Energy Integration Assessment of Renewable-dominated Regions based on Stochastic Co-optimization of G,T and Probabilistic Reserves

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IEEE PES Webinar

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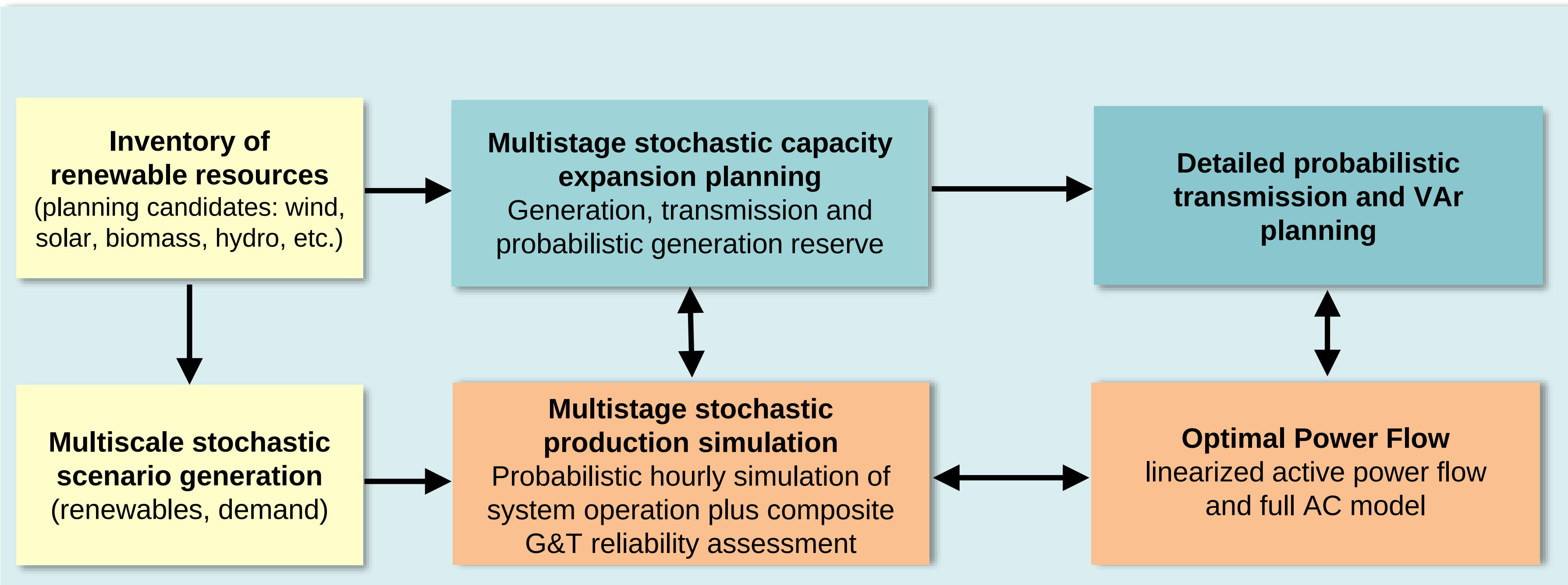
Motivation

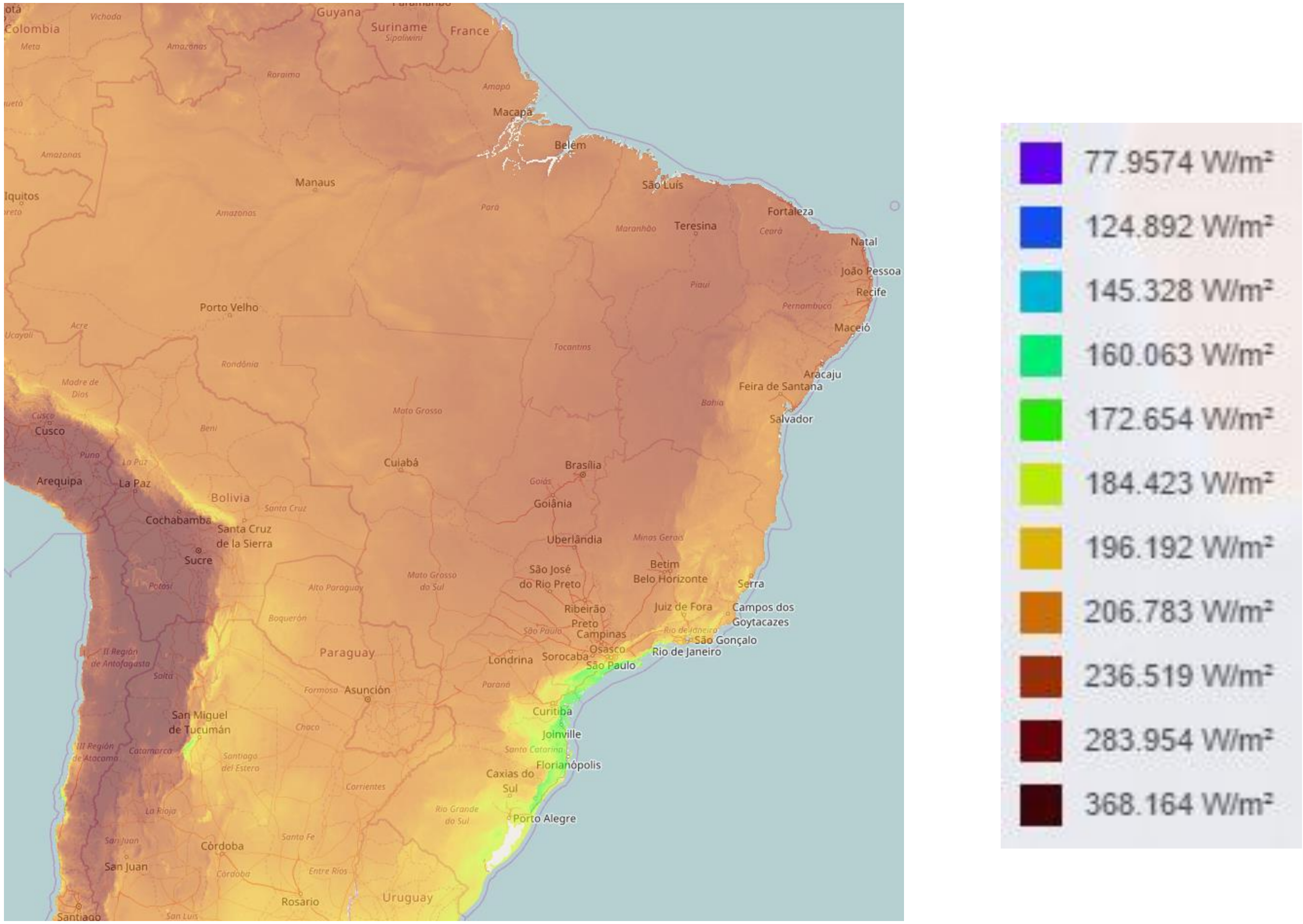
- Interest on optimal power system expansion planning has increased worldwide mainly because of renewables such as wind, solar and biomass.
- In emerging countries of Latin America, Asia and Africa, with high load growth and limited financial resources, the emphasis is on the most cost-effective expansion plan. Renewables are a competitive expansion option in these countries, however their modeling has increased the complexity of optimal planning models.
- In developed countries, load growth is usually flat. In these cases, renewables are being built as part of decarbonization policies and to displace more expensive thermal plants. As in the emerging countries, the variability of renewable production has created planning challenges associated with reserves, storage and transmission reinforcements.
- In this presentation, we will discuss some stochastic optimization techniques that have been shown to be useful for the integrated planning of generation, transmission and reserves, with focus on renewable penetration. These techniques have been applied in a large number of real planning studies of countries and regional (multi-country) *pools* in Latin America, Asia and Africa.

Analytical Tools for Probabilistic Expansion Planning



Inventory of renewable resources
(planning candidates: wind, solar, biomass, hydro, etc.)

Brazil: Wind and Solar Potentials



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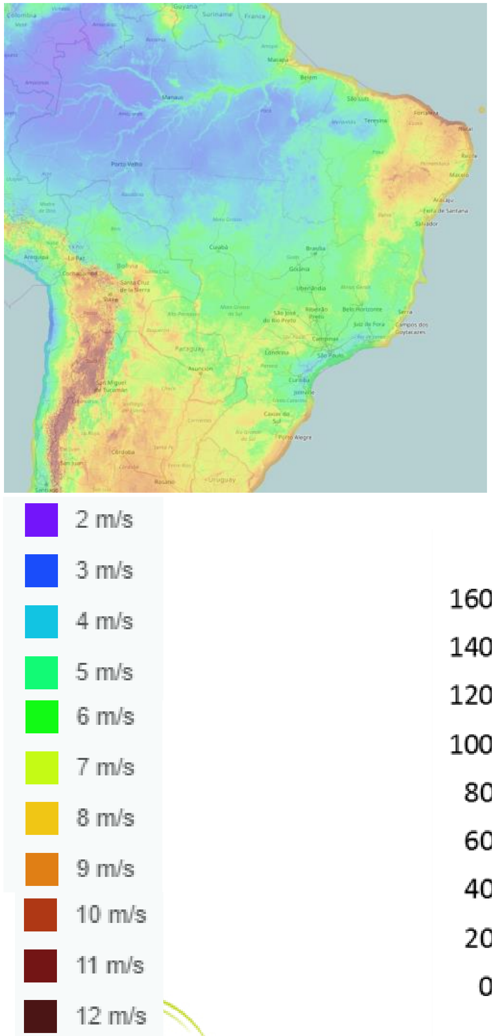
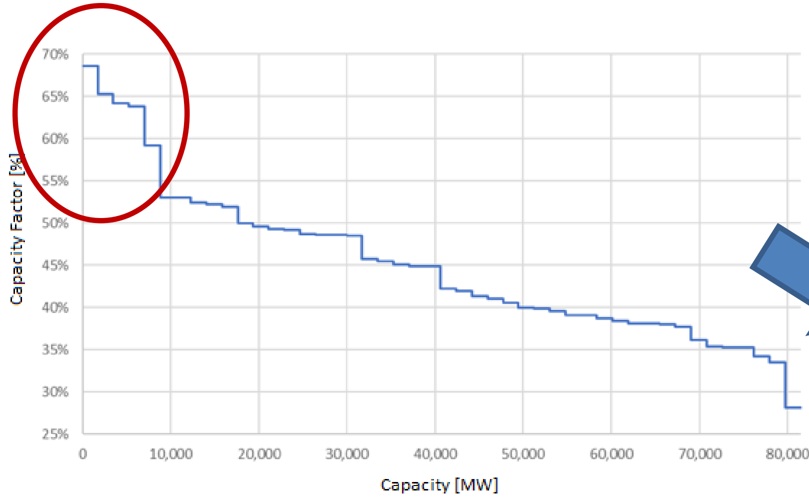
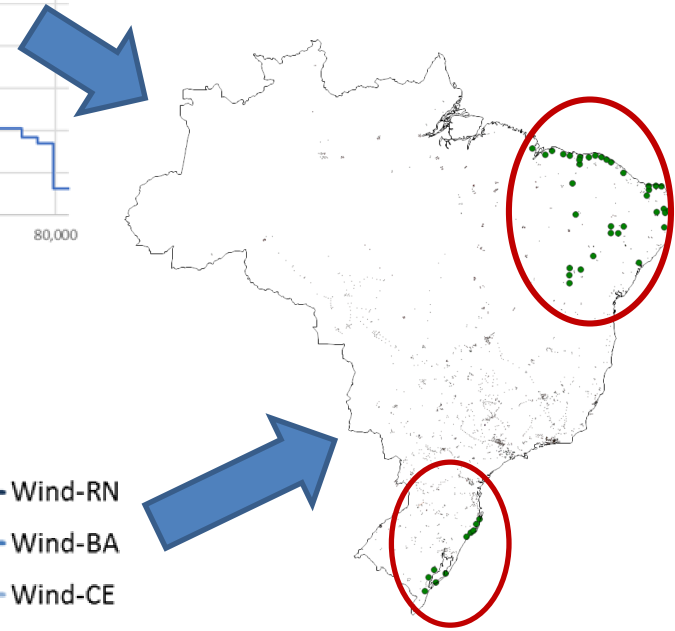
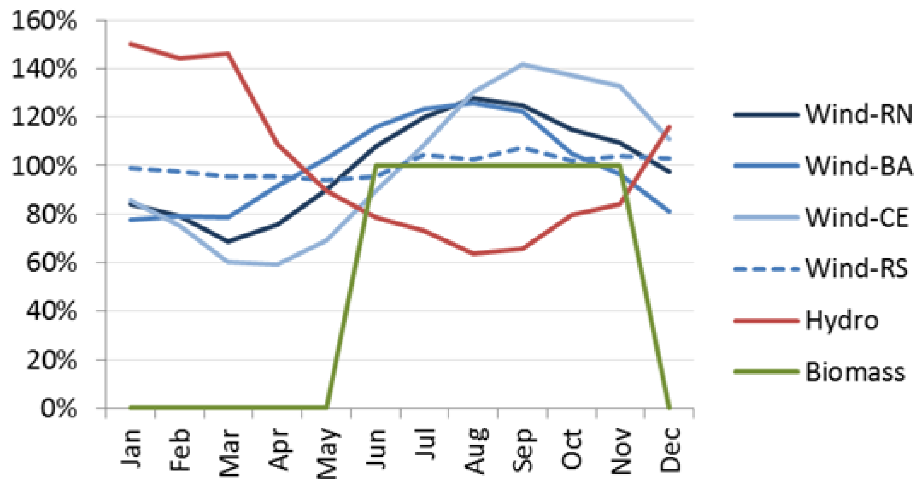
Brazil: Wind and Solar Potentials







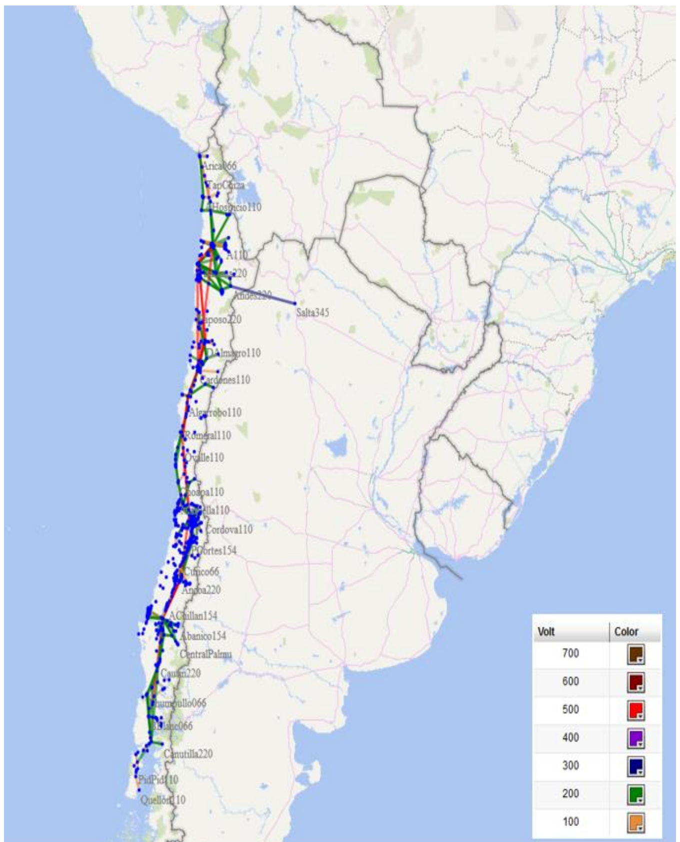
Seasonal generation patterns



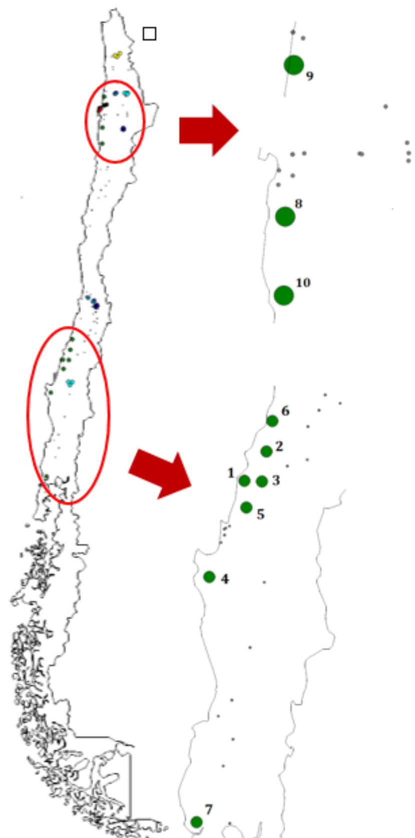
Inventory of renewable resources
(planning candidates: wind, solar, biomass, hydro, etc.)

Renewable Candidate Ranking (1/2)

- Some criteria: (i) capacity factors; (ii) distance to the grid; (iii) correlation with existing wind farms and hydros, etc.



Example: Chile

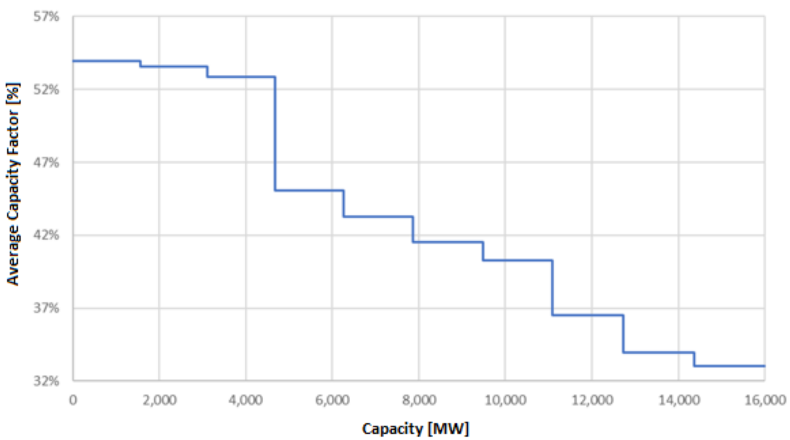


Spot	Average capacity factor
1	53.97%
2	53.57%
3	52.84%
4	45.09%
5	43.24%
6	41.51%
7	40.30%
8	36.54%
9	33.96%
10	33.01%

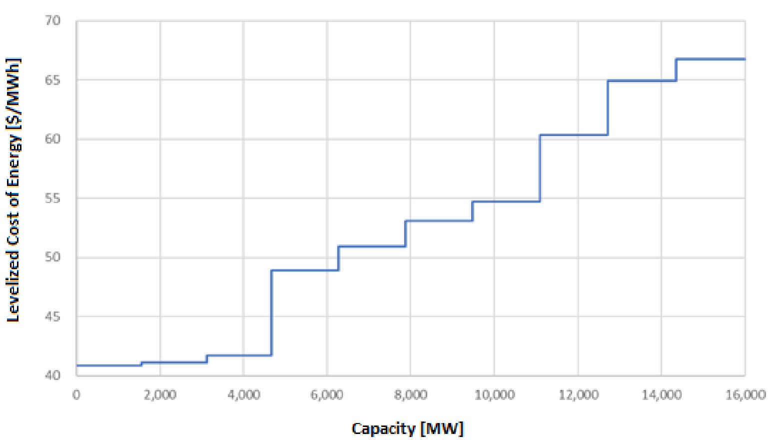
Inventory of renewable resources
(planning candidates: wind, solar, biomass, hydro, etc.)

Renewable Candidate Ranking (1/2)

- 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

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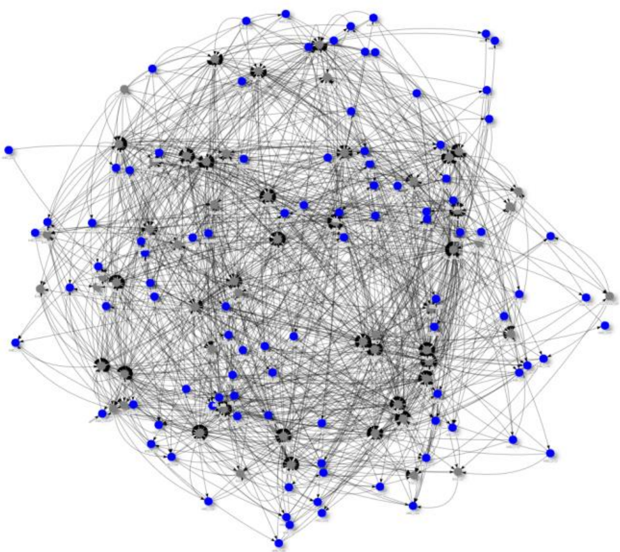
Multiscale stochastic scenario generation
(renewables, demand)

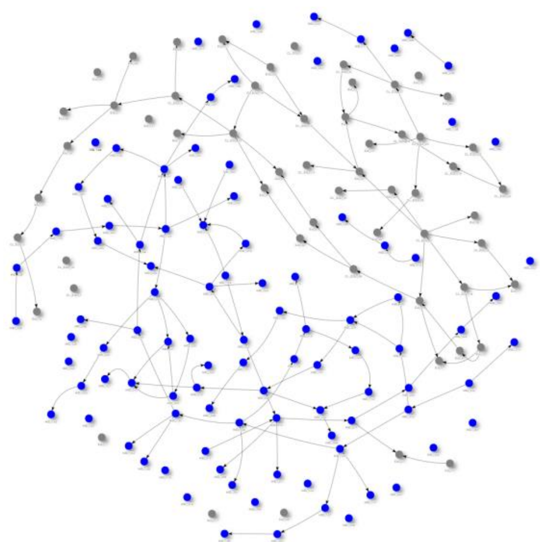
Spatial and Temporal Correlations

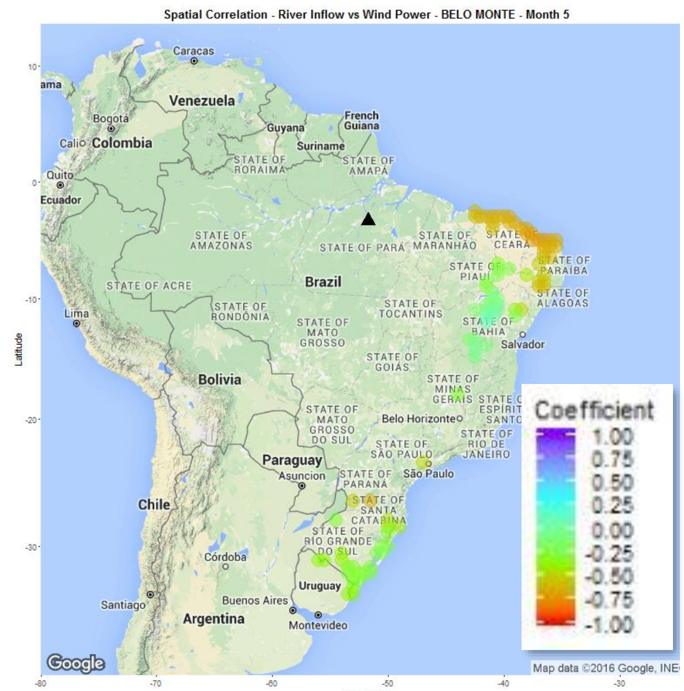
- Time Series Lab (TSL) produces renewable energy scenarios conditioned to the inflows, preserving spatial and temporal correlations.



Traditional methodology

Bayesian network

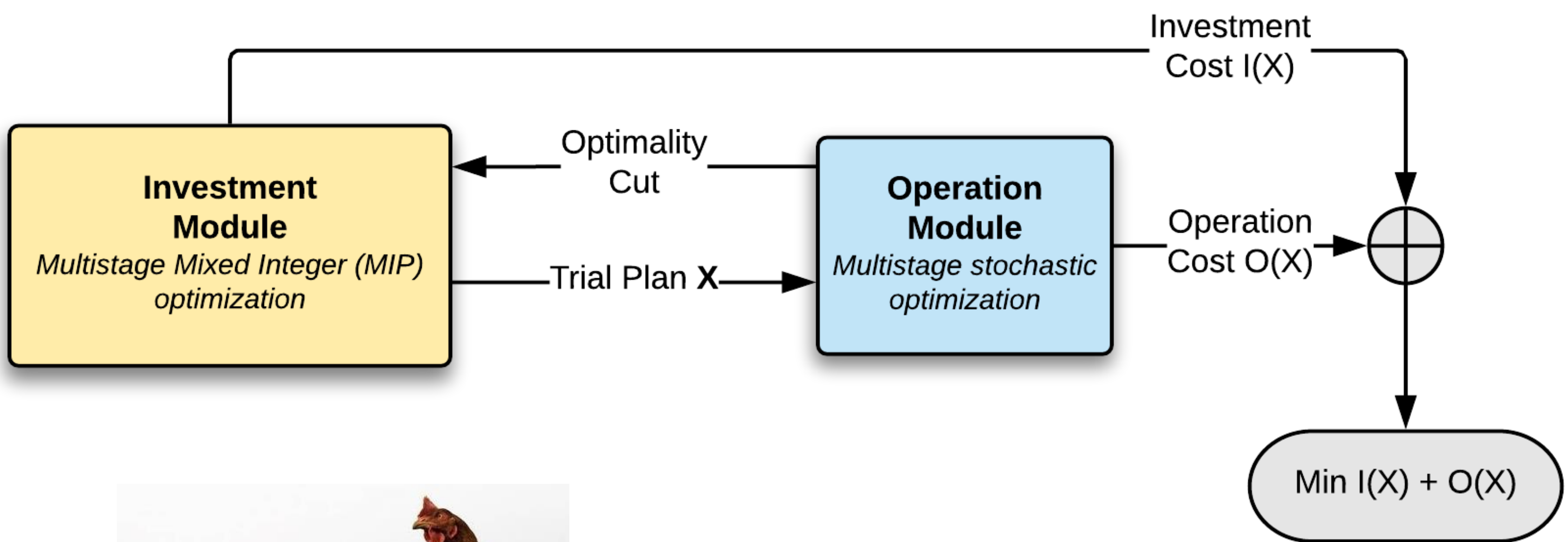




Wind & Inflows

The Expansion Planning Model

Generation-transmission Planning Method
Multistage Stochastic Benders Decomposition



Operation Module: Multistage Stochastic Optimization

- Weekly or monthly time steps; 25+ years horizon
  - Intra-stage: 5-21 load blocks to 168-730 hours
- Detailed generation modeling: thermal plants (gas, oil, nuclear etc.), renewables (hydro, wind, solar biomass etc.), storage (hydro reservoirs, pumped storage batteries etc.), co-generation, CHP and others
- Price-responsive load by region or by bus
- Fuels: production, storage and transportation network
- Interconnections or full transmission network: linearized power flow with quadratic losses
- Solution algorithm: Stochastic Dual Dynamic Programming (SDDP)

Stochastic Parameters Modeled in SDDP

- Hydro inflows and renewable generation (wind, solar, biomass etc.)
  - Multivariate stochastic model (PAR(p))
    - Inflows: macroclimatic events (El Niño), snowmelt and others
    - Spatial correlation of wind, solar and hydro
  - External analytical models can be used to produce renewable scenarios
- Uncertainty on fuel costs
  - Markov chains (hybrid SDDP/SDP model)
- Load uncertainty
  - Annual load growth rates
    - Markov chains/AR model
  - Within-stage variability
    - Monte Carlo sampling
- Wholesale energy market prices
  - Markov chains
- G&T equipment outages
  - Monte Carlo sampling

SDDP application example: Brazil

- Installed capacity: 125 GW
- 160 hydro plants (85 with storage), 140 thermal plants (gas, coal, oil and nuclear), 8 GW wind, 5 GW biomass, 1 GW solar
- Transmission network: 5 thousand buses, 7 thousand circuits

State variables: 85 (storage) + 160 x 2 = 320 (AR-2 past inflows) = 405

Monthly stages: 120 (10 years)

Forward scenarios: 1,200

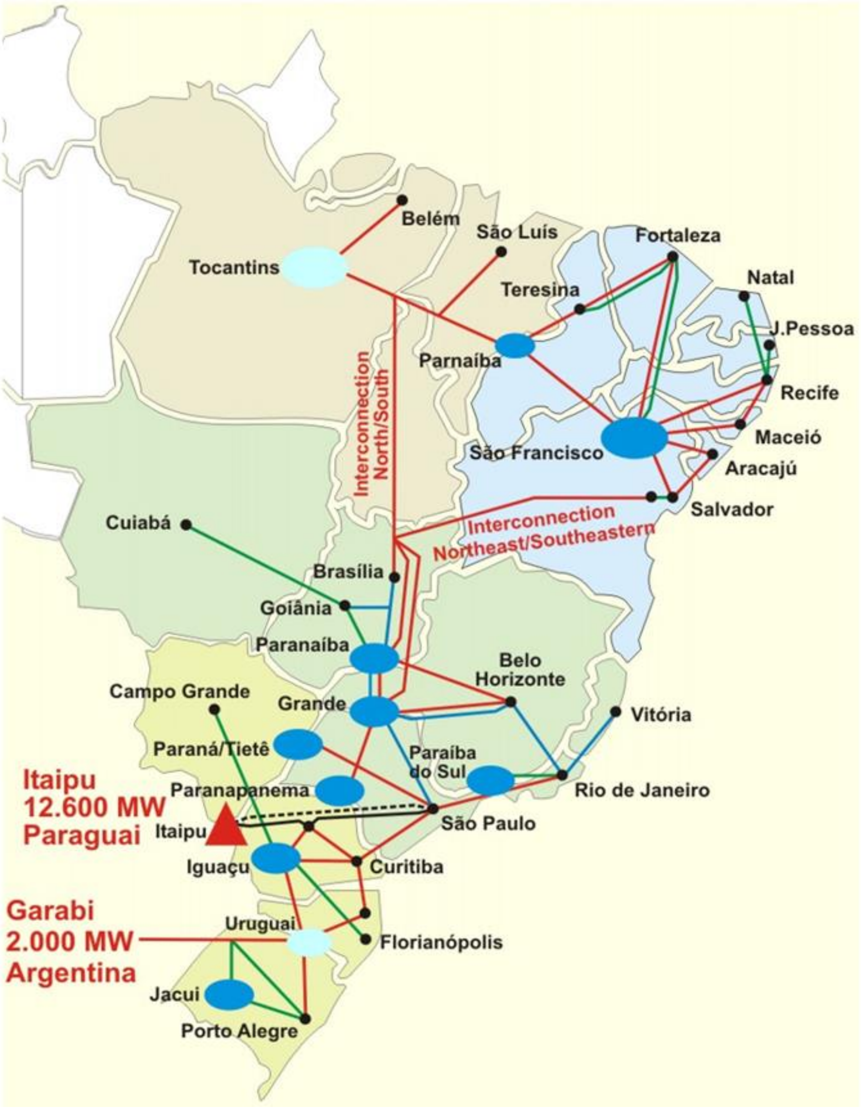
Backward branching: 30

LP problems per stage/iteration: 36,000

Number of SDDP iterations: 10

Total execution time: 90 minutes

25 servers with 16 processors each



Feedback from Operation to Investment Module

- Benders cuts representing the derivatives of expected operation cost with respect to the investment decisions are then calculated from the multistage transmission-constrained stochastic optimization of the system operation considering a large number of probabilistic scenarios (inflows, renewable production, load uncertainty, etc.)
- As examples:
  - Thermal generation:

$$g_{t,\tau,j} \le \overline{g}_j^* \left(= \overline{g}_j \times x_{t,j}^*\right) \ \forall j \in \mathbb{J}_x \quad \leftarrow \ \pi_{t,\tau,j}^{\overline{g}}$$

  - Candidate circuits:
    - Circuit Flow limit:

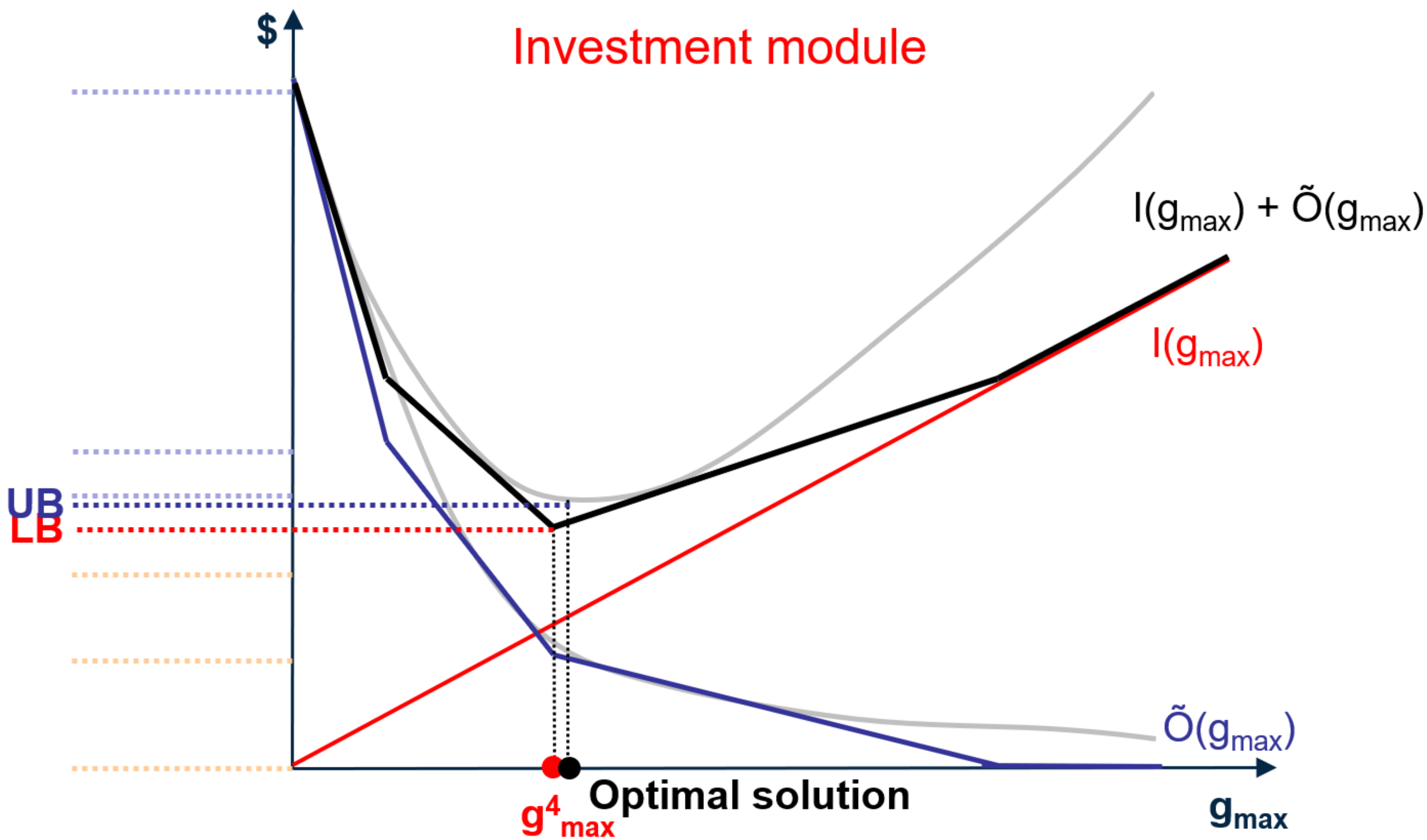
$$\left|f_{t,\tau,k}\right| \le \overline{f}_{t,k}^* \left(= \overline{f}_k x_{t,k}^*\right) \ \forall k \in \mathbb{K}_x \quad \leftarrow \ \pi_{t,\tau,k}^{\overline{f}}$$

    - Kirchhoff's second law:

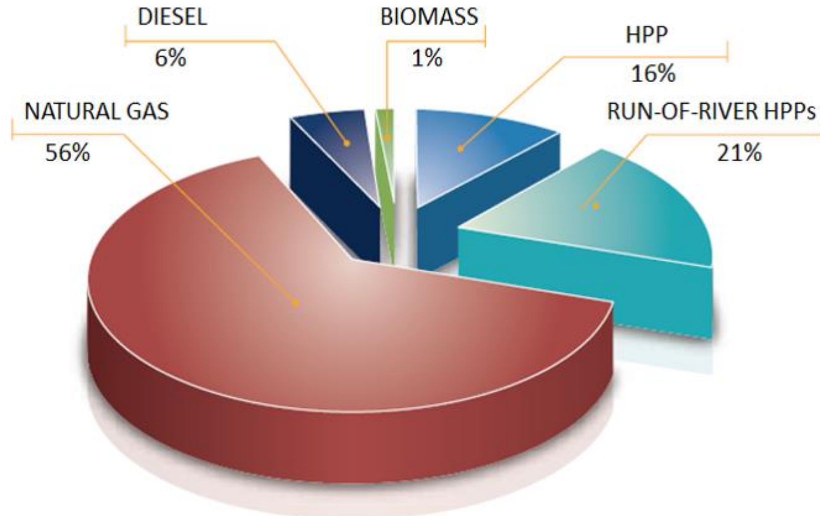
$$\left|f_{t,\tau,k} - \gamma_k(\theta_{t,\tau,F(k)} - \theta_{t,\tau,T(k)})\right| \le \Delta_{t,k}^* \left(= M_k[1 - x_{t,k}^*]\right) \quad \leftarrow \ \pi_{t,\tau,k}^{\gamma}$$

S. Binato, M. V. F. Pereira and S. Granville, "A New Benders Decomposition Approach to Solve Power Transmission Network Design Problems", IEEE Transactions on Power Systems, Vol 16, No. 2, 2001.

Investment-Operation Iterative process

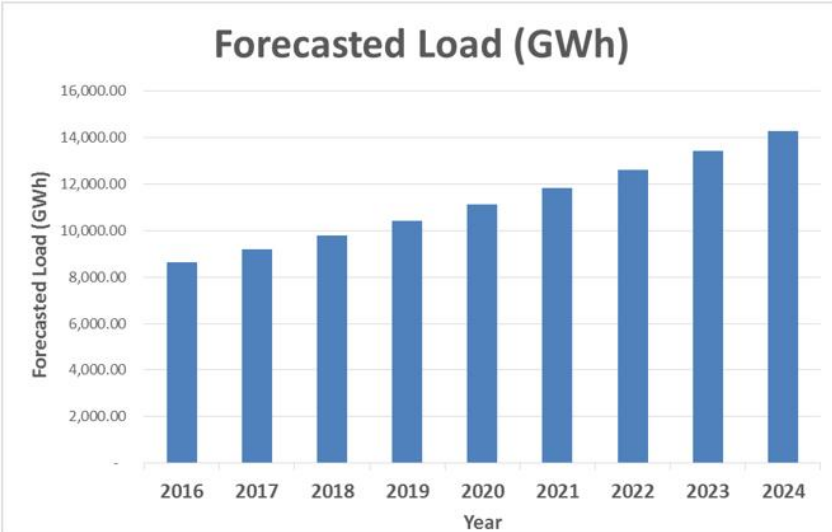


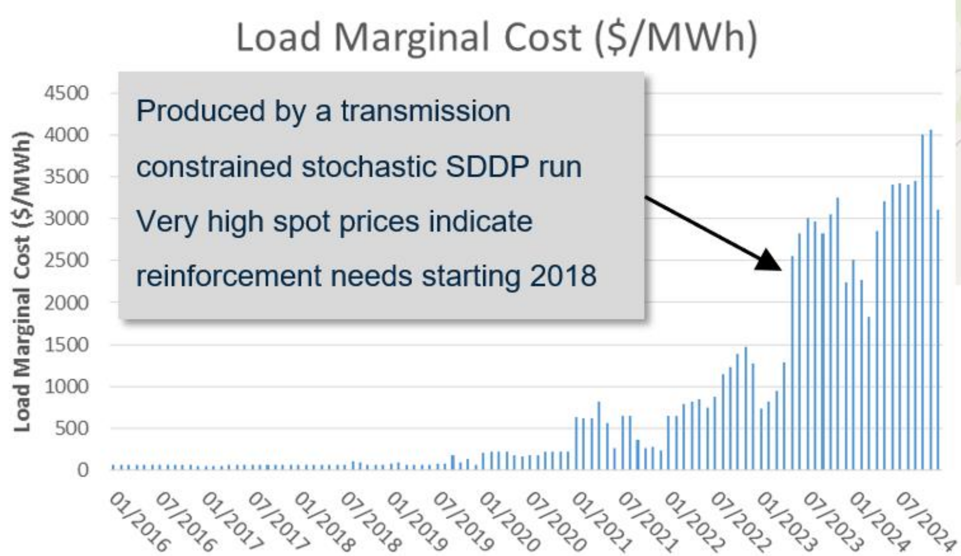
Example: Bolivia Integrated G&T planning



Transmission System	
Buses	**141**
230 kV	**29**
115 kV	**72**
69 kV	**40**
Circuits	**127**
Transmission Lines	**100**
Transformers	**27**

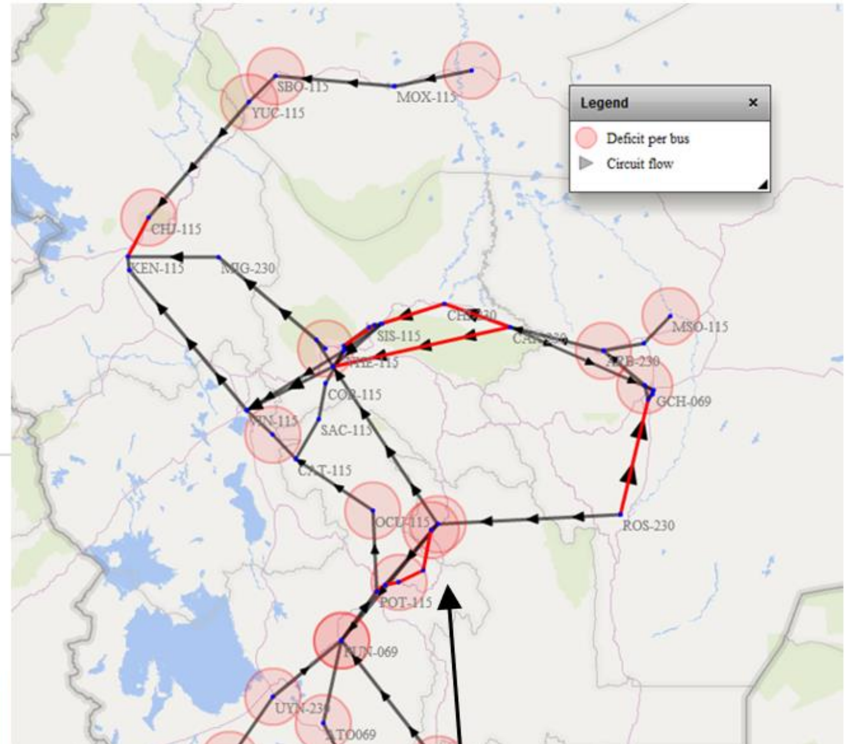
Example: Bolivia Integrated G&T planning





Produced by a transmission constrained stochastic SDDP run

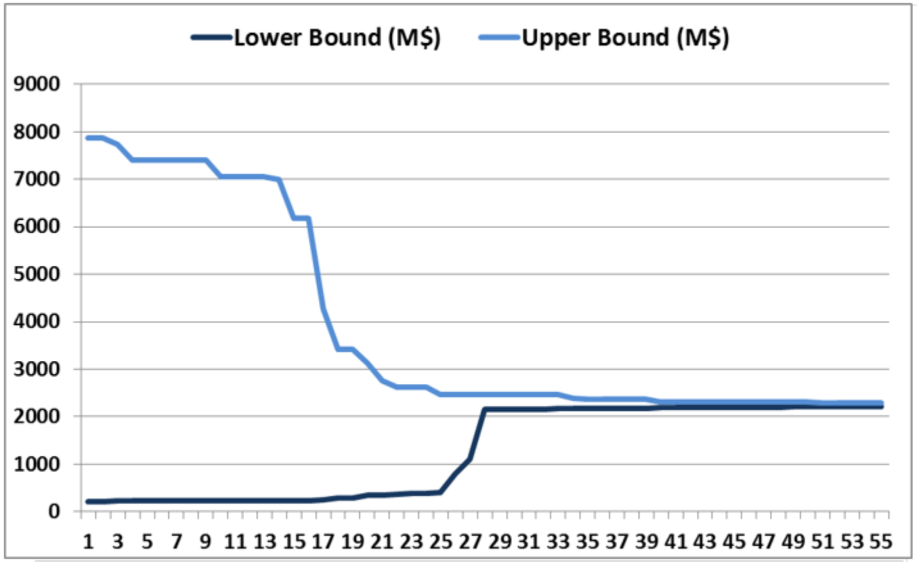
Very high spot prices indicate reinforcement needs starting 2018

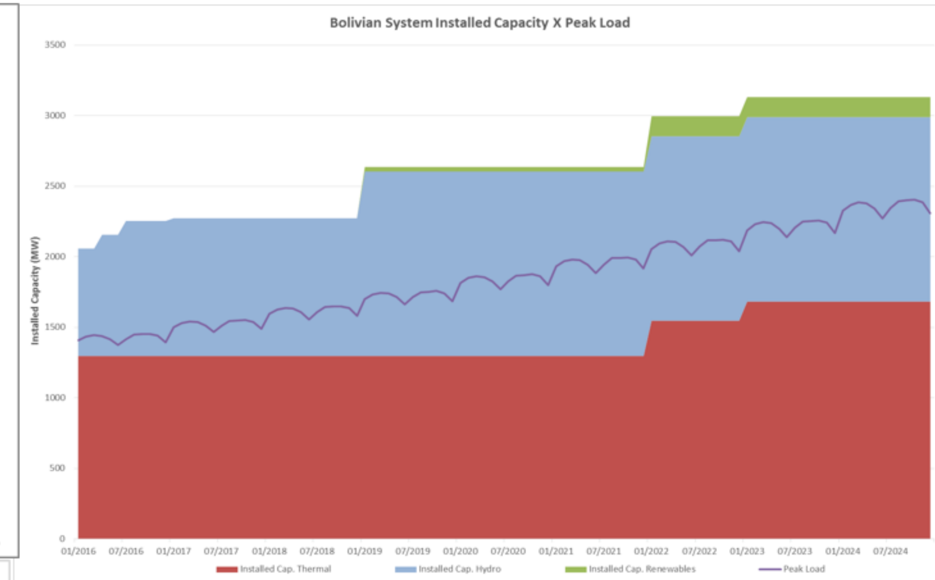


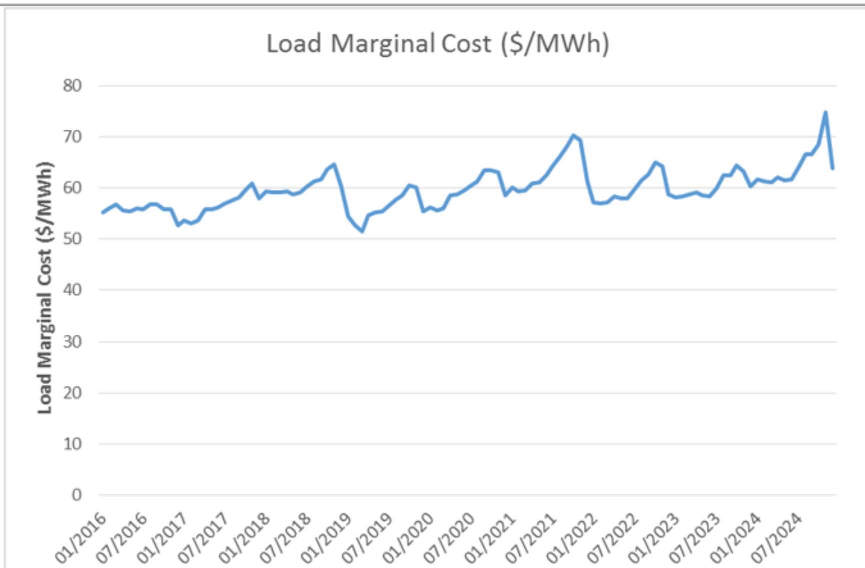
Buses with deficit

Lines at the maximum loading

Example: Bolivia Integrated G&T planning







G&T Optimal Expansion Plan:

G: 9 TPPs, 7 HPPs, 3 Wind Farms

T: 12 Circuits (9 TLs and 3 Transf.)

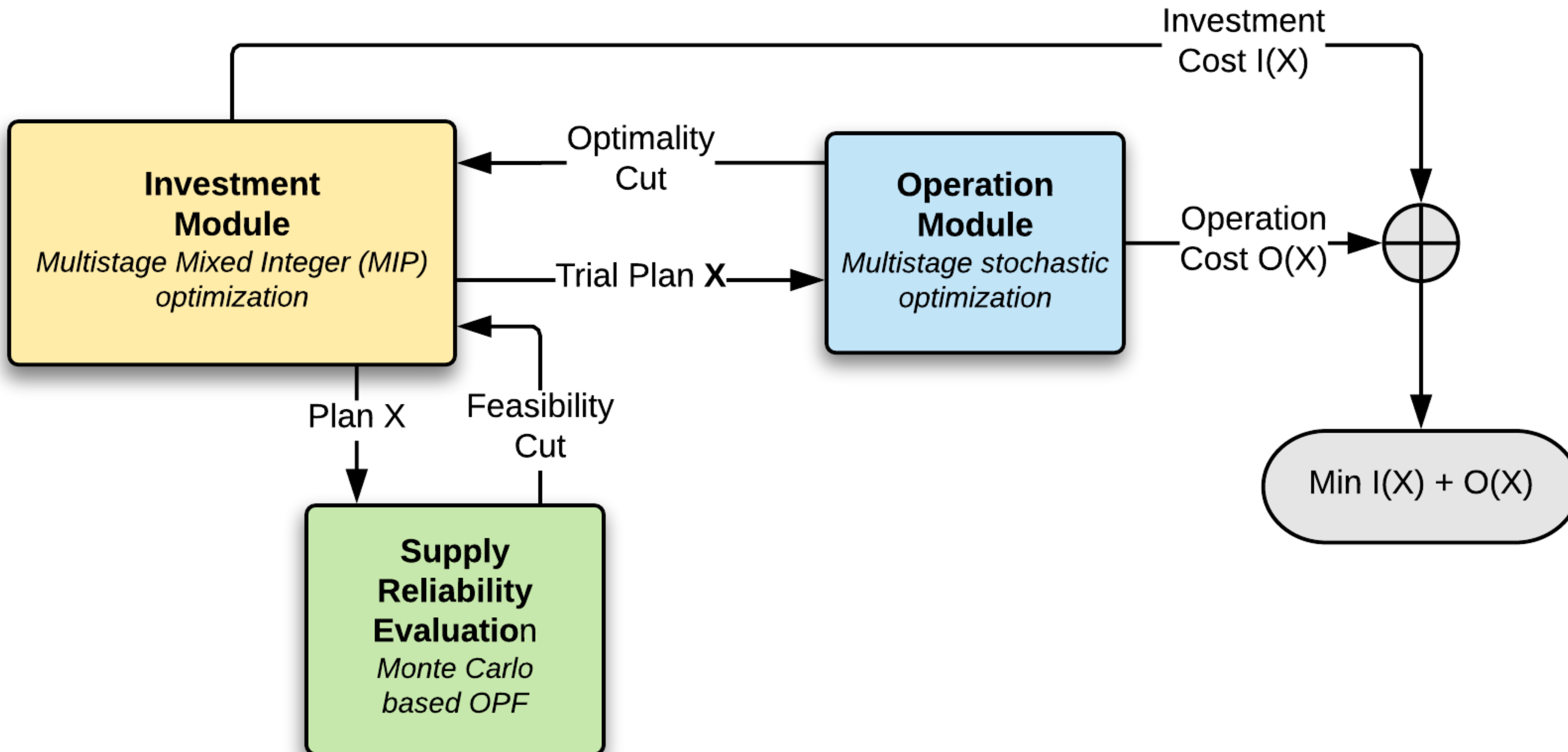
Real Life Implementations: Part 1

- Investment module:
  - Relax the integer variables during initial iterations
  - Sizing & Timing:
    - Horizon Year (HY): Sizing (S) → Timing (T)
    - Rolling Horizon (RH): S+T in each horizon
- Operation Module:
  - Aggregate hourly problems into profiles during initial iterations

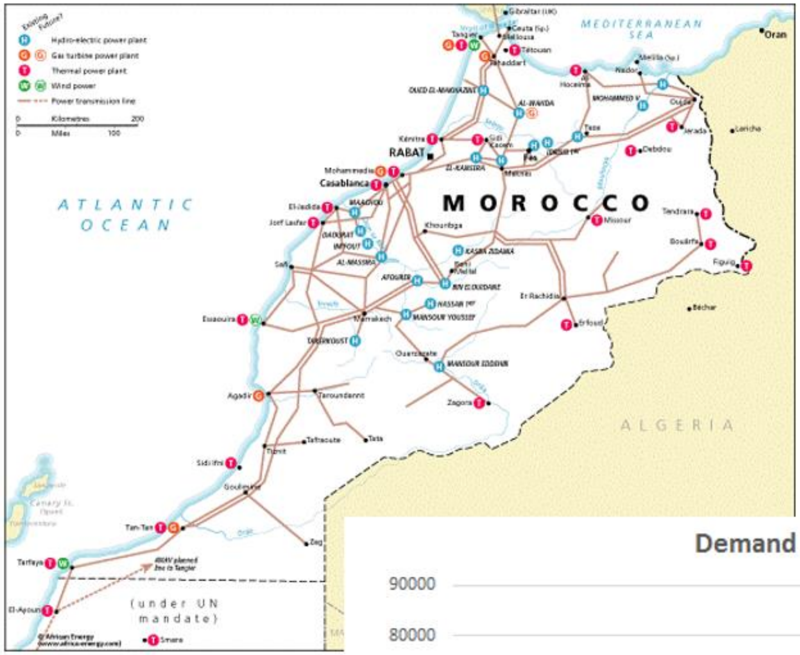
Recent Developments

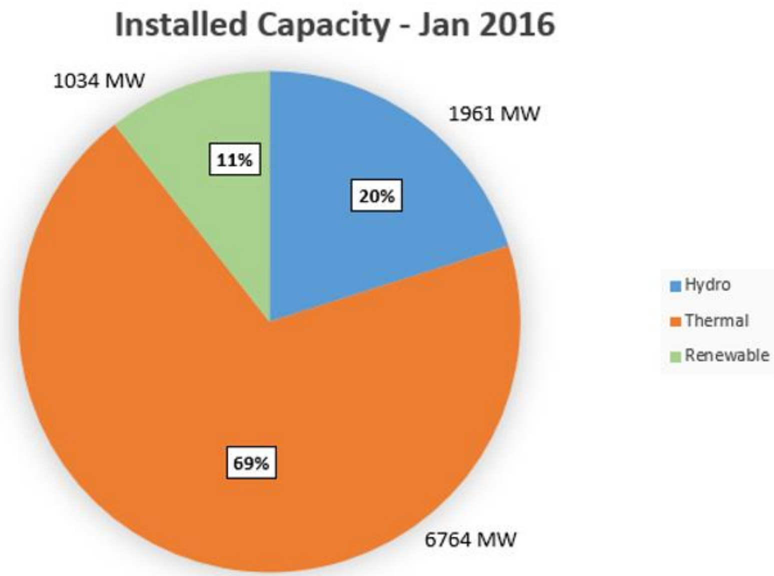
Incorporation of Reliability Criteria

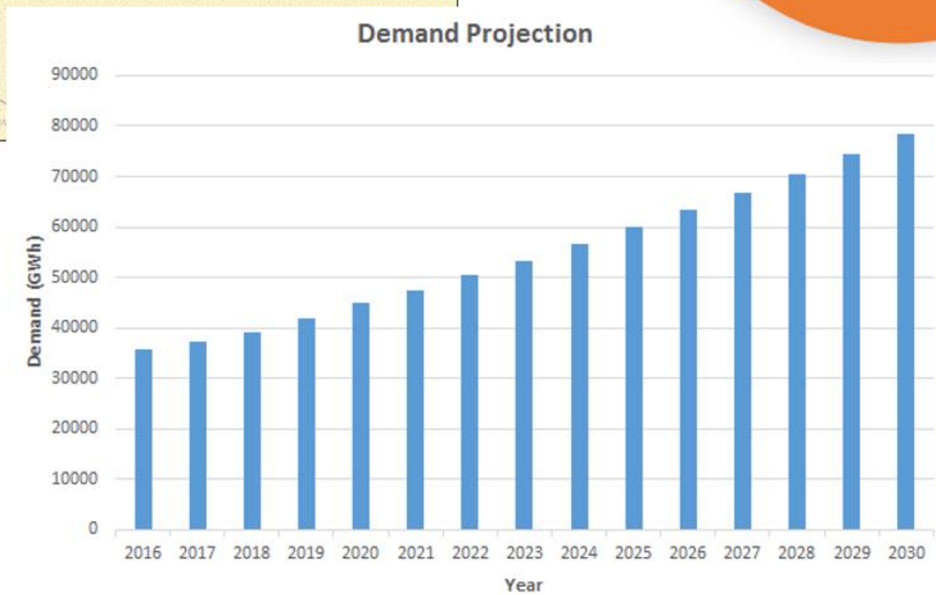
Incorporation of Reliability Criteria



Example: Morocco-Spain Expansion Plan







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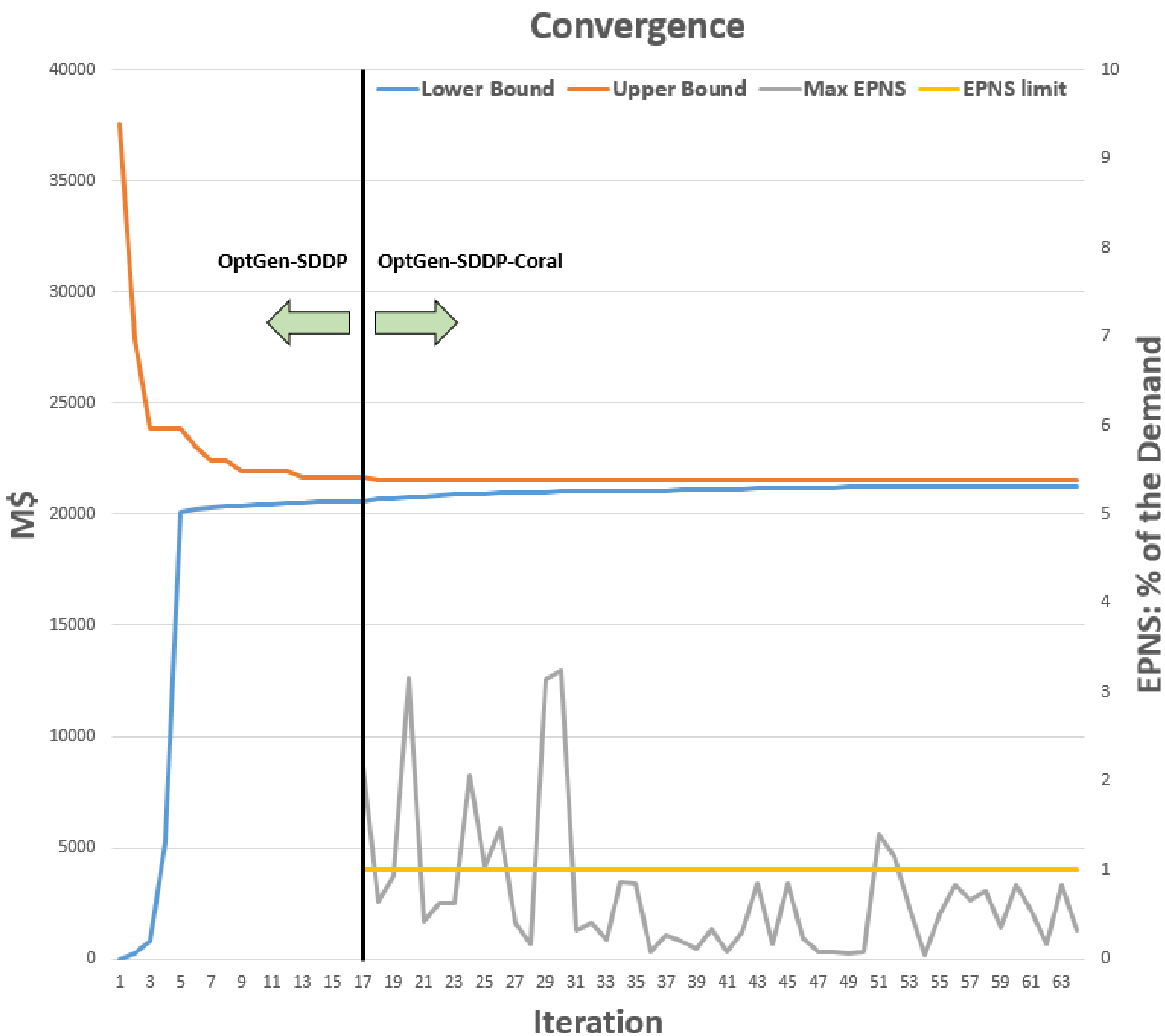
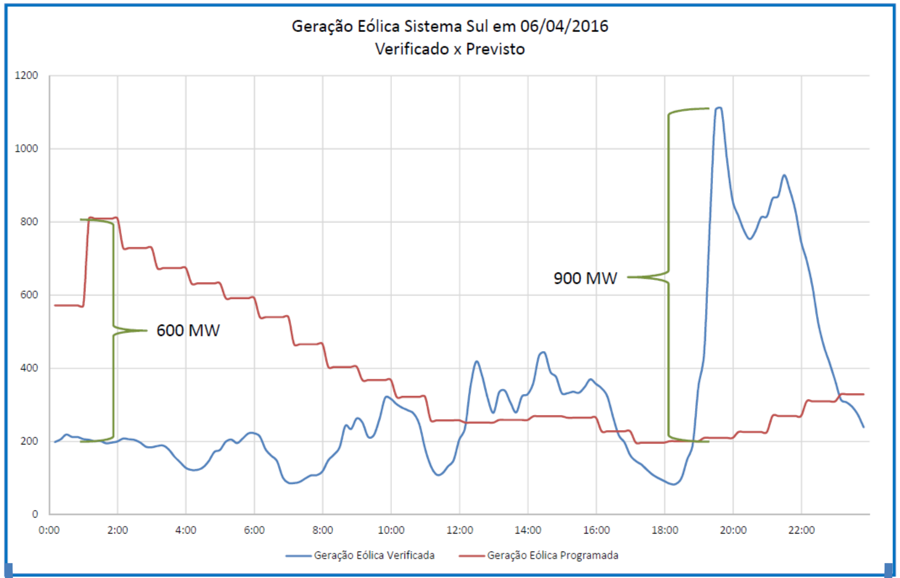
Example: Morocco-Spain Expansion Plan



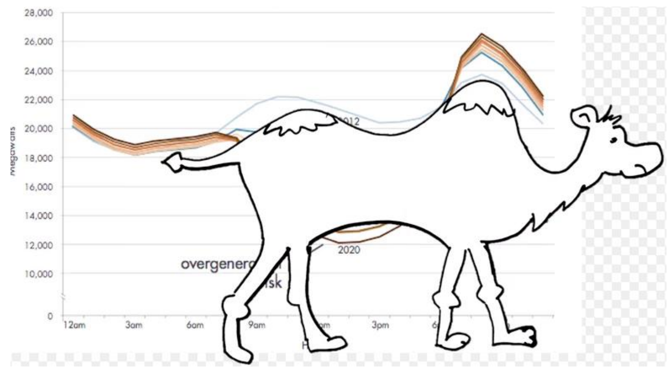
Incorporation of Probabilistic Dynamic Reserve

High Renewable Penetration - Challenges

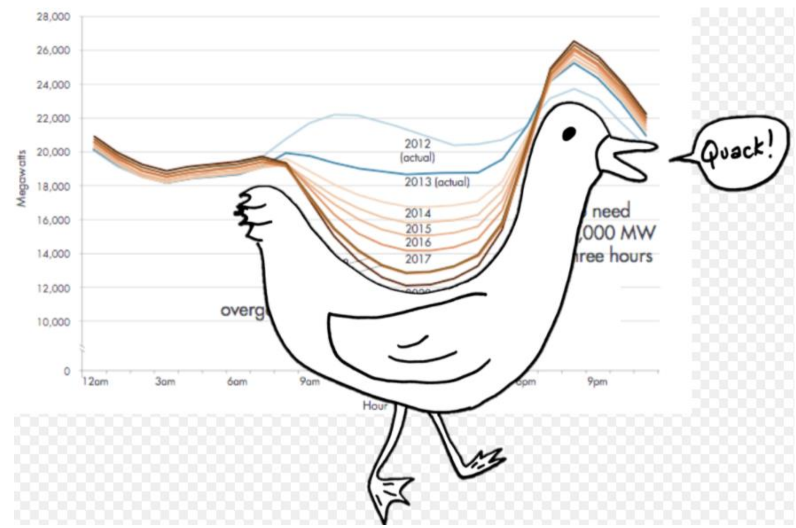


1000 MW ramp in 1 hour

900 MW difference between scheduled and verified



From dromedary to duck



- Operating Reserve: needed to guarantee security of supply

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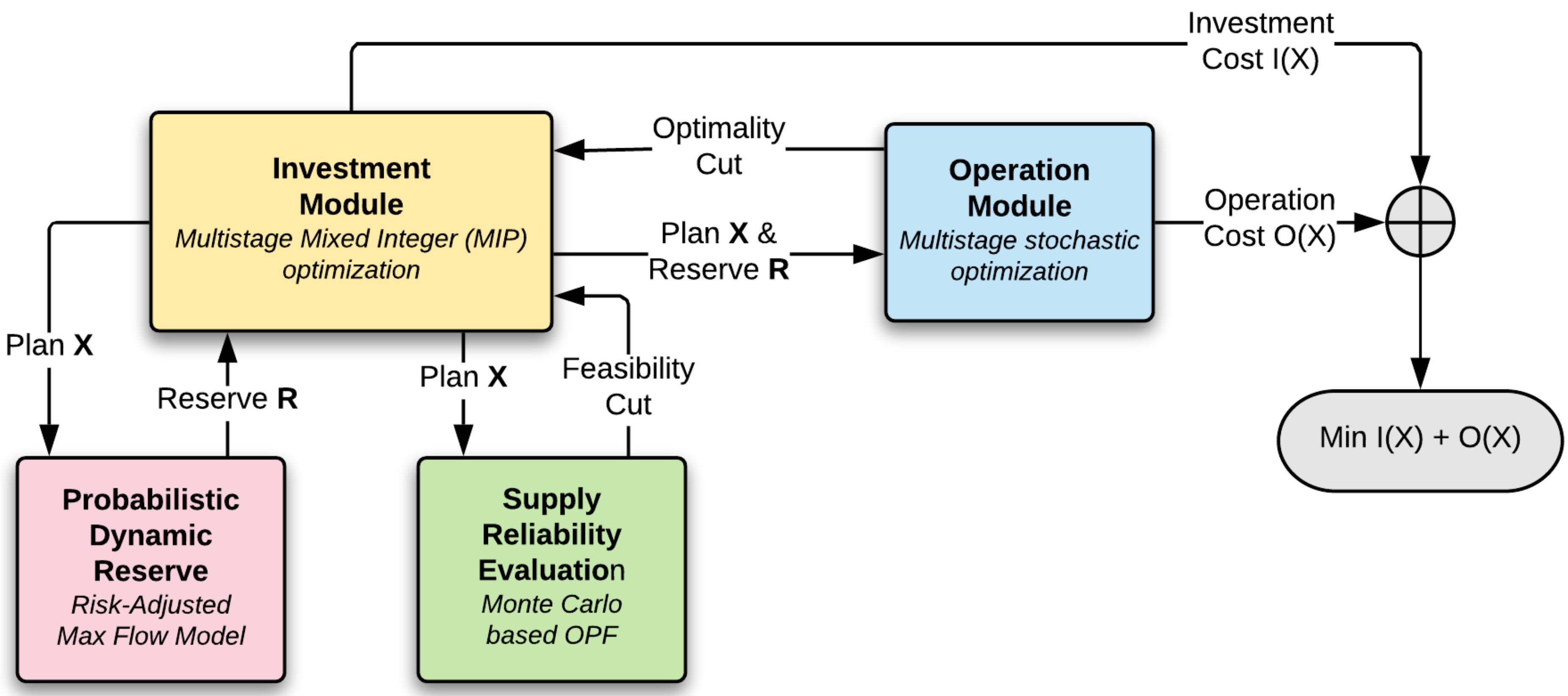
Incorporation of Probabilistic Dynamic Reserve



Case Study: The Expansion Planning of the Chilean System

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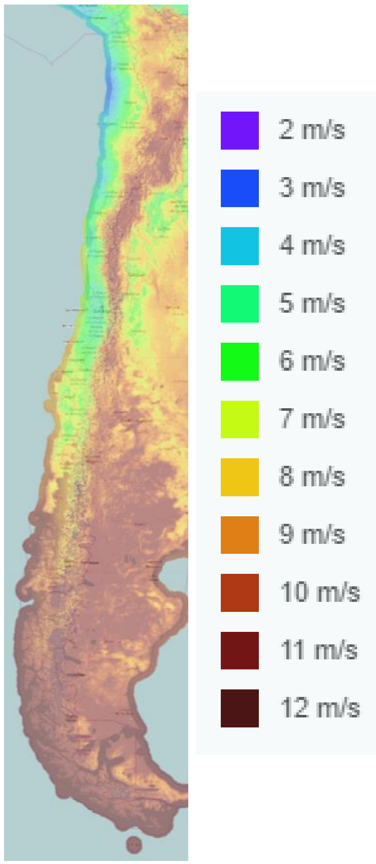
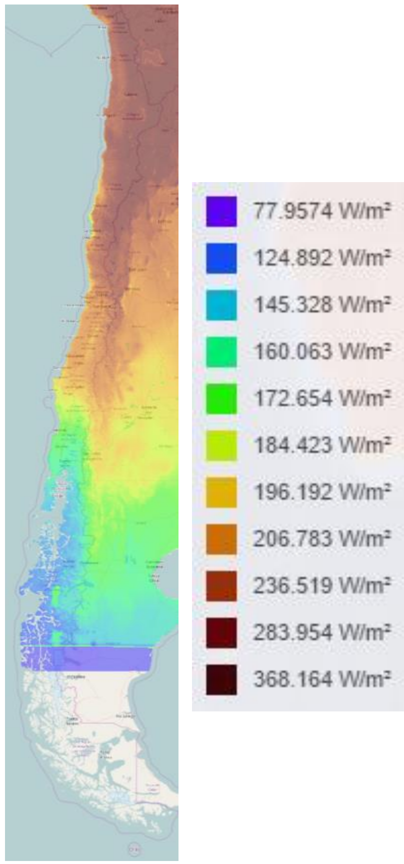
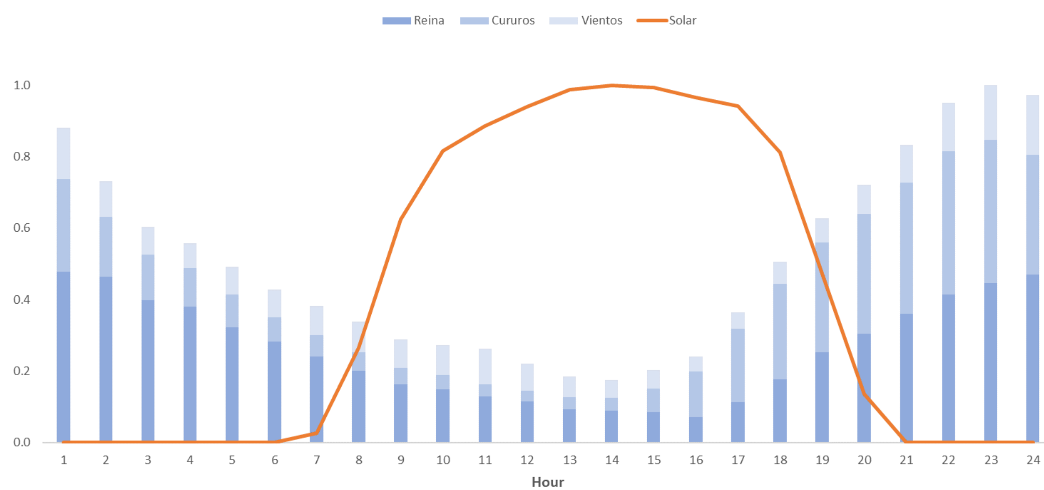
Wind



Solar





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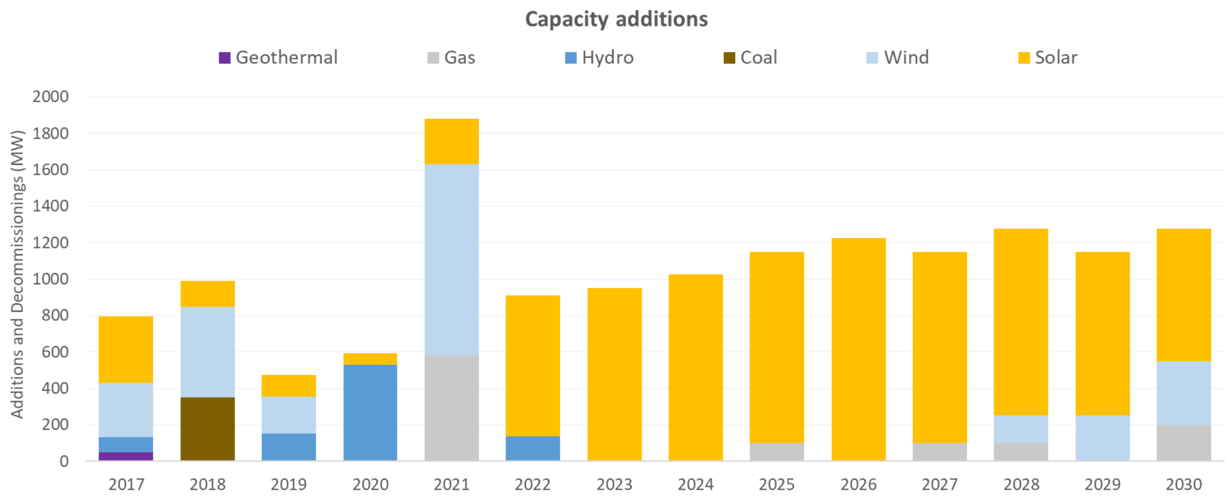

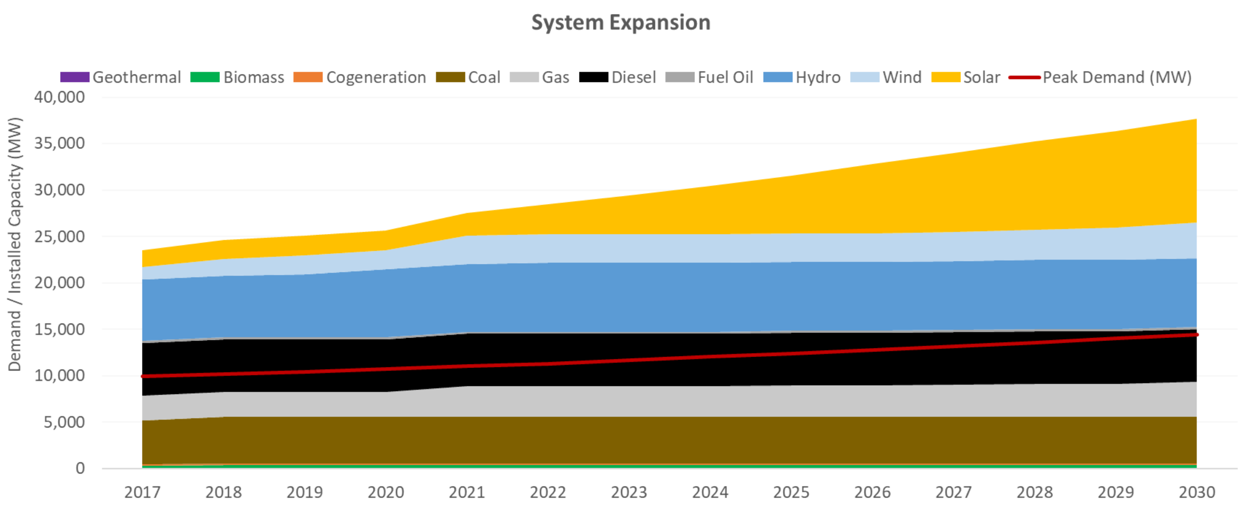

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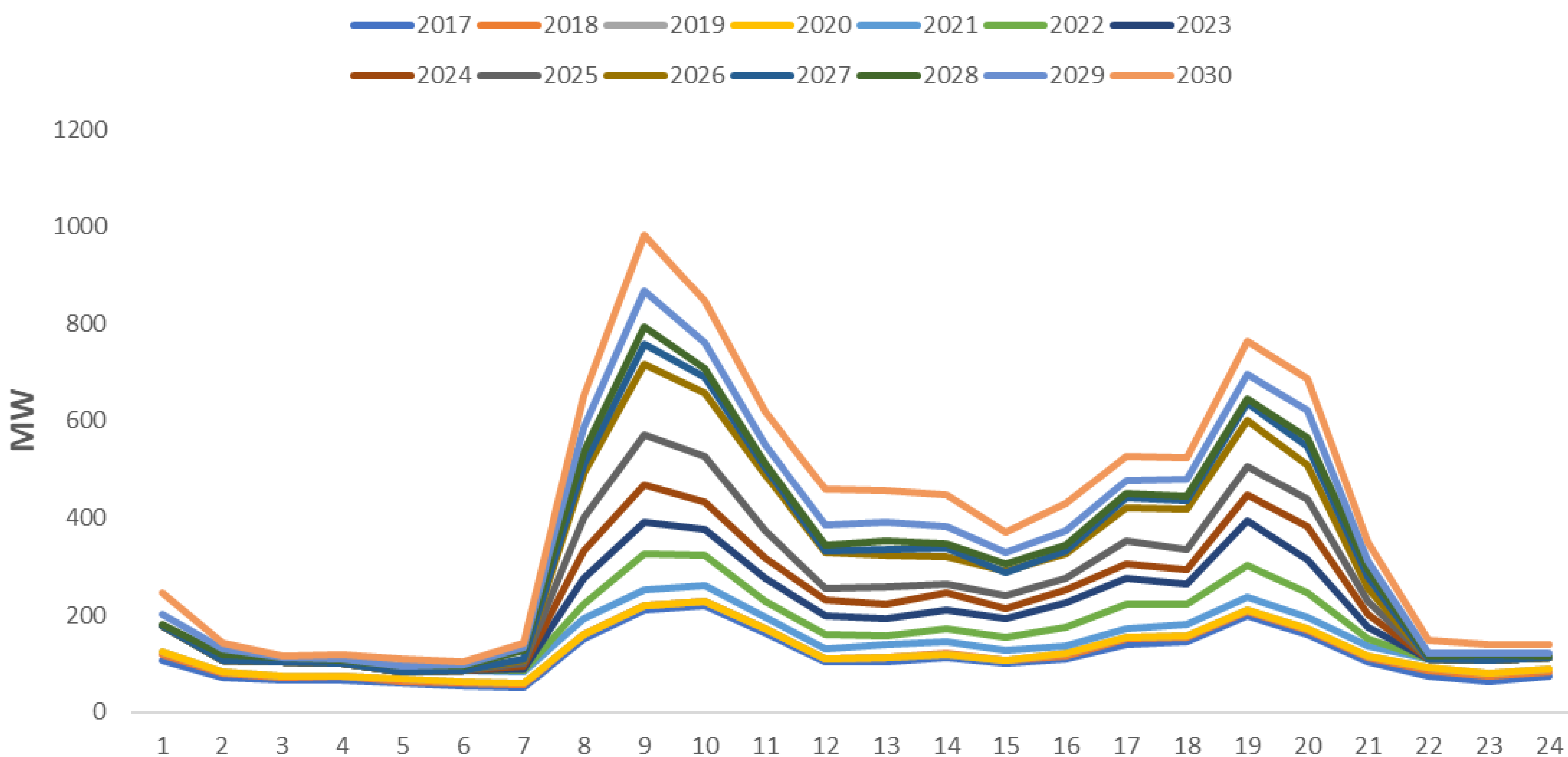
Calculation of the Probabilistic Reserve

Example R^*_{VRE} in Chile:

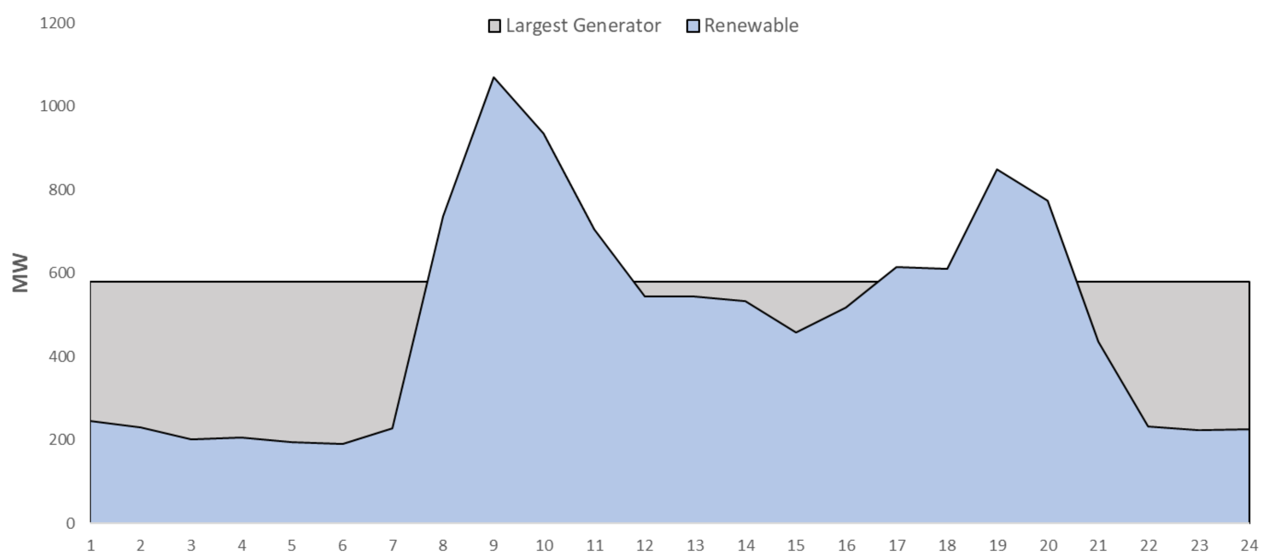


Calculation of the Probabilistic Reserve

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

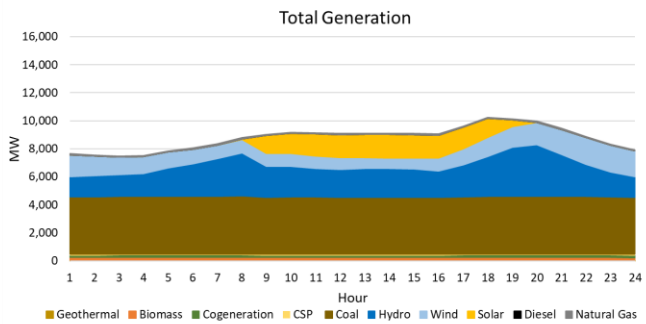
$$\mathbf{R} = \mathbf{Demand} + \mathbf{max}\{\overline{\boldsymbol{G}}\,, \boldsymbol{R}^*_{\boldsymbol{VRE}}\}$$

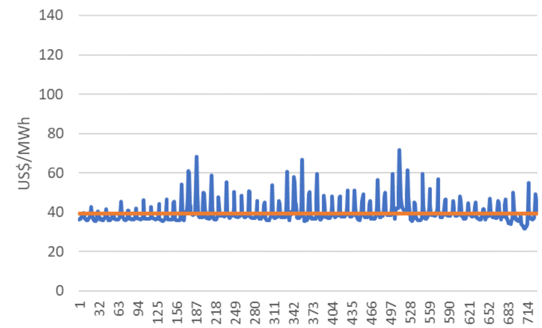
Example: $\bar{G}$ and R^*_{VRE} in Chile (2030):



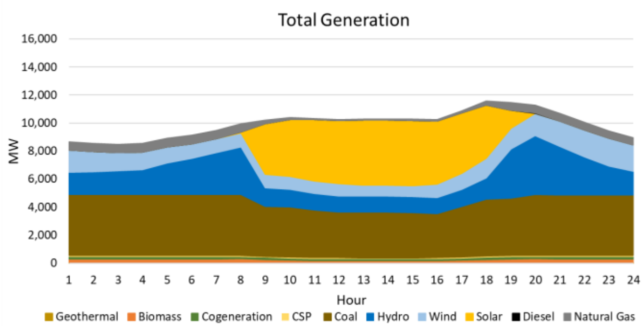
Case Study: The Expansion Planning of the Chilean System

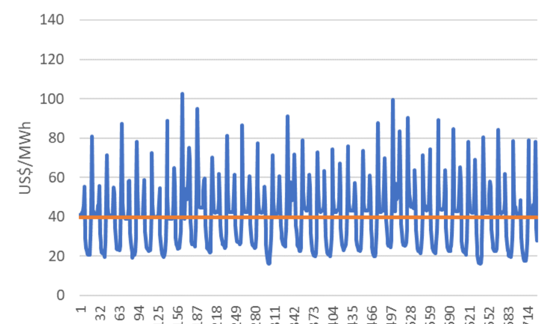
2021



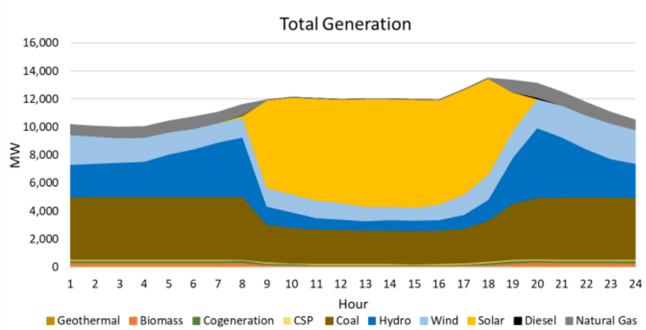


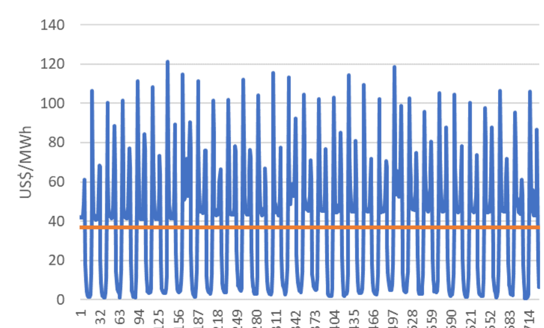
2025





2030

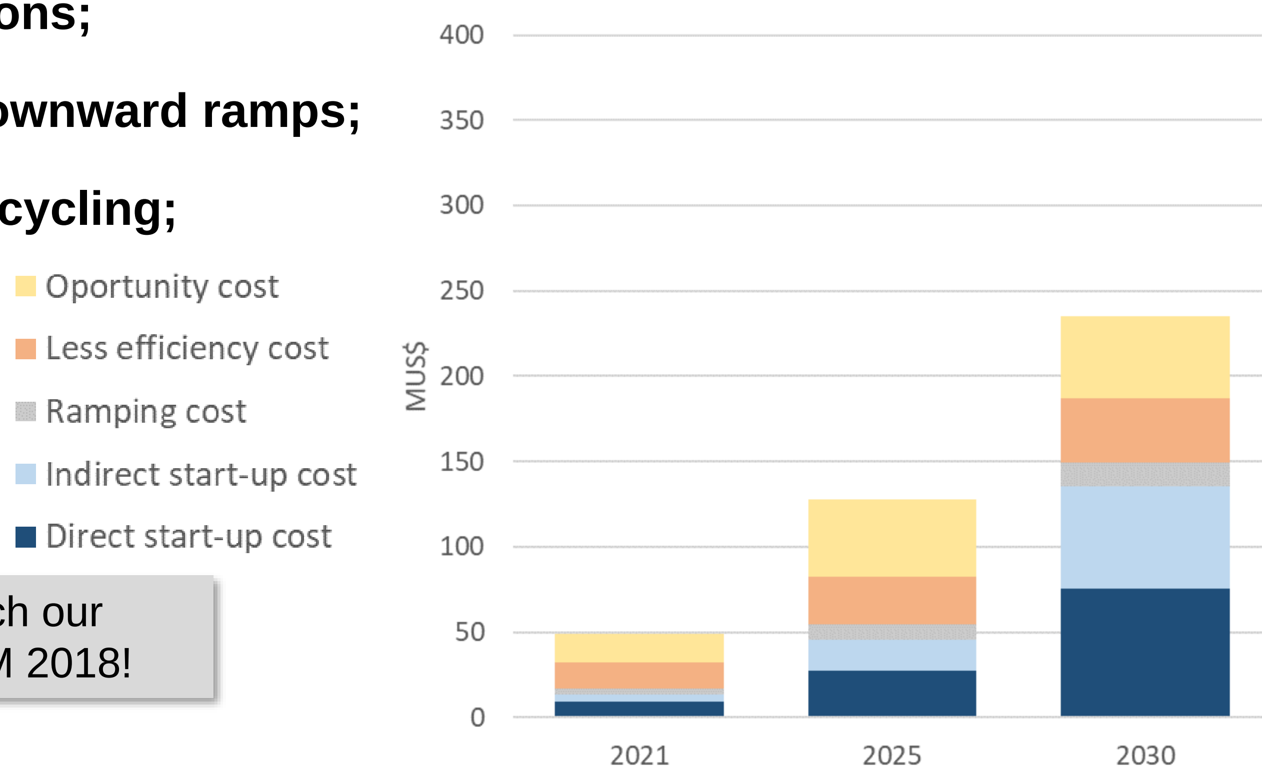




Case Study: The Expansion Planning of the Chilean System

- **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:



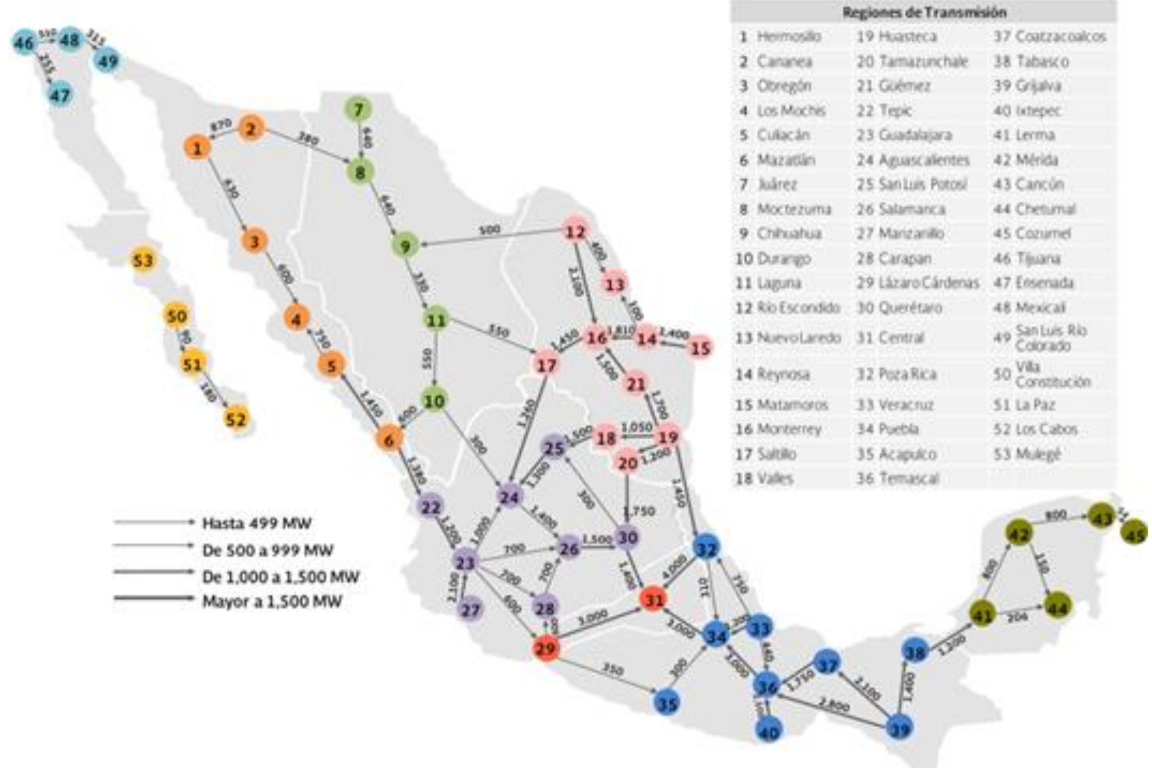
For more info, please watch our presentation in the IEEE GM 2018!

Real Life Implementations: Part 2

- Hierarchical planning of the transmission network:

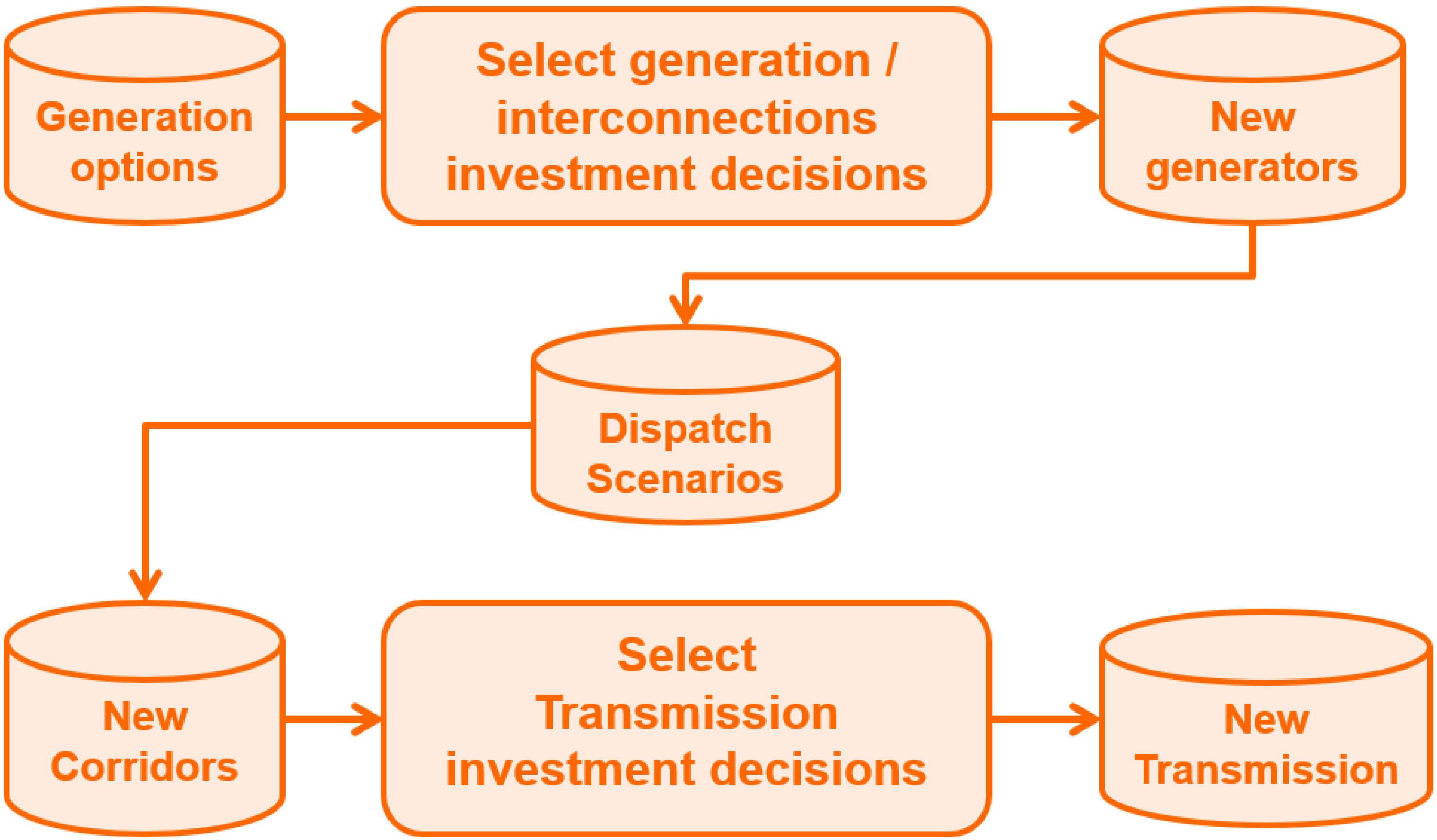
  Phase 1: Integrated expansion of generation and major transmission links

  Phase 2: Detailed Network Expansion (lower voltages)

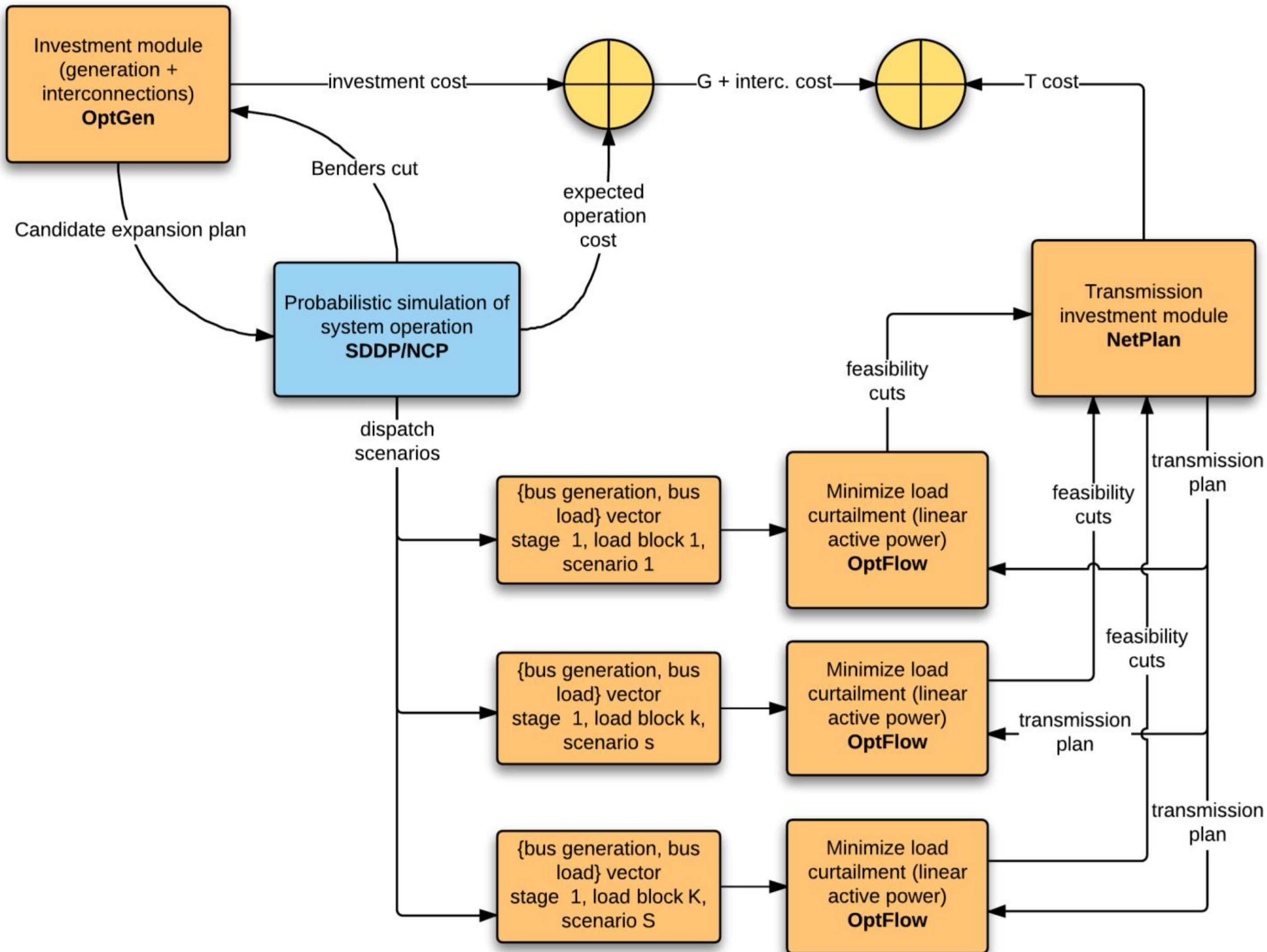


Regiones de Transmisión		
1 Hermosillo	19 Huasteca	37 Coatzacoalcos
2 Cananea	20 Tamazunchale	38 Tabasco
3 Obregón	21 Güémez	39 Grijalva
4 Los Mochis	22 Tepic	40 Ixtepec
5 Culiacán	23 Guadalajara	41 Lerma
6 Mazatlán	24 Aguascalientes	42 Mérida
7 Juárez	25 San Luis Potosí	43 Cancún
8 Moctezuma	26 Salamanca	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



Hierarchical Planning Methodology



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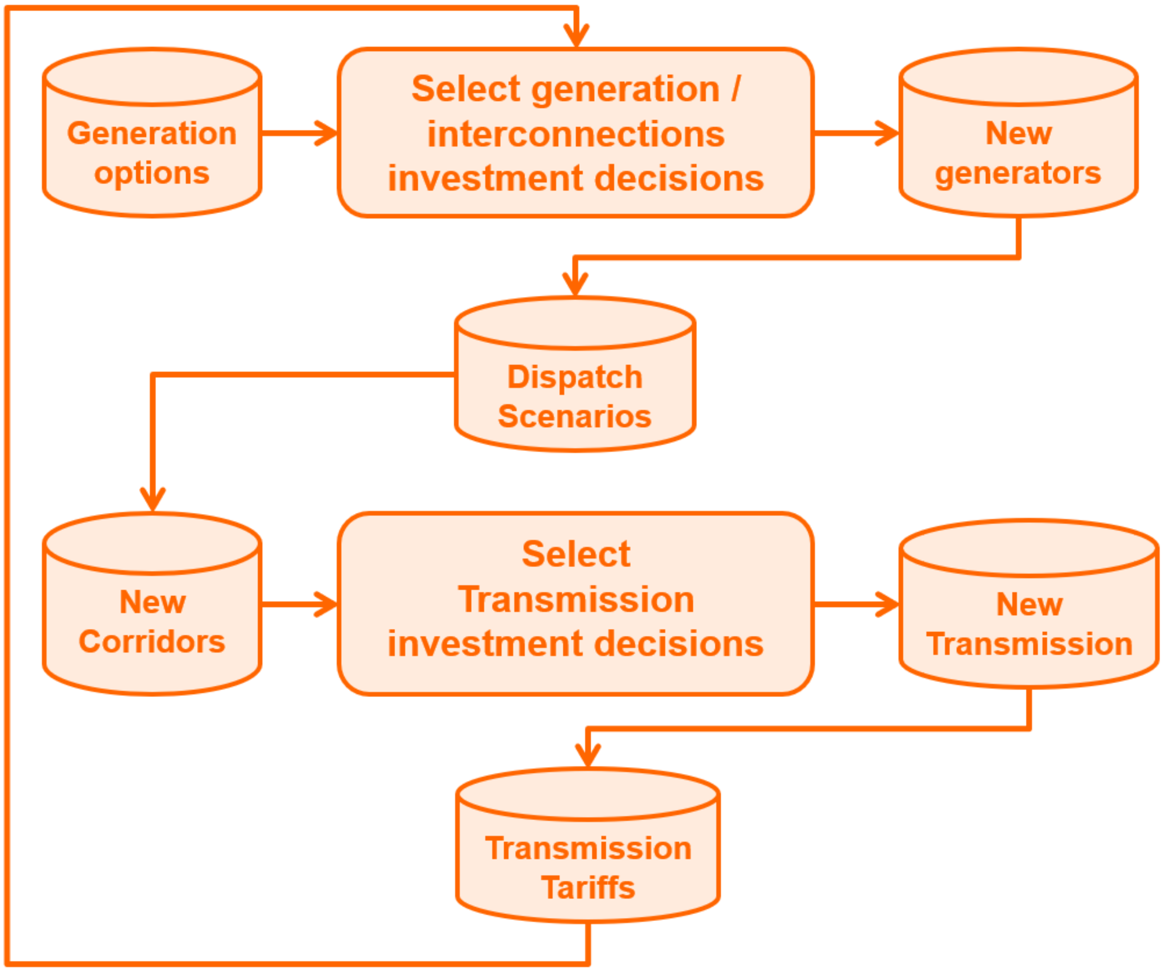
Example 1: Central America

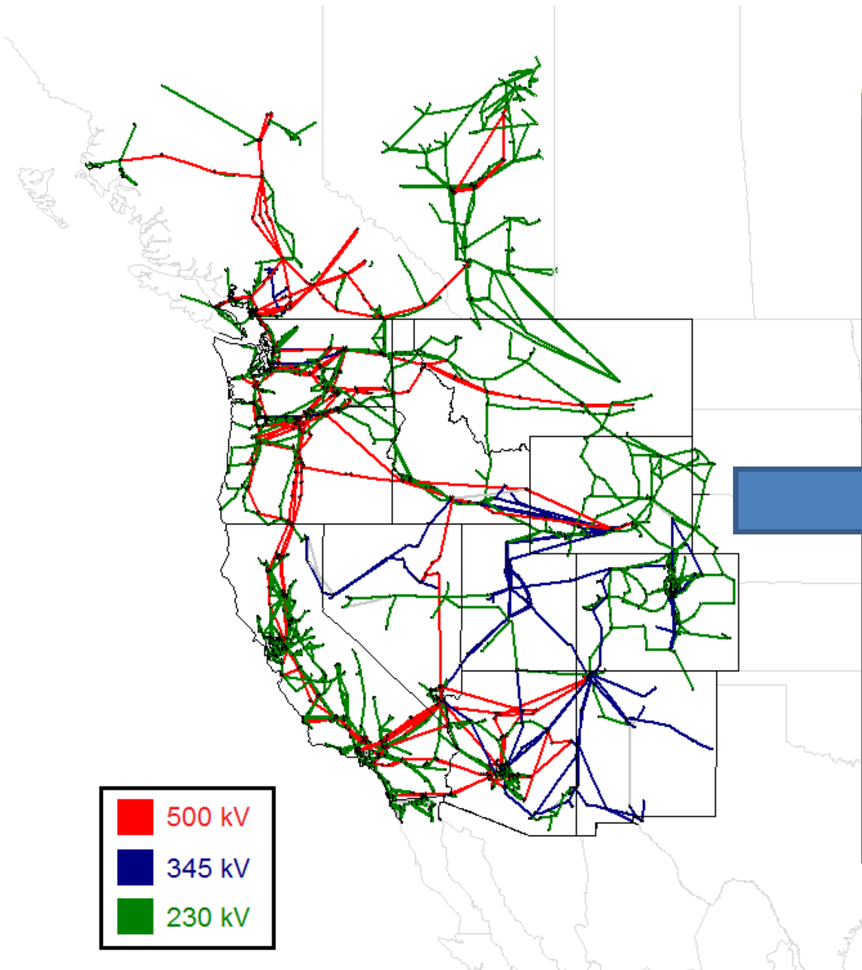
Transmission System	
Num. of Buses:	**1980**
< 69 kV	1291
69 kV	283
115 kV	74
138 kV	151
230 kV	179
400 kV	2
Num of Circuits:	**2075**
Interconnections	13
Lines	920
Transformers	1142

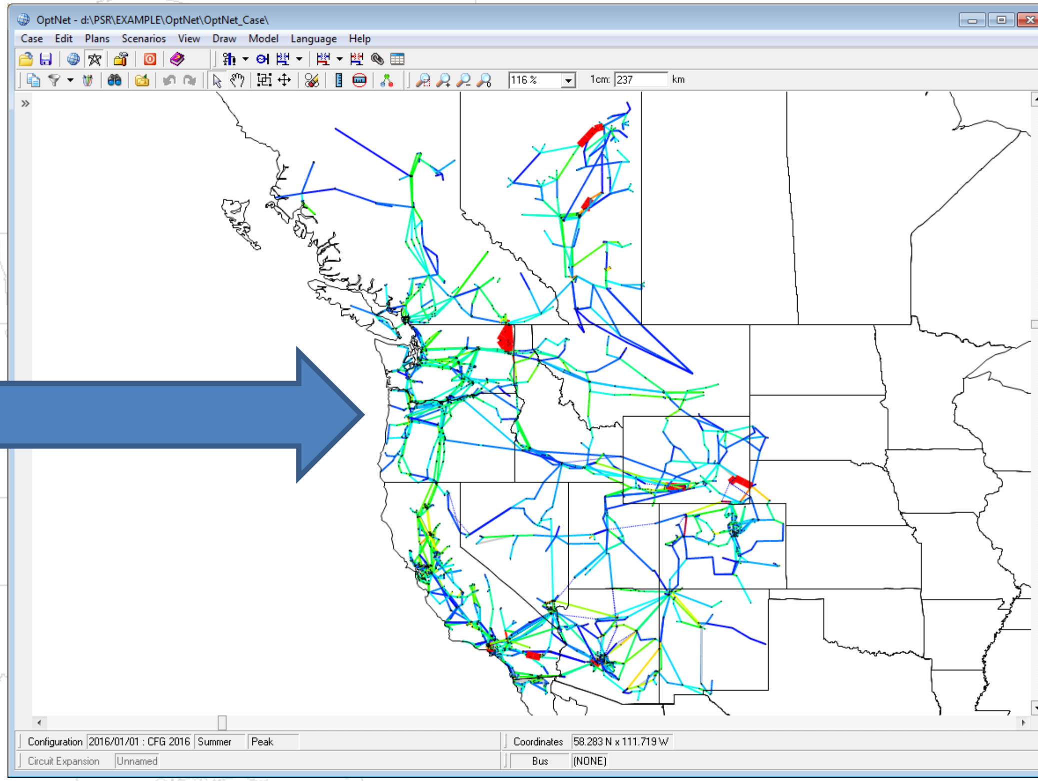
Interactive Transmission Planning

- The main difference here is the feedback: Transmission Tariffs → Generators



Example 2: WECC





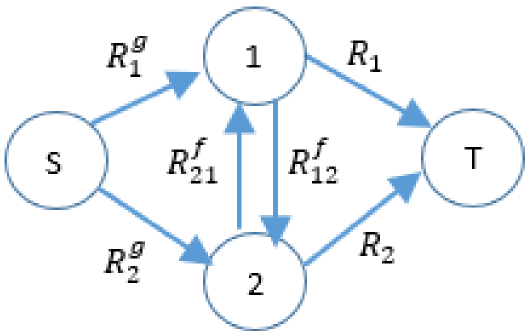
Energy Integration Assessment

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

Calculation of the Dynamic Probabilistic Reserve – Multi-area

- Graph representation:



$$R_i^g = \sum_{k \in i} (\overline{G_k} - g_k)$$

$$R_{ij}^f = \overline{F_{ij}} - f_{ij}$$

- Minimum cut to generate constraints related to exchange of reserve between areas:

$$R_1^g + R_2^g \geq R_1 + R_2$$

$$R_1^g + R_{21}^f + R_2 \geq R_1 + R_2$$

$$R_2^g + R_{12}^f + R_1 \geq R_1 + R_2$$

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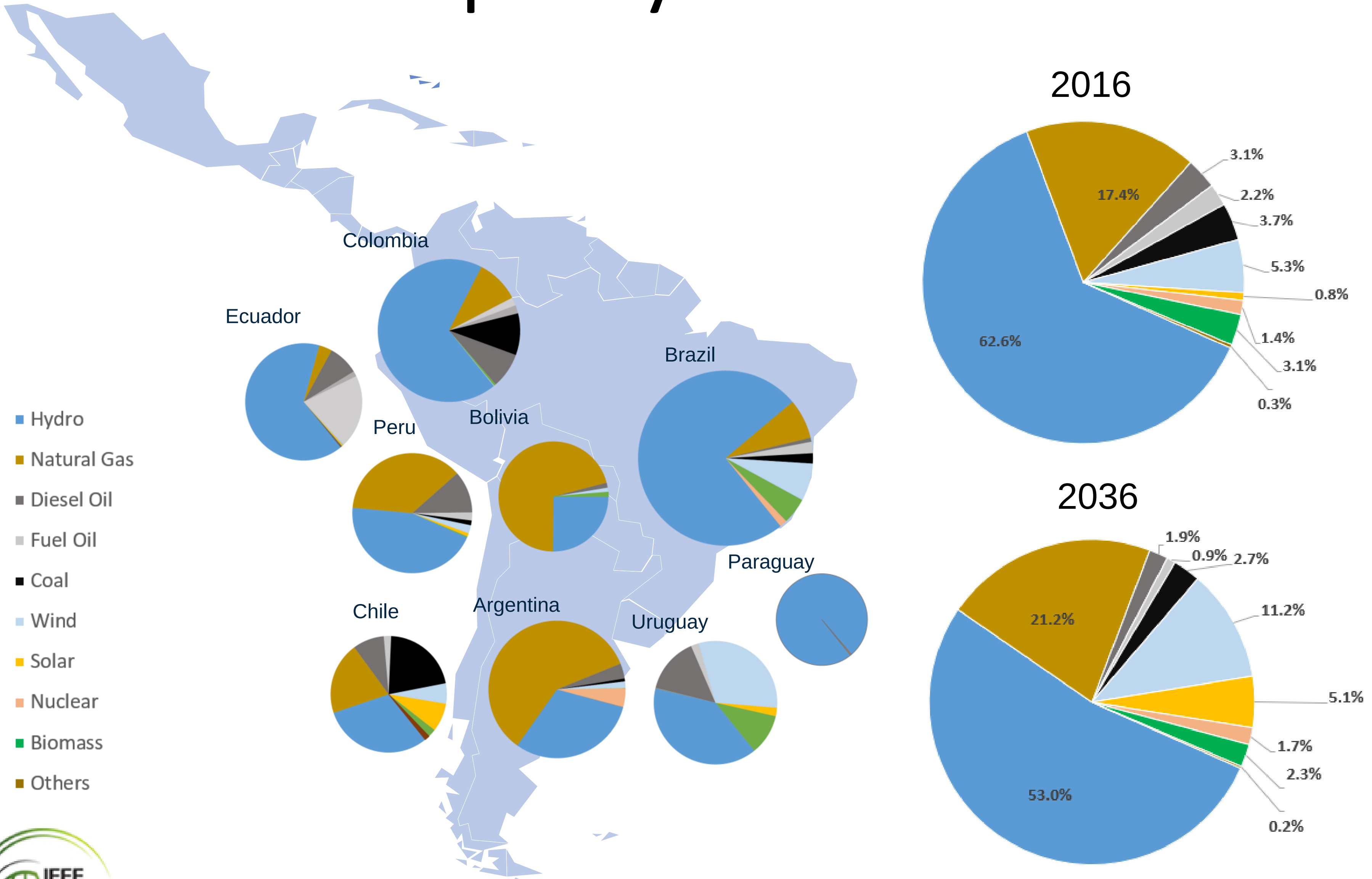
Installed Capacity – South America



Interconnections Analysed

Interconnections Evaluated
CO-EC
CO=EC
AR-UY // BR
AR-UY-BR
CH // AR-UY-BR
CH-AR-UY-BR
CH=AR-UY-BR
CO-EC // PE
CO=EC // PE
CO=EC-PE
CO=EC-PE //CH=AR-UY-BR
CO=EC-PE-CH=AR-UY-BR
CO=EC-PE=CH=AR-UY-BR
CO=EC-PE-CH=AR-UY-BR // BO
CO=EC-PE-CH=AR-UY-BR + PE-BO
CO=EC-PE-CH=AR-UY-BR + BO-AR
CO=EC-PE-CH=AR-UY-BR + PE-BO-AR
CO=EC-PE-CH=AR-UY-BR + PE-BO-AR-BR
BR//BO
BR-BO
CO=EC-PE-CH=AR-UY-BR // BO
CO=EC-PE-CH=AR-UY-BR + PE-BO-AR
CO=EC-PE-CH=AR-UY-BR + PE-BO-AR-BR

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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%

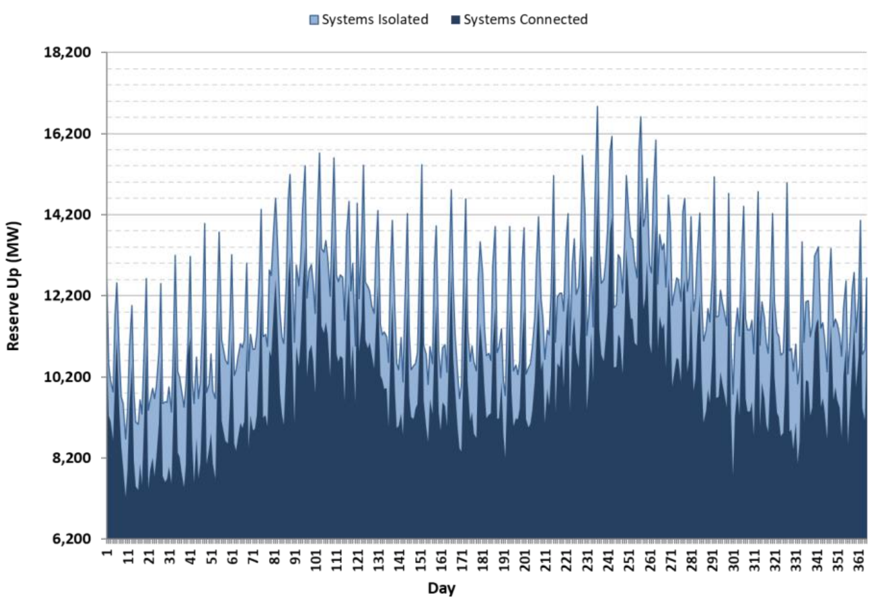
Investment Cost = 92 $MUS\$$

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

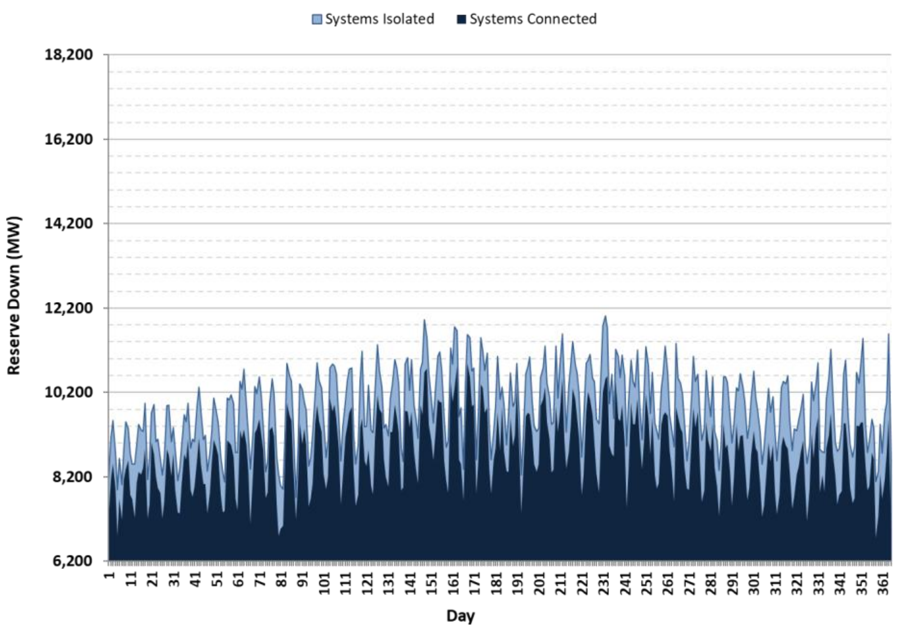
Results

- Reduction of secondary reserve requirements:

Upwards:

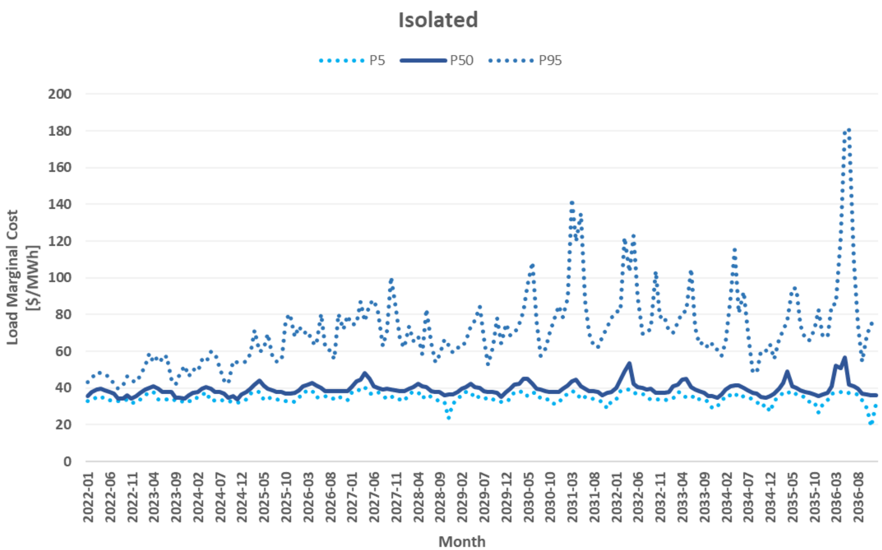


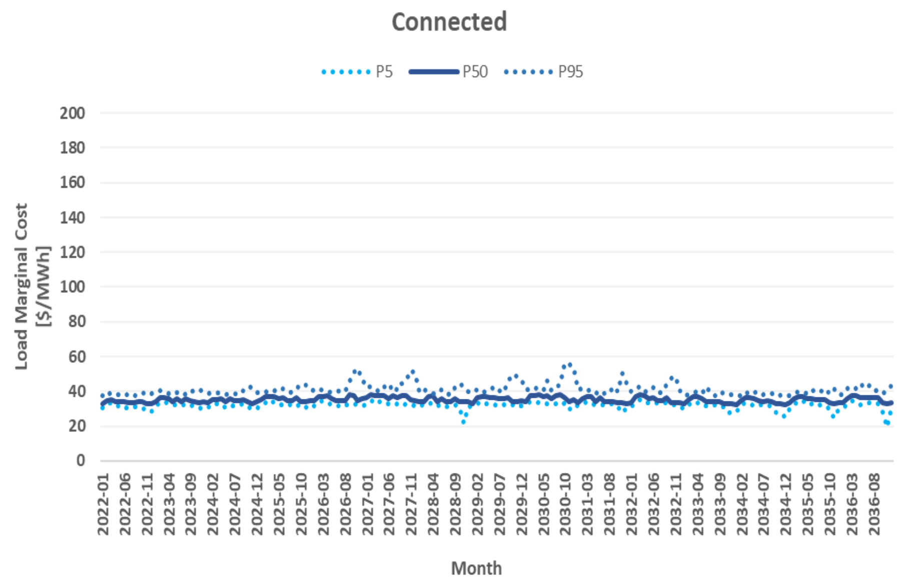
Downwards:



Other Results

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





In summary…

- The optimal capacity planning problem is very challenging for several reasons: stochastic, multistage, nonconvex (binary decisions), multiscale (from hourly resolution in operations to multi-year planning horizons) and they are large scale problems
- As illustrated in this presentation, one effective solution approach is Benders decomposition, which iteratively solves an investment subproblem, formulated as a MIP optimization and an operation subproblem, formulated as a multistage stochastic optimization model, which is solved by a Stochastic Dual Dynamic Programming algorithm
- The Benders scheme is very flexible and allows the use of several solution strategies, such as relaxation in the initial iterations, rolling horizon, sizing and timing schemes and others
- The Benders planning scheme has been applied by our team in real-life planning studies of dozens of countries worldwide, with system sizes ranging from 2 GW to 180 GW. In addition, it has been applied in regional studies covering up to 9 countries with an area larger than the US or the EU, with a total installed capacity of 250 GW
- Some recent extensions of the Benders planning scheme include the representation of supply reliability constraints and the co-optimization of: (i) probabilistic reserve (to manage renewable variability); (ii) generation investments; and (iii) operating costs

Ongoing developments

- Use of decision trees to represent uncertainties in the future cost of renewables, annual load growth rates (important for emerging economies) and construction times and costs
- Use of a novel Monte Carlo Markov Chain / Cross Entropy scheme to reduce the computation effort of the supply reliability evaluation model
- Use of the recently developed extension of the SDDP algorithm, SDDiP, to handle nonconvexities in the feedback from the operations to the investment model
- Integration of time consistent risk aversion schemes such as CVaR (already used in SDDP) into an optimal expansion planning scheme

Questions? Thanks!

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IEEE PES Webinar
PSOPE Committee
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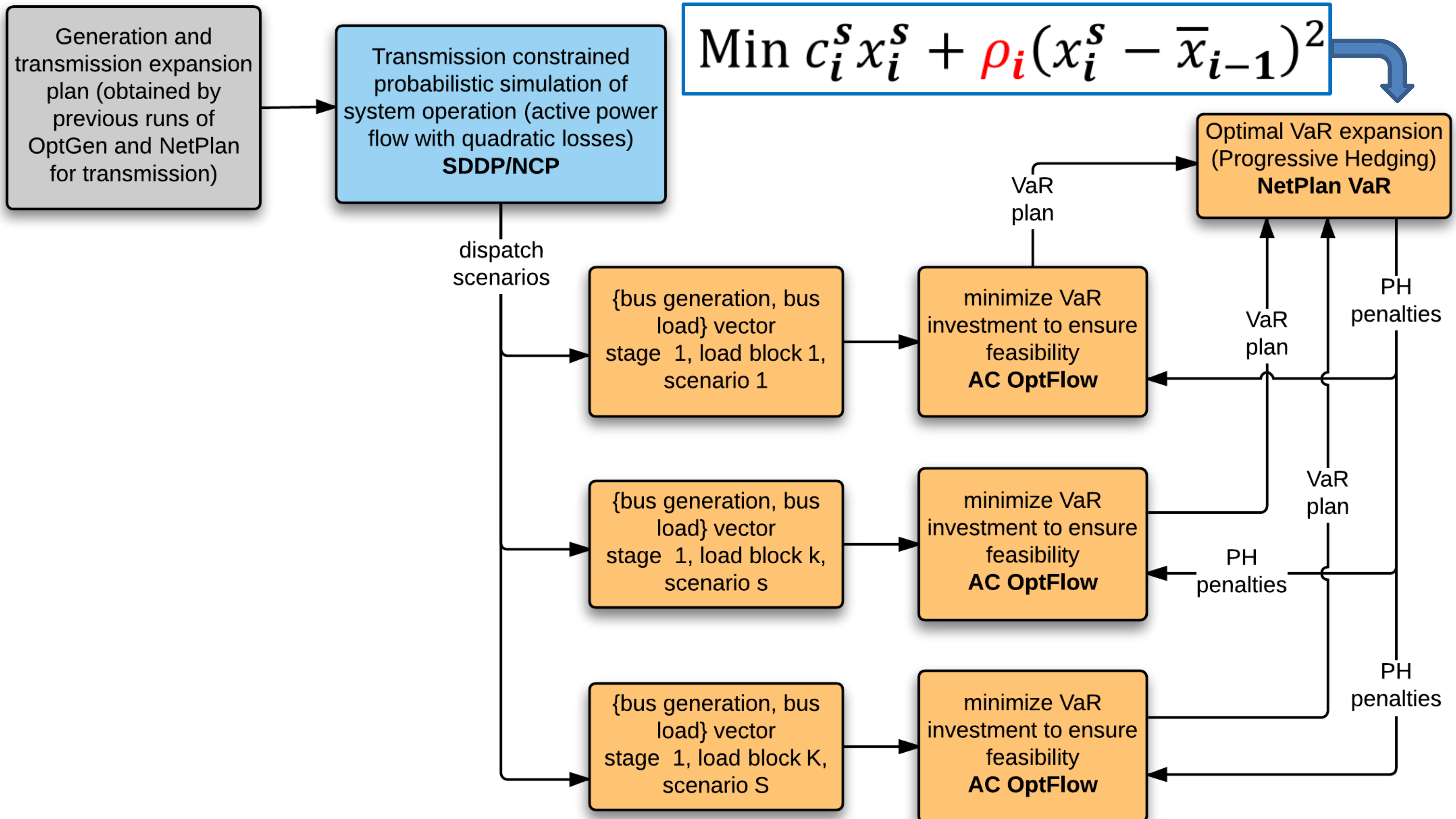
Appendix

Optimal VAr Planning

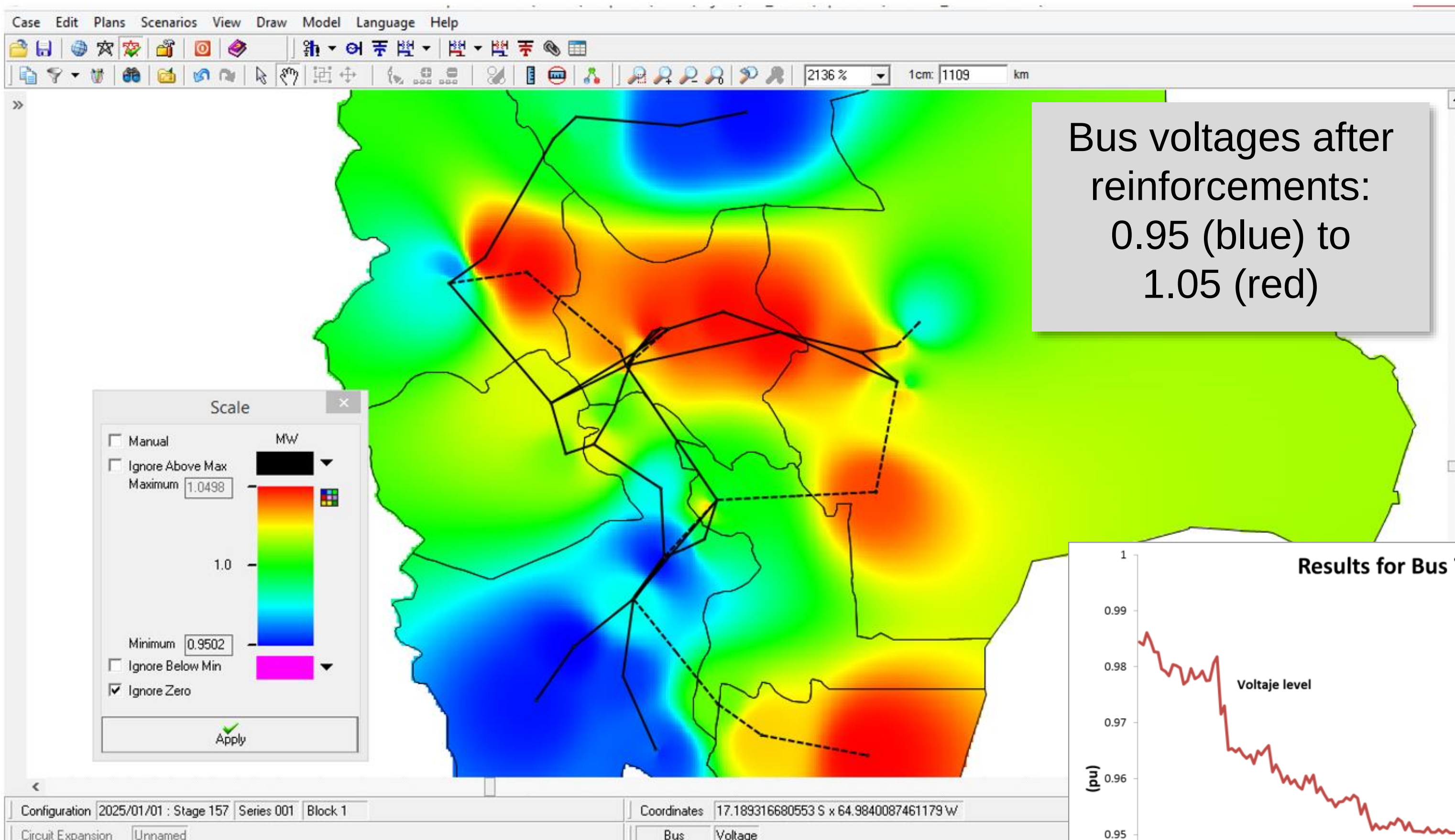
- The VAr planning model is executed after the transmission planning model
- The planning scheme is also based on a set of dispatch scenarios, produced by a probabilistic transmission-constrained simulation of system operation:
  - In this case, the simulation assumes that the transmission reinforcements have been implemented and uses a linearized optimal power flow model with quadratic losses.
- The optimal Var plan is obtained by a progressive hedging (PH) algorithm
  - Each dispatch scenario is evaluated by a full AC optimal power flow model, where the objective is to minimize investment costs in VaR resources (capacitors, reactors) that eliminate operating violations (typically bus voltage limits) + a quadratic term associated to the PH scheme

Optimal VAr Planning

$$\text{Min } c_i^s x_i^s + \rho_i (x_i^s - \bar{x}_{i-1})^2$$



Application Example: Bolivia



Bus voltages after reinforcements: 0.95 (blue) to 1.05 (red)