TSL: Scenario generation

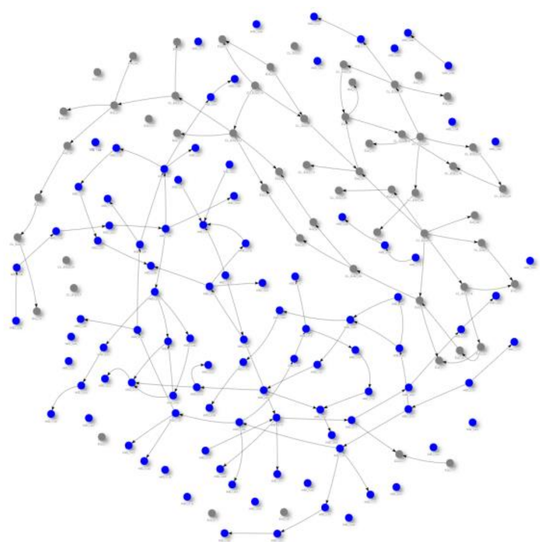
Time Series Lab
Multiscale stochastic scenarios (inflow, renewable, demand)

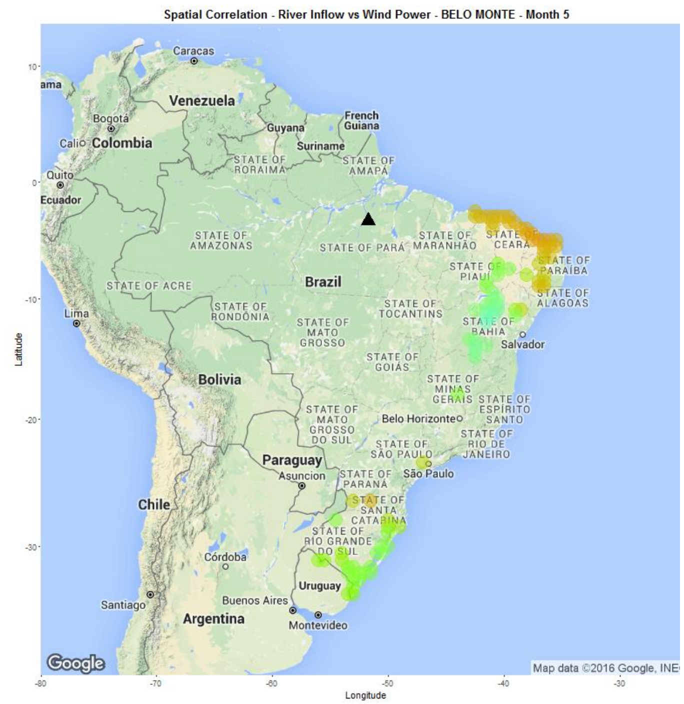
- Time Series Lab (TSL) produces renewable energy scenarios conditioned to the inflows, preserving spatial and temporal correlations.



Traditional methodology

Bayesian network





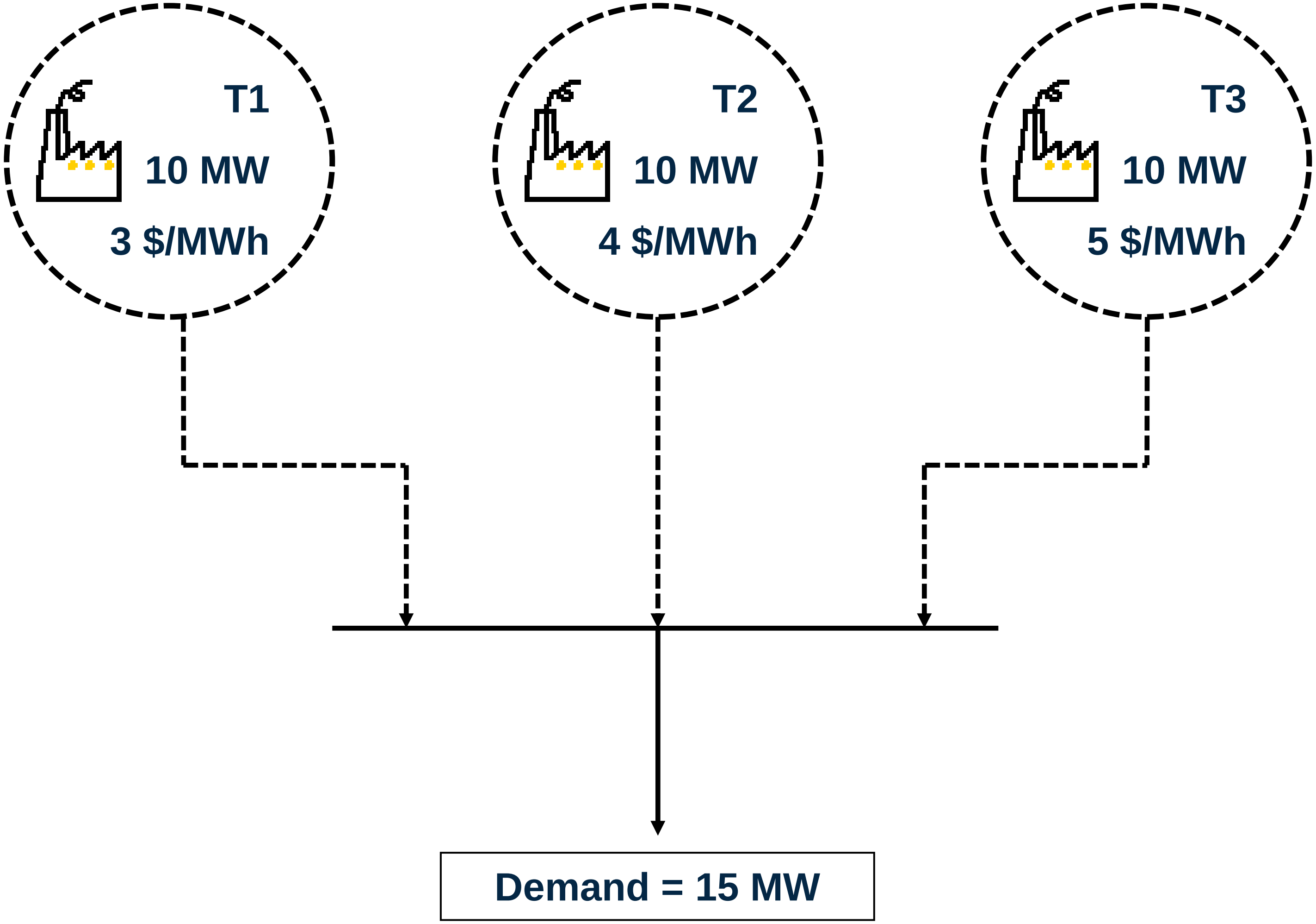
Wind & Inflows

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

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

s.t.

$$g_1 + g_2 + g_3 + def = D$$

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

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

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

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

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

Example of expansion planning problem

$$\text{Min} \quad \underbrace{I_1 g^1_{max} + I_2 g^2_{max} + I_3 g^3_{max}}_{\textbf{Investment cost}} + \underbrace{c_1 g_1 + c_2 g_2 + c_3 g_3 + c_{def}\, def}_{\textbf{Operation cost}}$$

s.t.

$$g_1 + g_2 + g_3 + def = D$$

$$\left.\begin{aligned} g_1 - g^1_{max} &\leq 0 \\ g_2 - g^2_{max} &\leq 0 \\ g_3 - g^3_{max} &\leq 0 \end{aligned}\right\} \textbf{Operative limits}$$

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

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

    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

$$\text{Min} \quad \underbrace{10\, g^1_{max} + 10\, g^2_{max} + 10\, g^3_{max}}_{\textbf{Investment cost}} + \underbrace{3\, g_1 + 4\, g_2 + 5\, g_3 + 50\, def}_{\textbf{Operation cost}}$$

s.t.

$$g_1 + g_2 + g_3 + def = 15$$

$$\left.\begin{aligned} g_1 - g^1_{max} &\leq 0 \\ g_2 - g^2_{max} &\leq 0 \\ g_3 - g^3_{max} &\leq 0 \end{aligned}\right\} \textbf{Operative limits}$$

Generators maximum capacity : 10 MW

Enumerating solutions

- Investment cost

$I(0) = 10 \,.\, 0 + 10 \,.\, 0 + 10 \,.\, 0$

- Operation cost

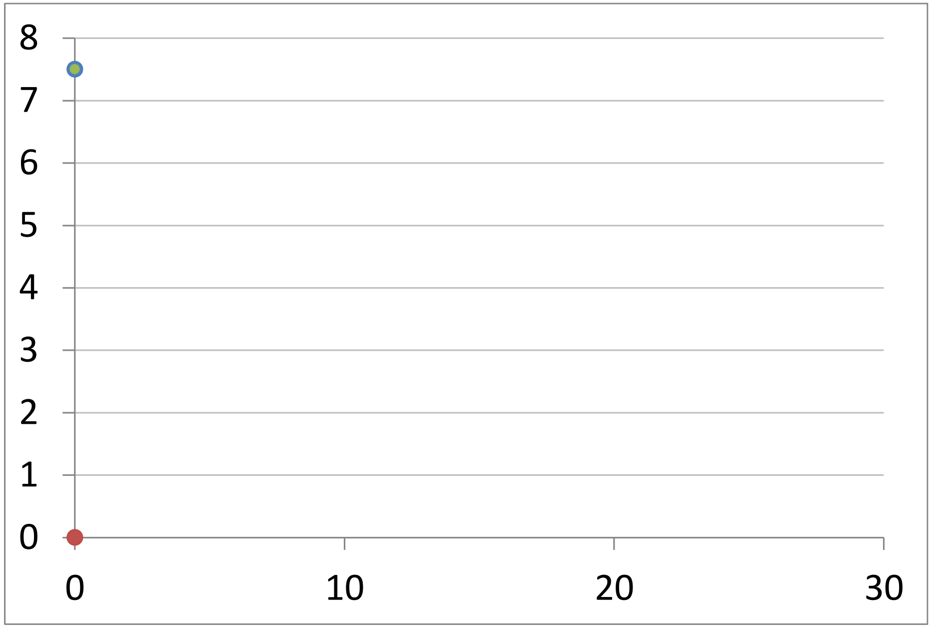
$O(0) = \text{Min } 3\, g_1 + 4\, g_2 + 5\, g_3 + 50\, def$

s/t $\quad g_1 + g_2 + g_3 + def = 15$

$g_1 \leq 0$

$g_2 \leq 0$

$g_3 \leq 0$



I(0) = 0 k$			
O(0) = 750 k$			
750 k$			

Enumerating solutions

Investment cost

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

Operation cost

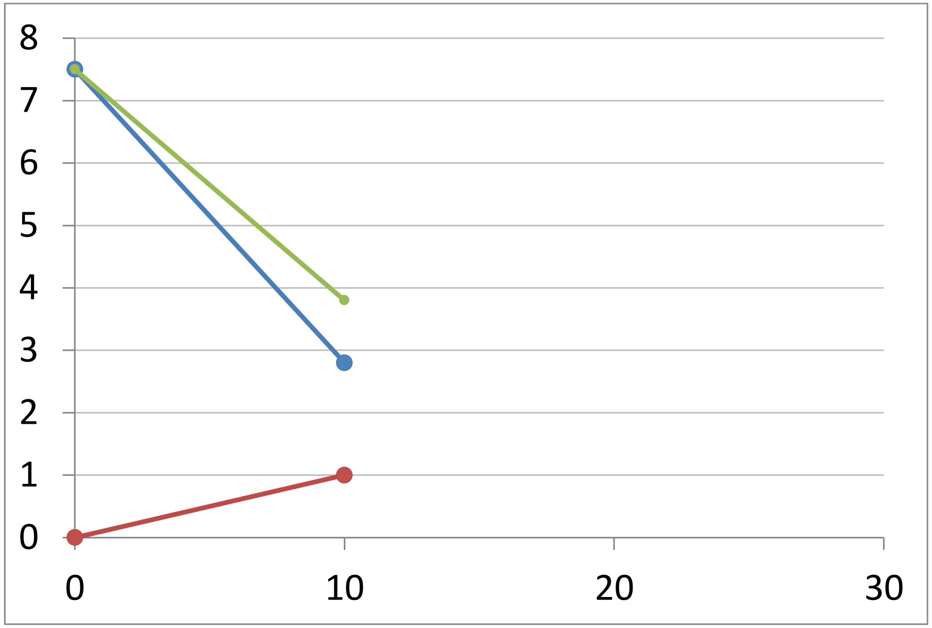
$$O(10) = \text{Min } 3\,g_1 + 4\,g_2 + 5\,g_3 + 50\,def$$

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

$$g_1 \le 10$$

$$g_2 \le 0$$

$$g_3 \le 0$$



I(0) = 0 k\$	I(10) = 100 k\$
O(0) = 750 k\$	O(10) = 280 k\$
750 k\$	**380 k\$**

Enumerating solutions

▶ Investment cost

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

▶ Operation cost

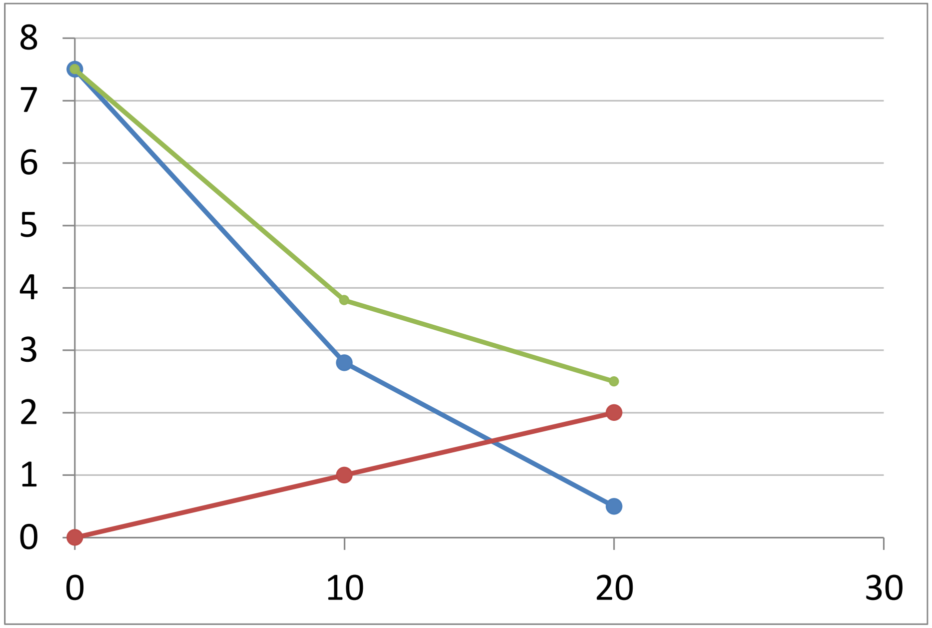
$$O(20) = \text{Min } 3\, g_1 + 4\, g_2 + 5\, g_3 + 50\, def$$

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

$$g_1 \leq 10$$

$$g_2 \leq 10$$

$$g_3 \leq 0$$



I(0) = 0 k$	I(10) = 100 k$	I(20) = 200 k$
O(0) = 750 k$	O(10) = 280 k$	O(20) = 50 k$
750 k$	380 k$	250 k$

Enumerating solutions

▶ Investment cost

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

▶ Operation cost

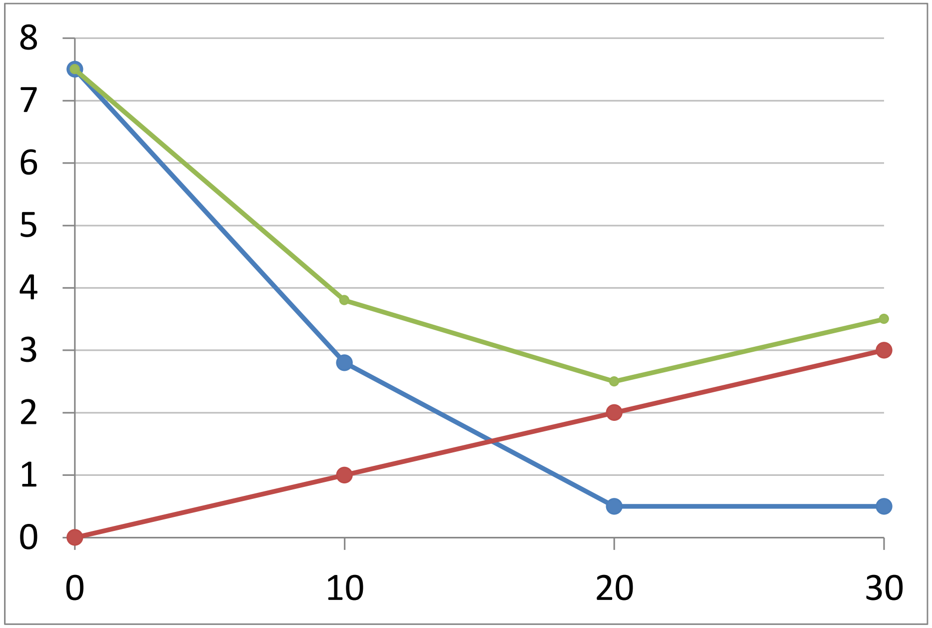
$O(30) = \text{Min } 3\, g_1 + 4\, g_2 + 5\, g_3 + 50\, def$

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

$$g_1 \leq 10$$

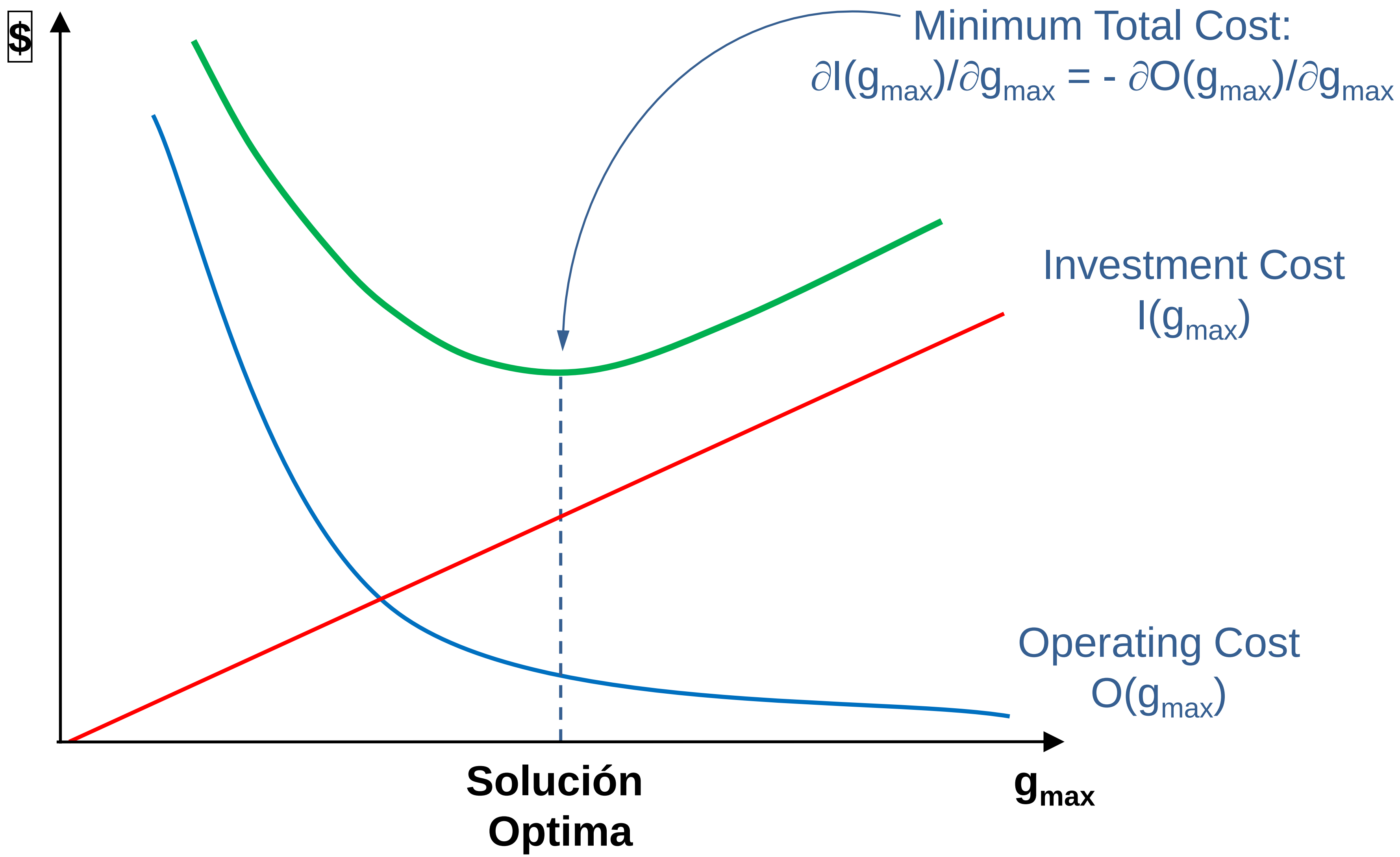
$$g_2 \leq 10$$

$$g_3 \leq 10$$



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

The GEP Task – Solution method



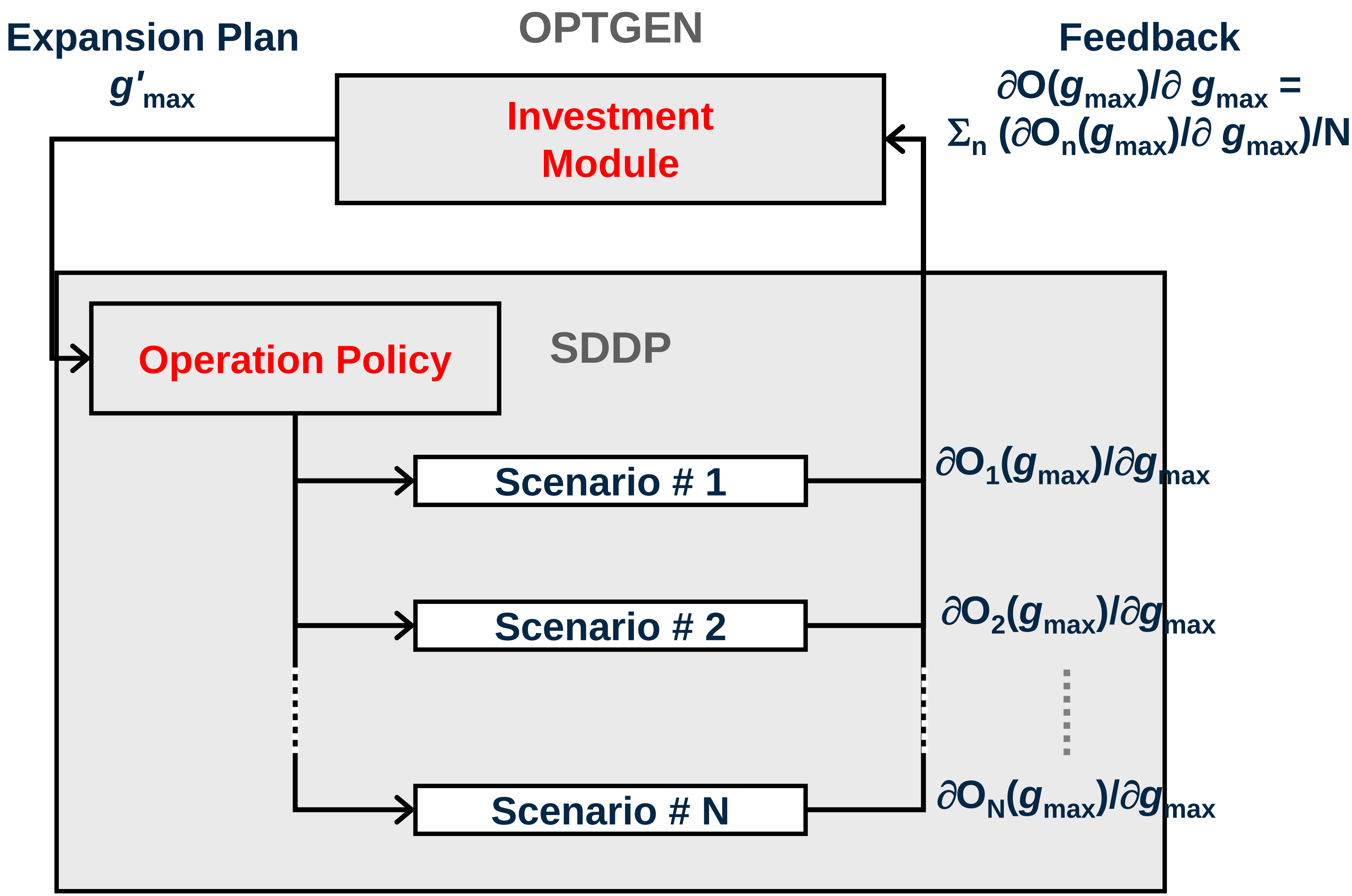
The GEP Task – Plants and system modeling

- 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

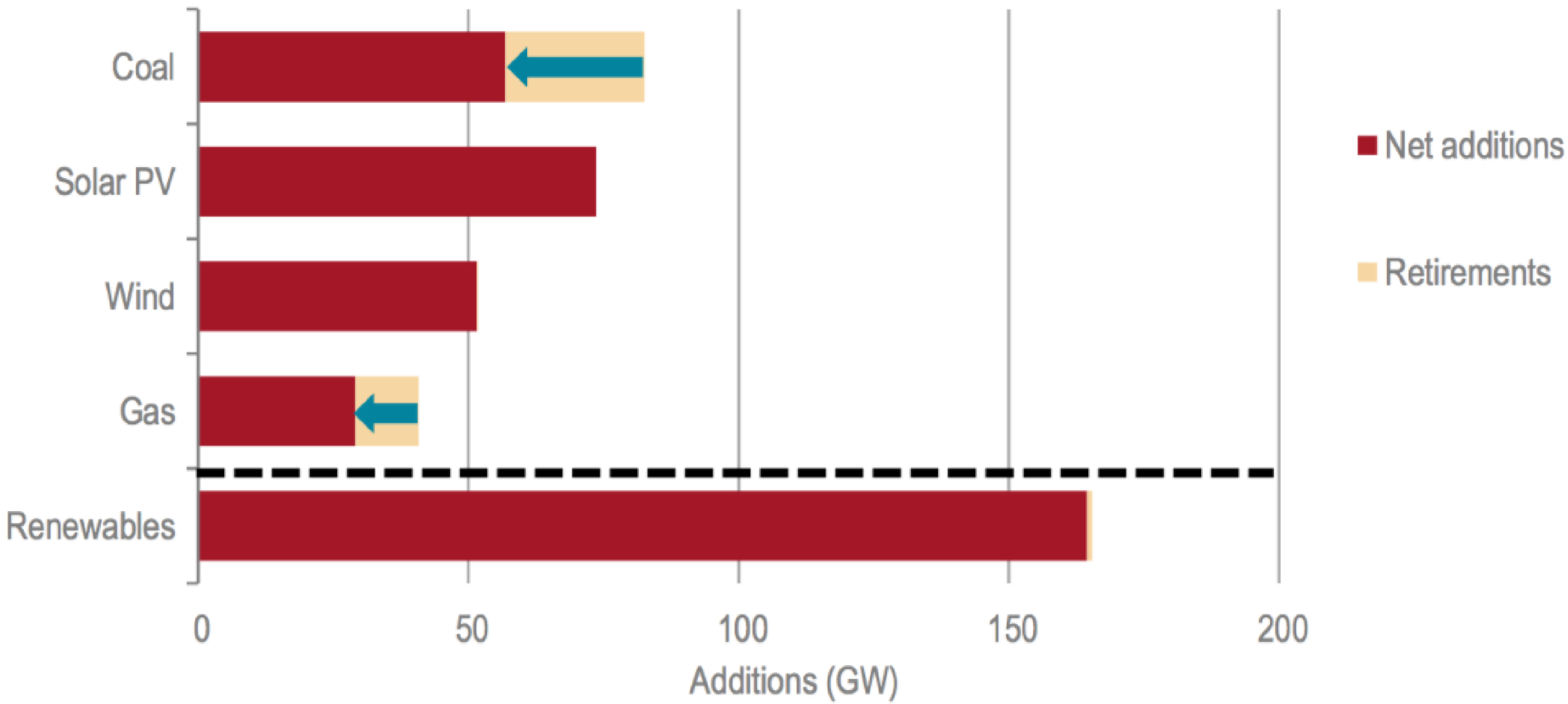
- The least-cost GEP is achieved by optimizing the trade-off between investment costs to build new projects and the expected value of operative costs obtained from the stochastic hydrothermal dispatch model, which allows a detailed representation of the electric-gas system's operation under uncertainty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

Optgen + SDDP as operation module



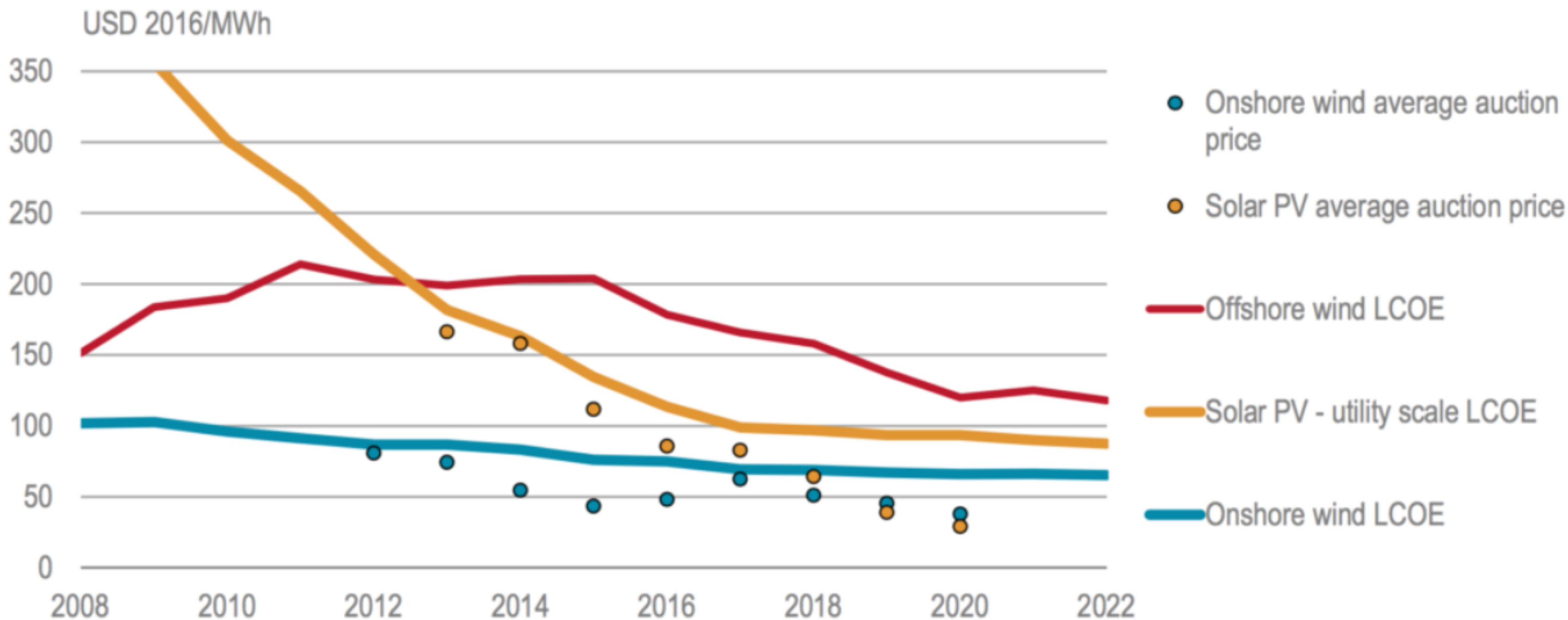
Expansion Planning – Current Scenario

Expansion planning – Current scenario



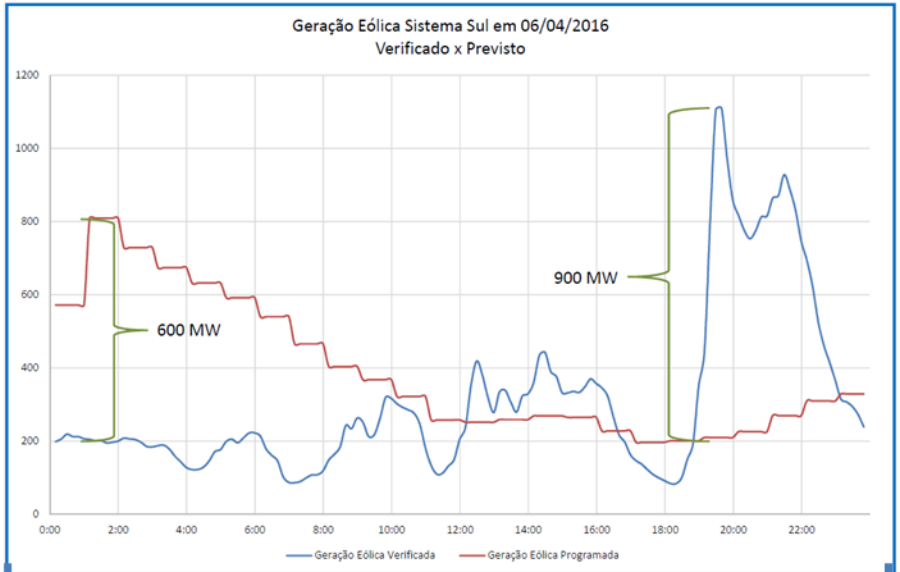
Electricity capacity additions by fuel 2016. Source: Renewables 2017 Pre-launch Media Webinar.

Expansion planning – Current scenario



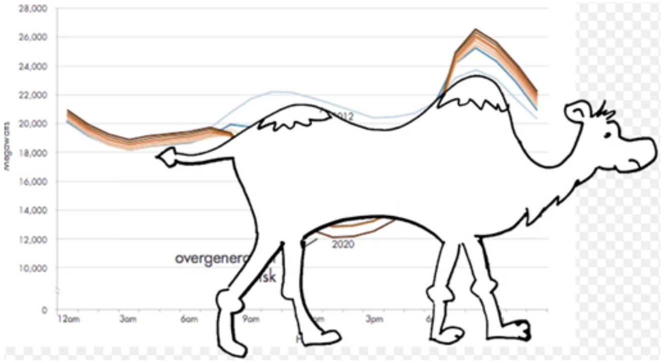
Global average levelised cost of energy (LCOE) and auction results for projects by commissioning date. Source: Renewables 2017, IEA.

High Renewable Penetration - Challenges

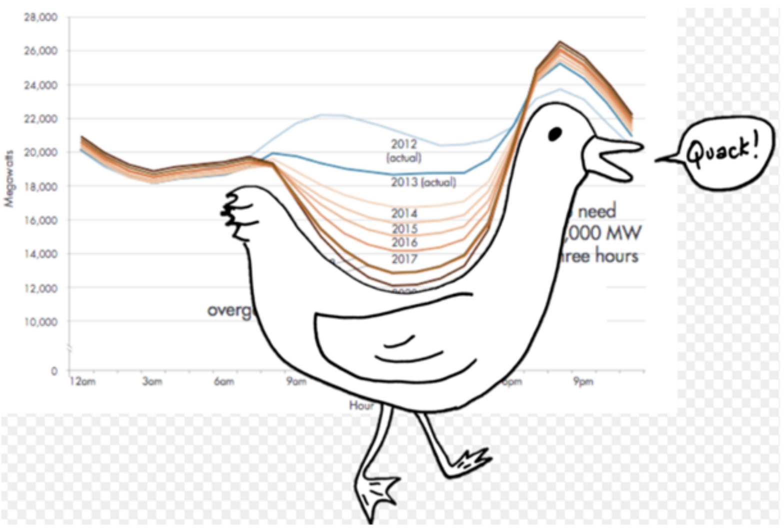


1000 MW ramp in 1 hour

900 MW difference between scheduled and verified



From dromedary to duck

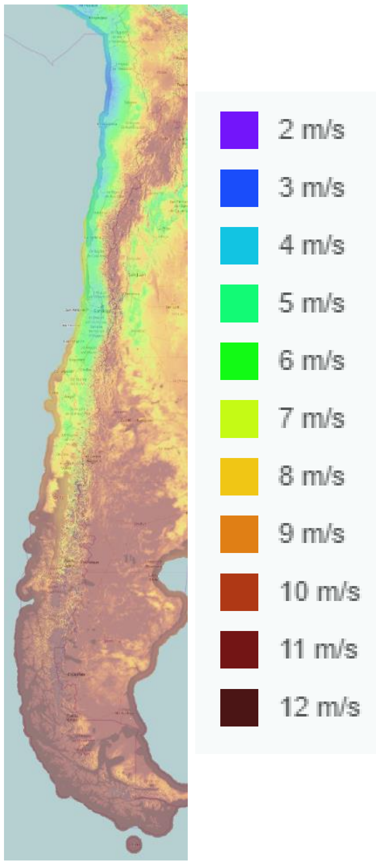


- **Operating Reserve:** needed to guarantee security of supply

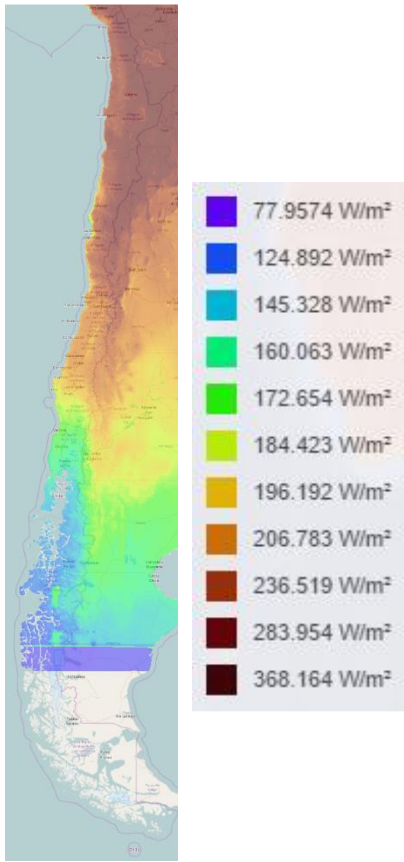
Case Study: The Expansion Planning of the Chilean System

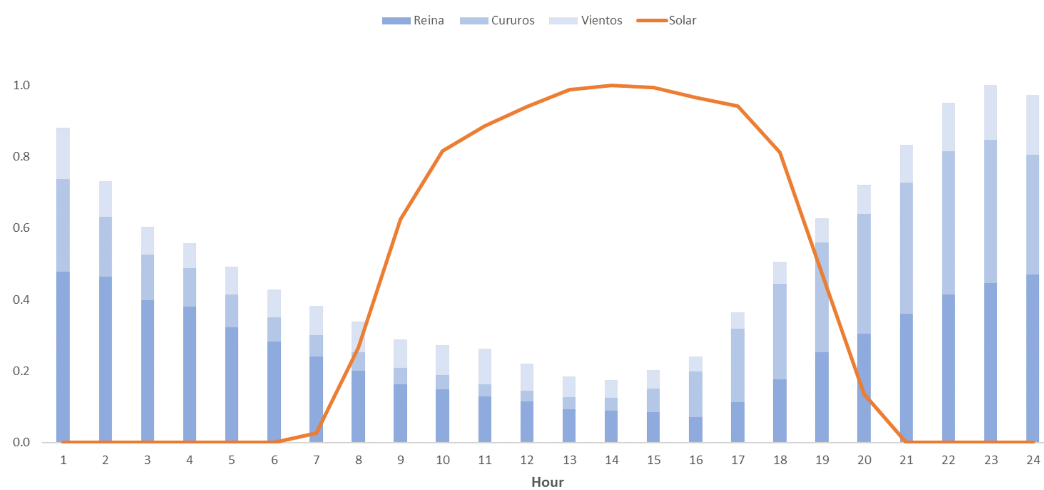
The Expansion Planning of the Chilean System

Wind

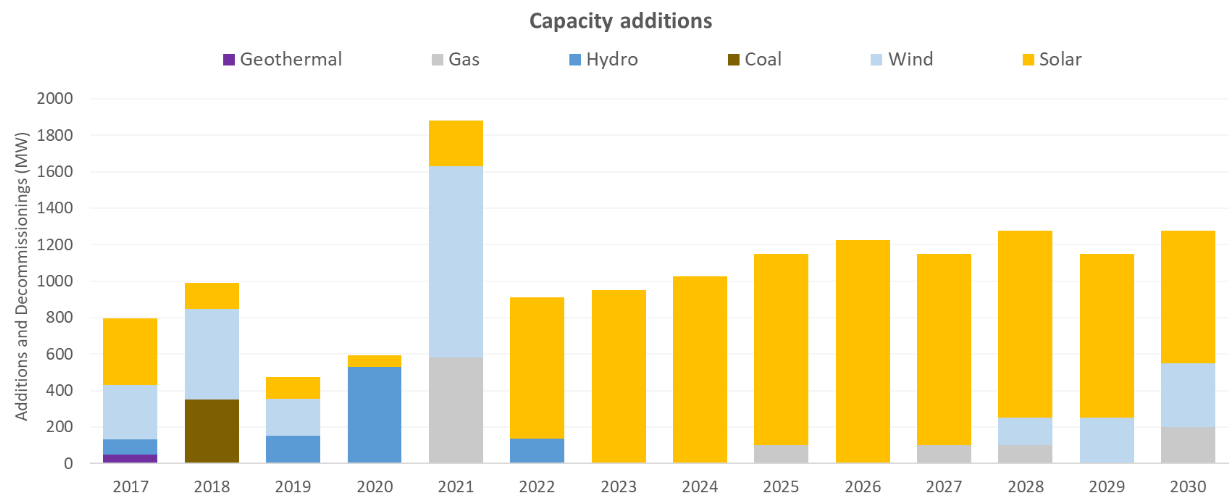


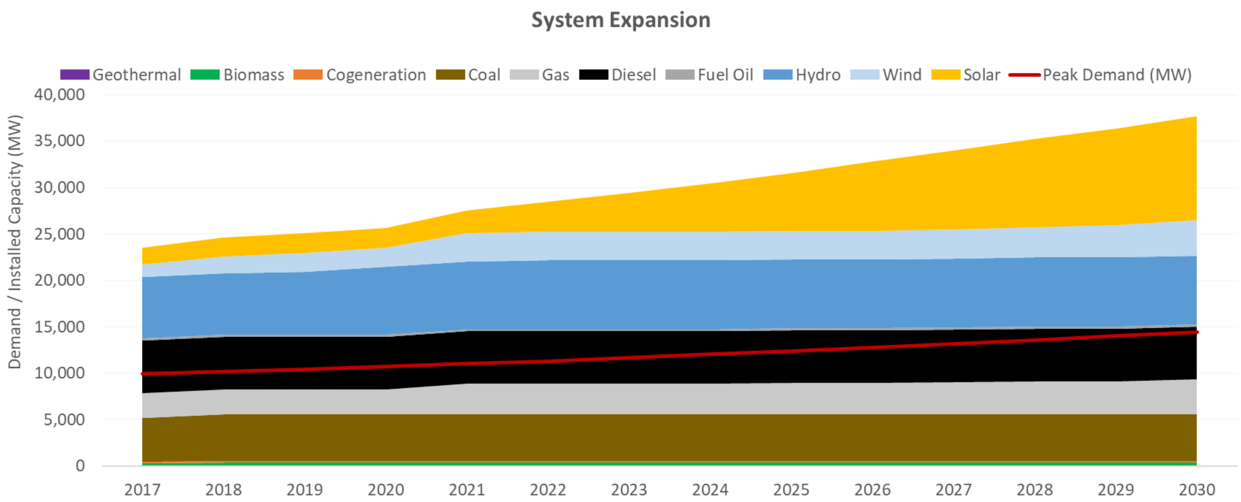
Solar





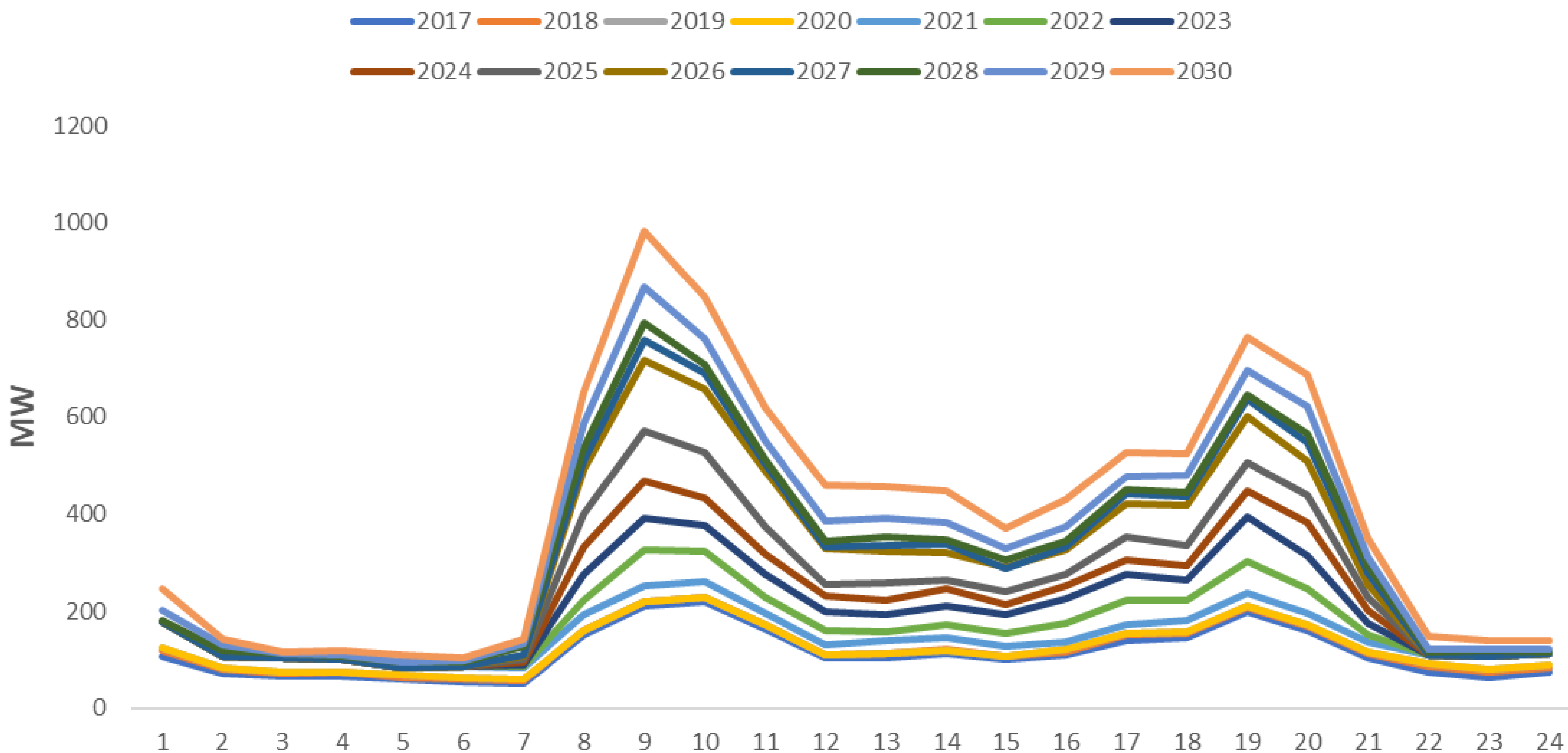
The Expansion Planning of the Chilean System





The Expansion Planning of the Chilean System

Example R^{*}_{VRE} in Chile:

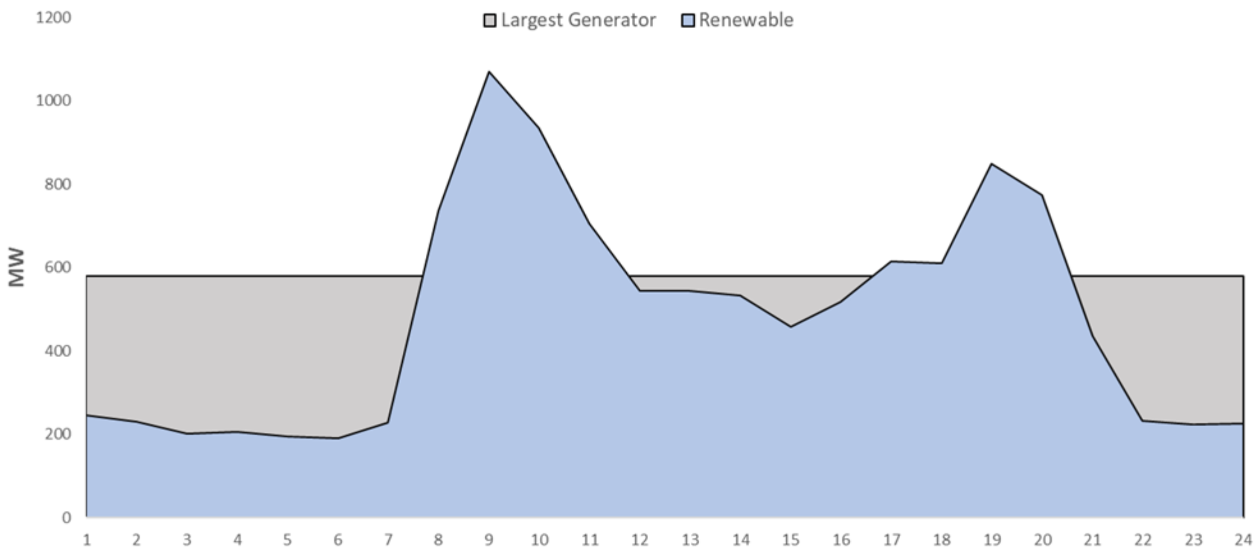


The Expansion Planning of the Chilean System

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

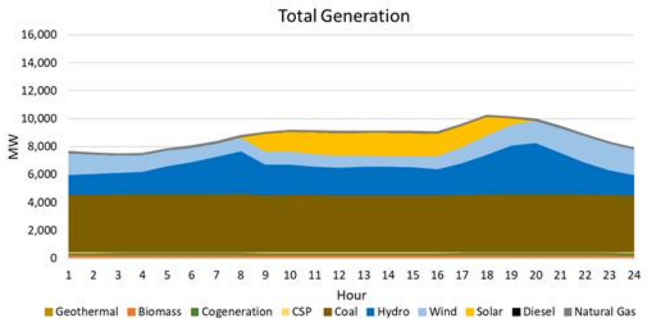
$$\mathbf{R = Demand + max}\{\bar{G}, R^*_{VRE}\}$$

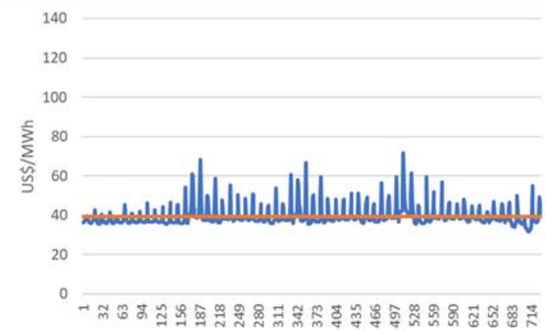
Example: $\bar{G}$ and R^*_{VRE} in Chile (2030):



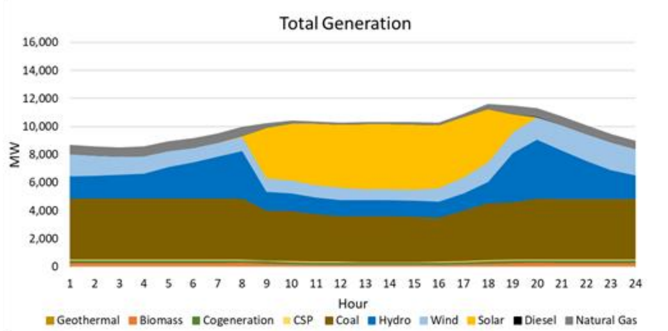
The Expansion Planning of the Chilean System

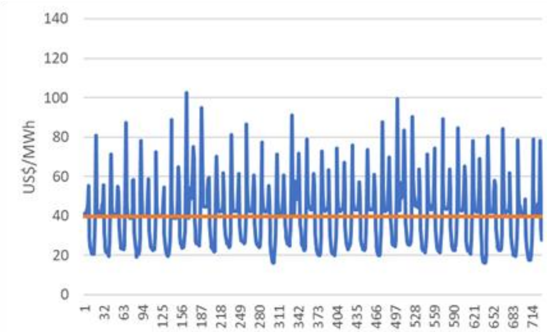
2021



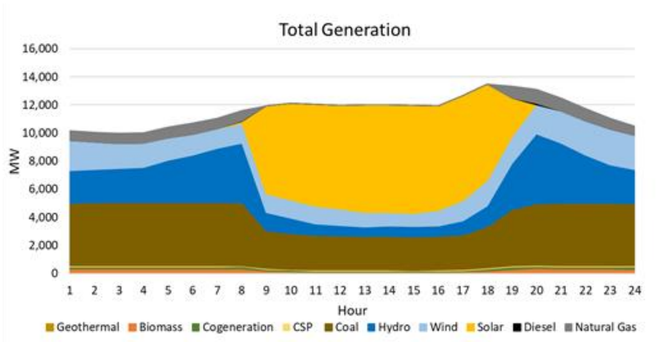


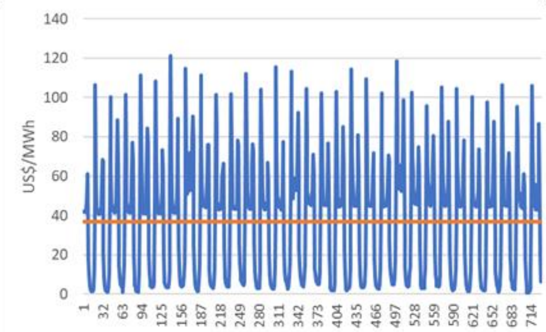
2025





2030

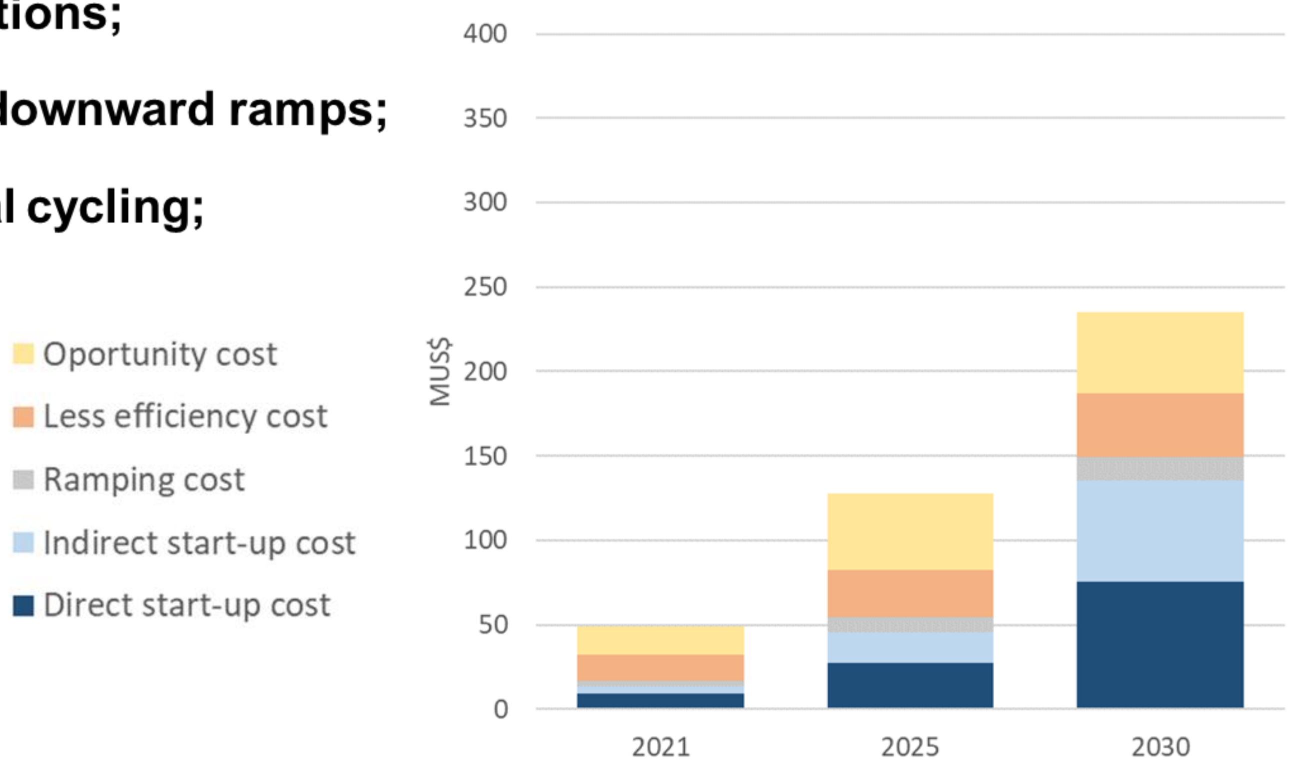




The Expansion Planning of the Chilean System

- **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

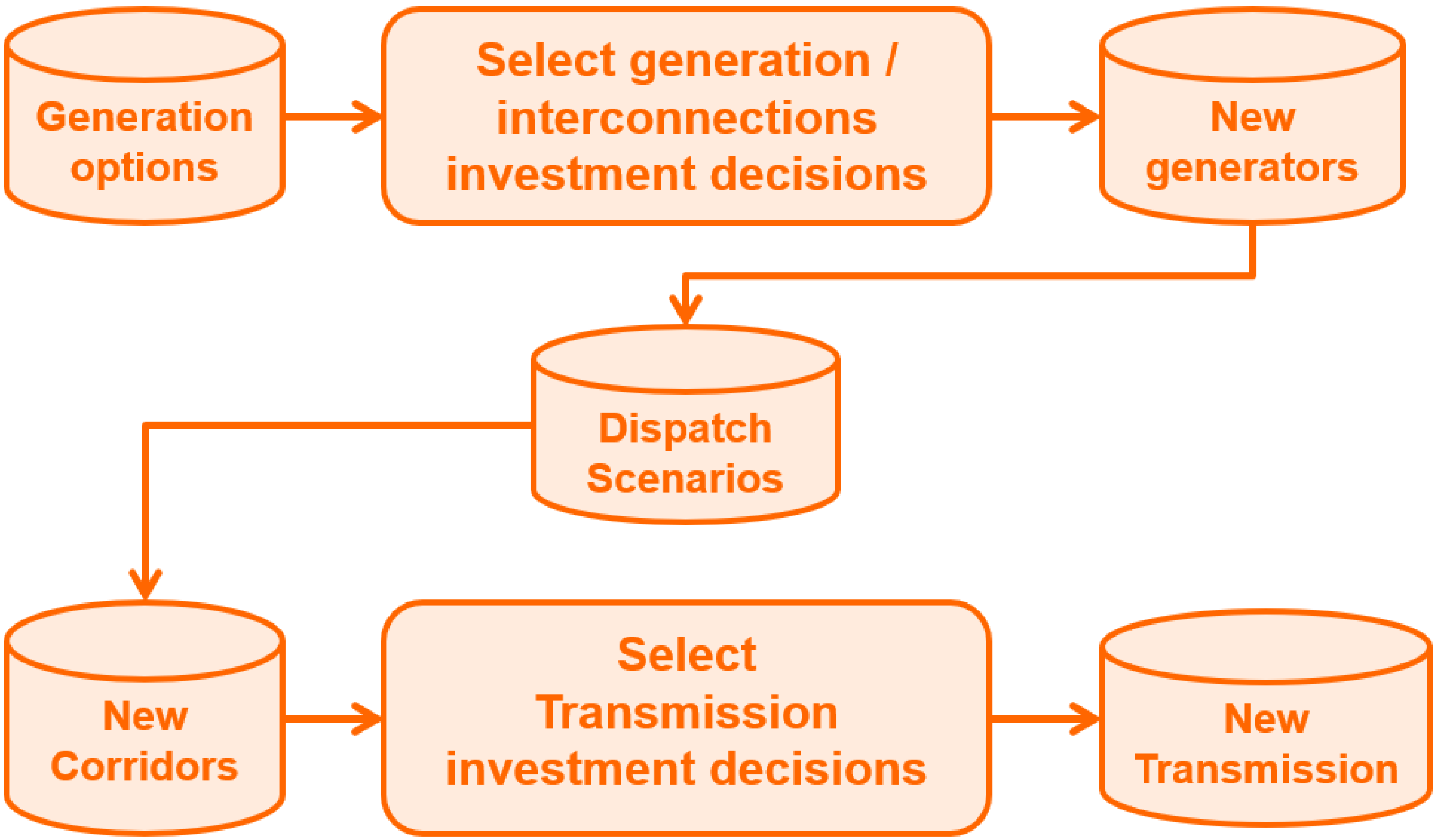
- Hierarchical planning of the transmission network:

  Phase 1: Integrated expansion of generation and major transmission links

  Phase 2: Detailed Network Expansion (lower voltages)

Regiones de Transmisión		
1 Hermosillo	19 Huasteca	37 Coatzacoalcos
2 Cananea	20 Tamazunchale	38 Tabasco
3 Obregón	21 Güémez	39 Grijalva
4 Los Mochis	22 Tepic	40 Ixtepec
5 Culiacán	23 Guadalajara	41 Lerma
6 Mazatlán	24 Aguascalientes	42 Mérida
7 Juárez	25 San Luis Potosí	43 Cancún
8 Moctezuma	26 Salamanca	44 Chetumal
9 Chihuahua	27 Manzanillo	45 Cozumel
10 Durango	28 Carapan	46 Tijuana
11 Laguna	29 Lázaro Cárdenas	47 Ensenada
12 Río Escondido	30 Querétaro	48 Mexicali
13 Nuevo Laredo	31 Central	49 San Luis Río Colorado
14 Reynosa	32 Poza Rica	50 Villa Constitución
15 Matamoros	33 Veracruz	51 La Paz
16 Monterrey	34 Puebla	52 Los Cabos
17 Saltillo	35 Acapulco	53 Mulegé
18 Valles	36 Temascal	

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

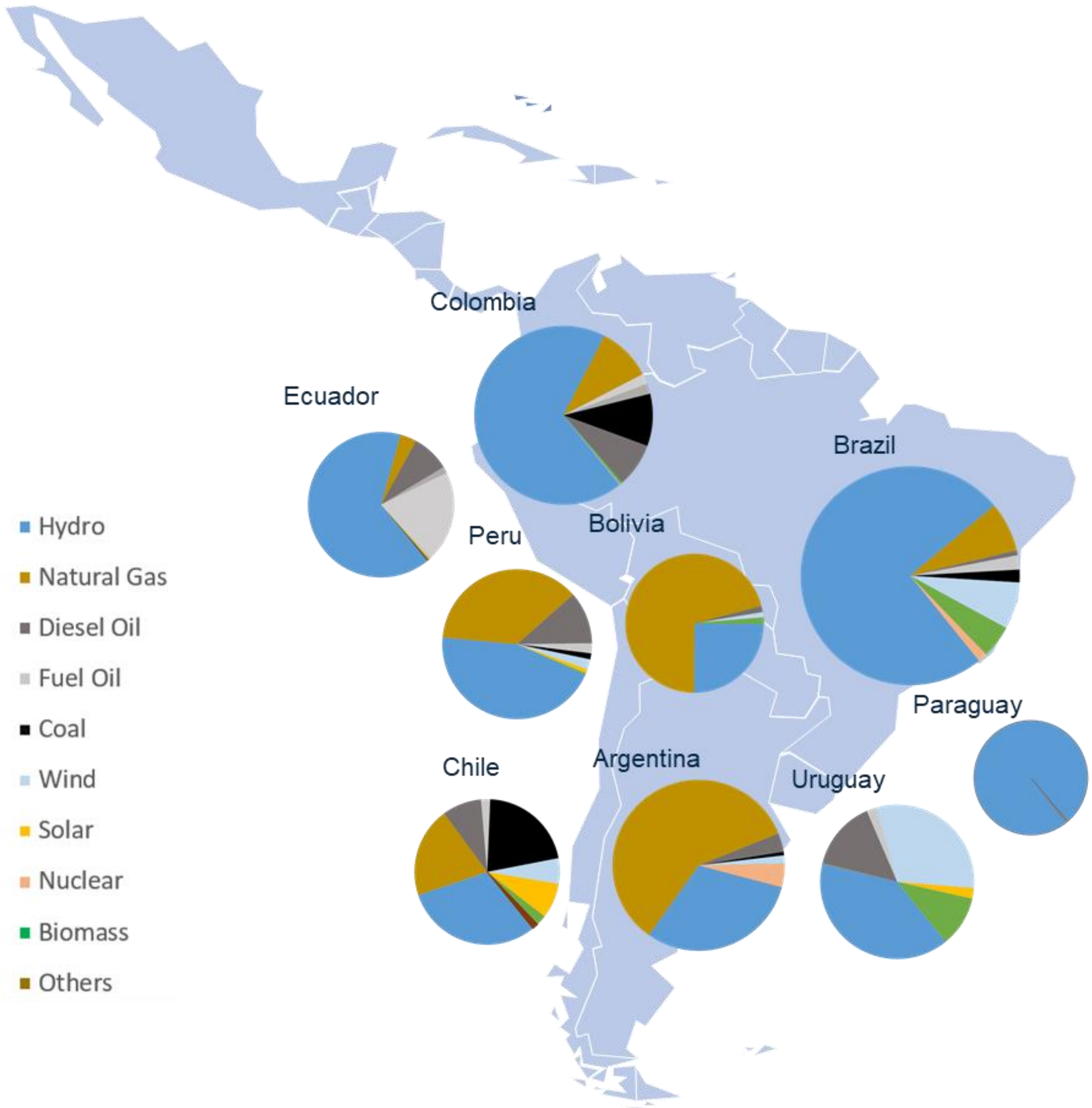
PSR

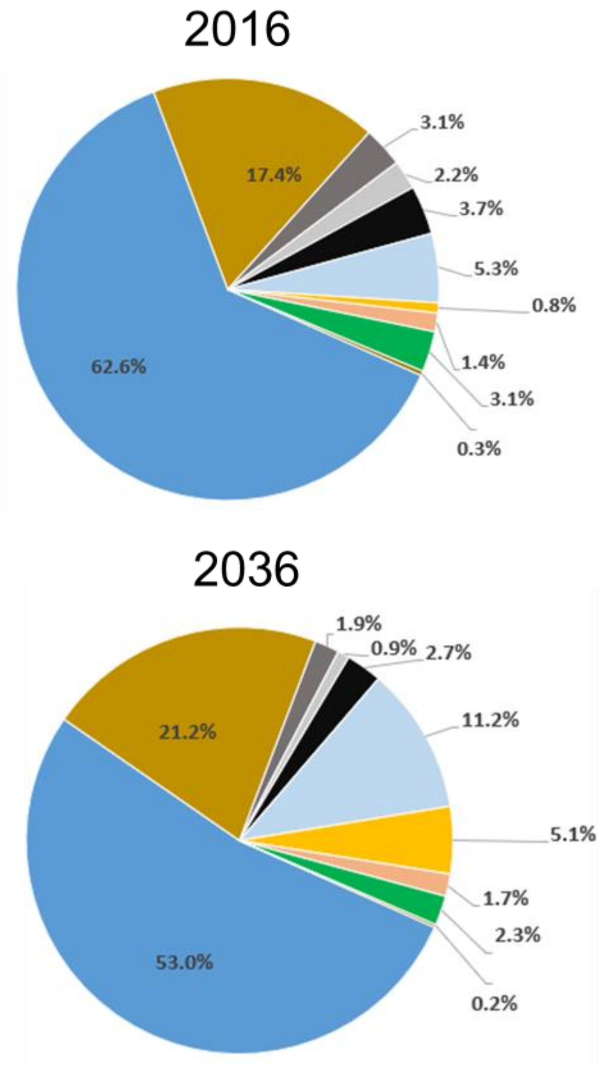
Energy Integration Assessment

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 CO_2 emissions
  - Increase in firm capacity
  - Reduction of secondary reserve requirements
- Benefit-cost ratio calculation

Installed Capacity – South America





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%

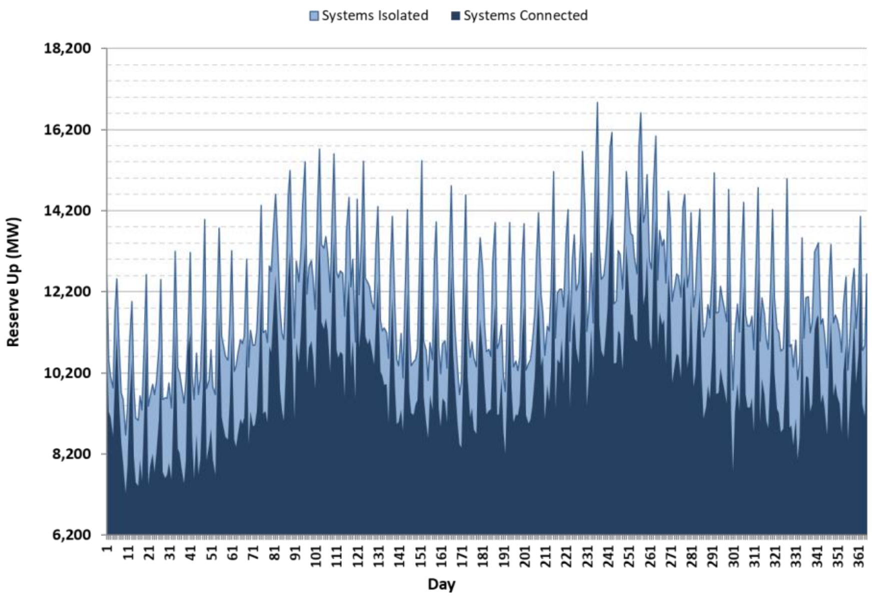
Investment Cost = 92 $MUS\$$

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

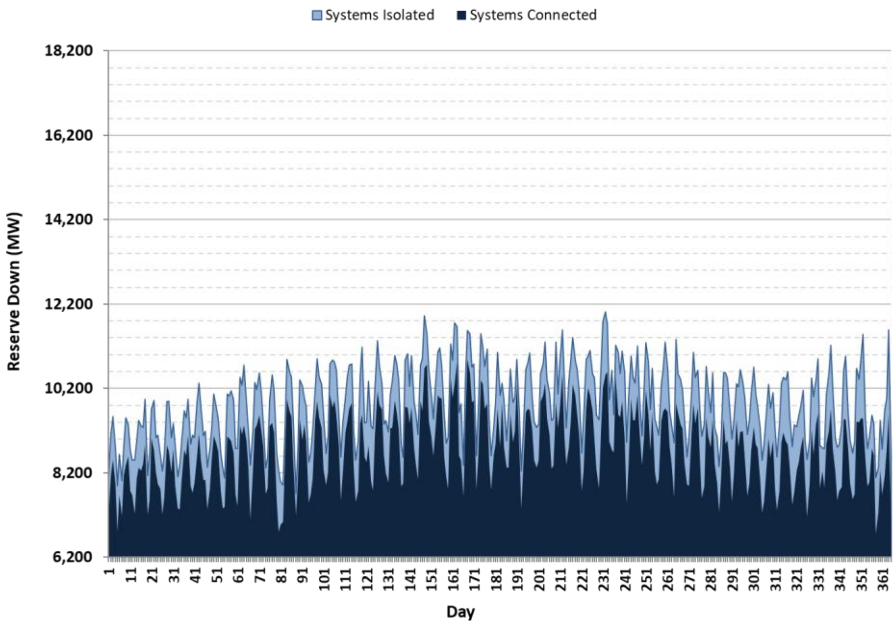
Results

- Reduction of secondary reserve requirements:

Upwards:

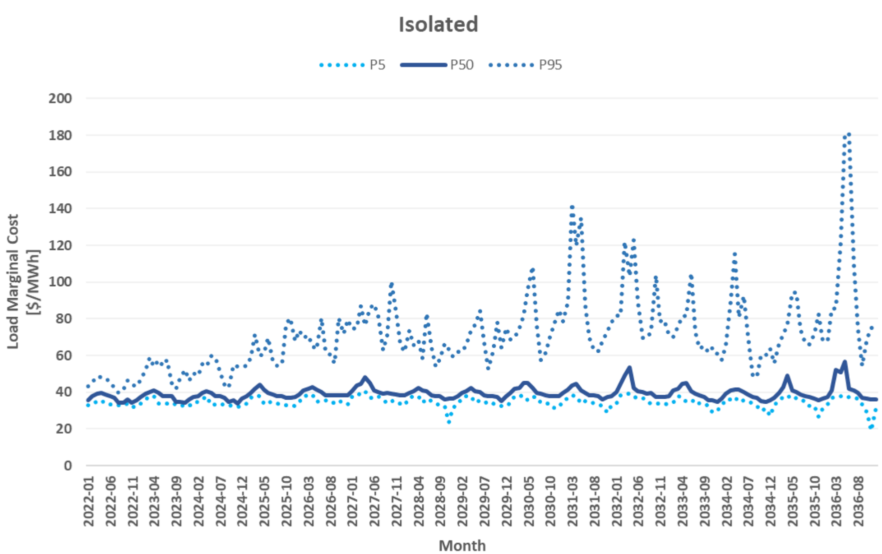


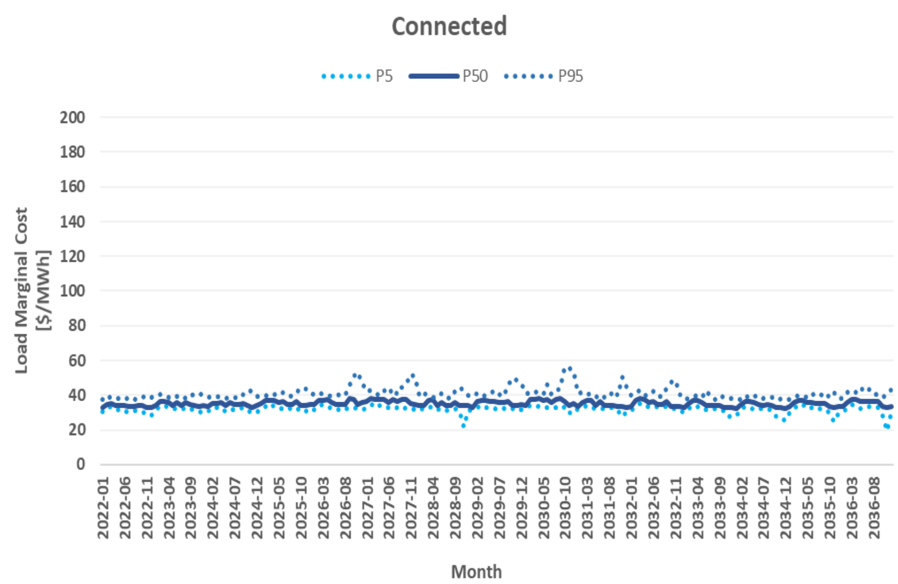
Downwards:



Other Results

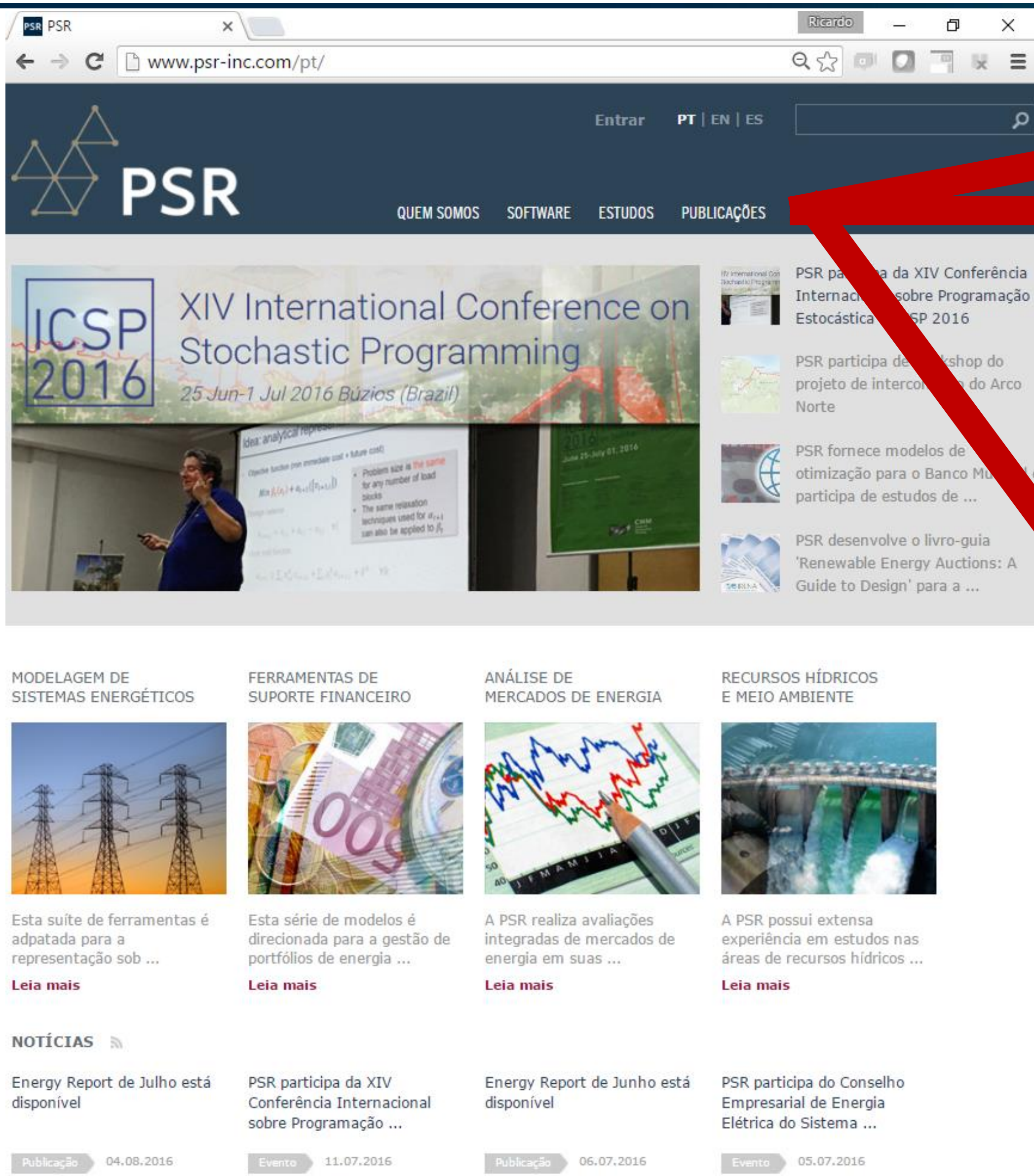
- Another result that deserves attention is the dispersion of the load marginal costs:






One more thing...

Follow us!



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QUESTIONS?

Obrigado!!

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