LABORATORY OF APPLIED MATHEMATICAL PROGRAMMING AND STATISTICS

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Optimization Models for Transmission Expansion Planning under Uncertainty: a Review of Best Practices and Key Concepts

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AGENDA

In this talk

- Key concepts
- Inconsistency threats
- Uncertainty
- Optimization models and frameworks
- Conclusions

Motivation and key concepts

What is the objective of a transmission plan?

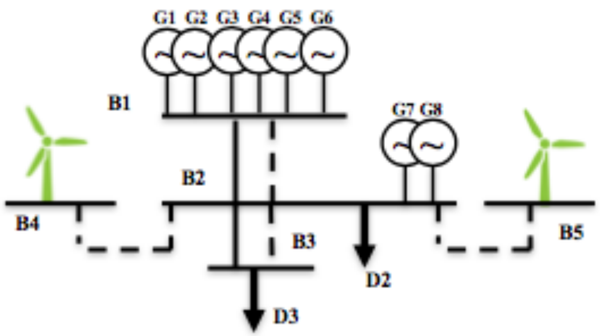
To define 3W's:

- whether, when, and what types
- of transmission facilities to build
- minimizing costs and maximizing economic, reliability, and environmental benefits for the future operation of the system to society

Motivation and key concepts

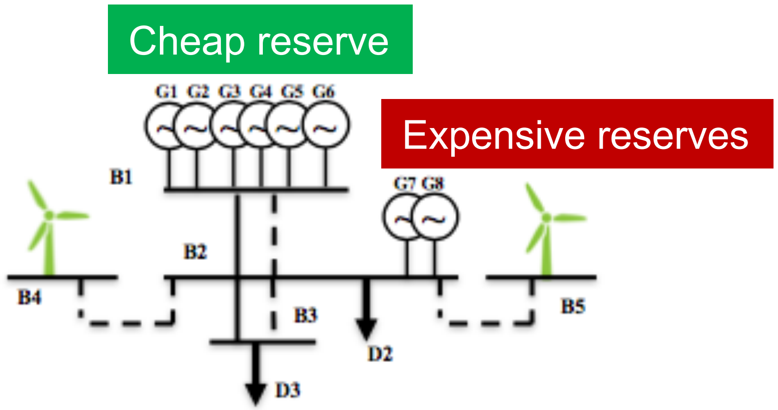
It is key to consider complex interactions between substitute and complementary resources

- Transmission resources and generation investment and sitting
  - Proactive vs reactive planning
  - Anticipative proactive planning to foster investments in ”correct places”
- How to capture such complex interaction?
  - GT co-optimization plays a key role!
  - Competition is a key feature needed to align gradients and make things work as expected



Motivation and key concepts

It is key to consider complex interactions between substitute and complementary resources

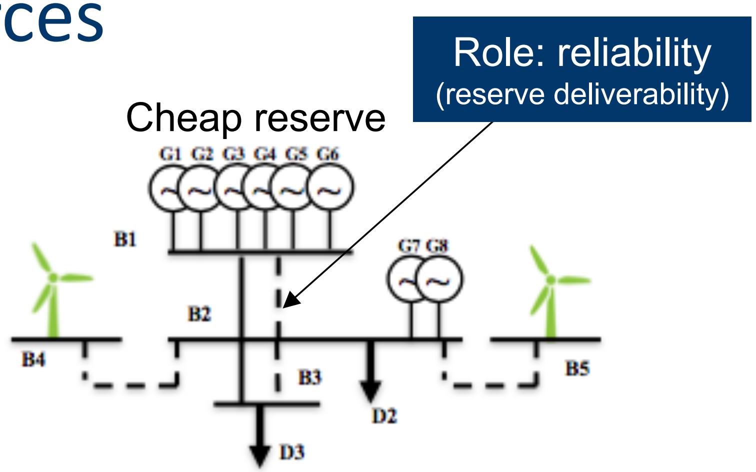


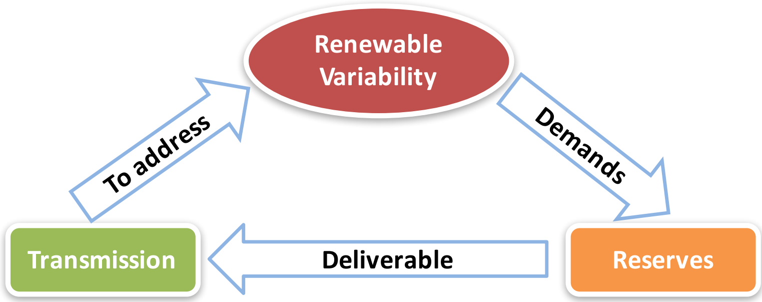
- Renewable generation and reserve levels
  - Connecting renewables requires more reserves
- How to capture this complex interaction?
  - Uncertainty modeling plays a key role!

Motivation and key concepts

It is key to consider complex interactions between substitute and complementary resources

- New transmission lines may avoid expensive reserve deployment and ensure deliverability
  - New lines can bring cheap reserves from other areas
  - Voltage Kirchhoff's Law (KVL) and security criteria constraints must be considered
- How to capture this complex interaction?
  - Short-term operation modeling plays a key role!





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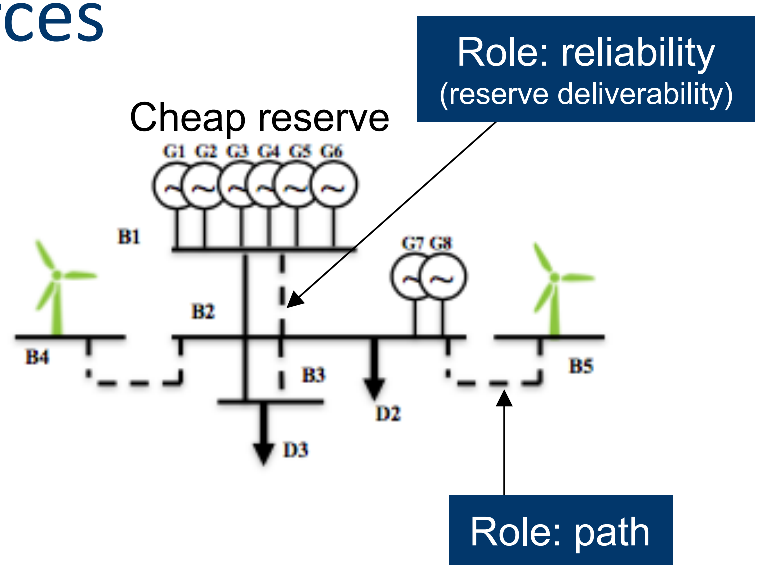

- Connecting renewables demand new lines to provide both path and reliability
- It is crucial to represent short-term uncertainties and operational constraints to capture the reliability and flexibility role of transmission assets

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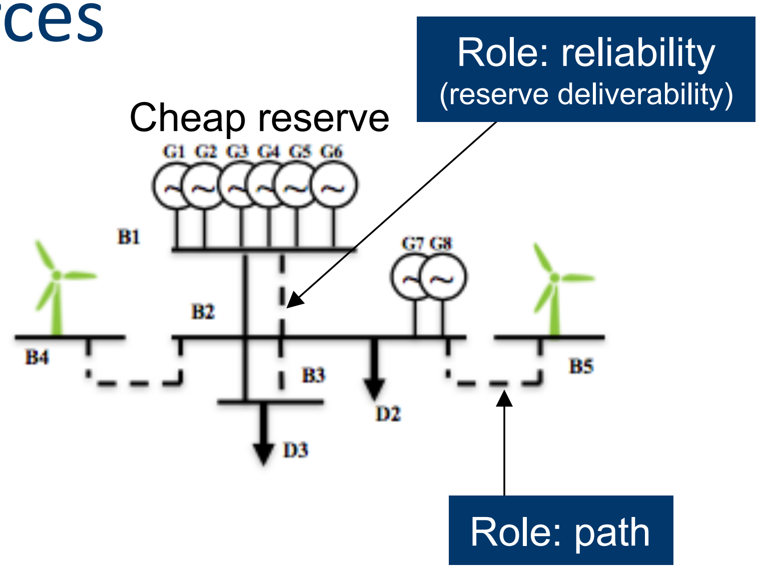

- Connecting renewables demand new lines to provide both path and reliability
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Key concepts and best practices

The key concepts that a TEP model should consider:

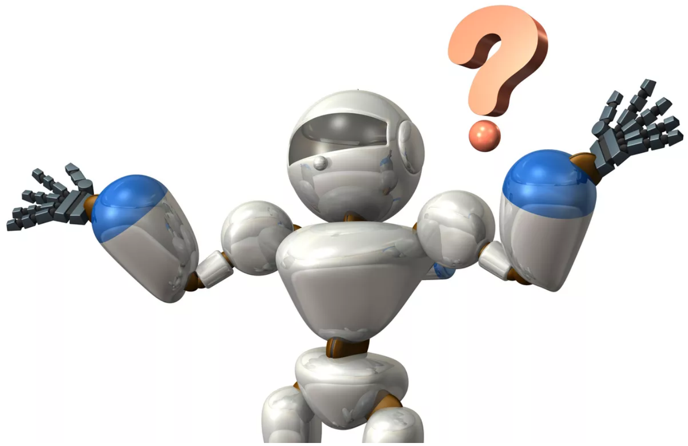
- Complex interactions between transmission assets, new generation, and reserves
- Flexibility and Adaptability
- Short-term generation and load variability

Please, take a moment to read the first two articles

How to define a good practice?

How to make computer models to capture those relevant feature?

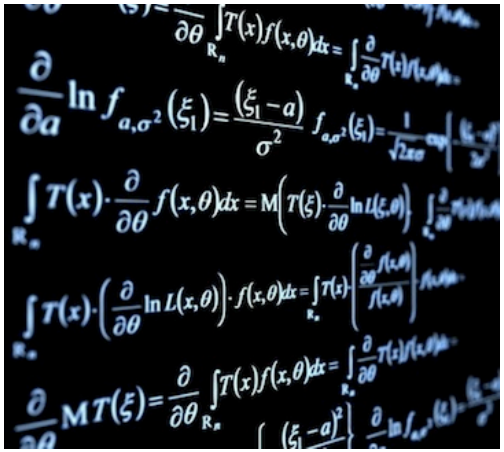
- We need to tell them what we want
- But it can not be done case by case…



How to define a good practice?

This is the goal of Operations Research

1. We express our goals through an objective function
2. We teach them how our world functions through mathematical expressions (constraints and variables)
3. And this is converted into a code that runs and give us a solution

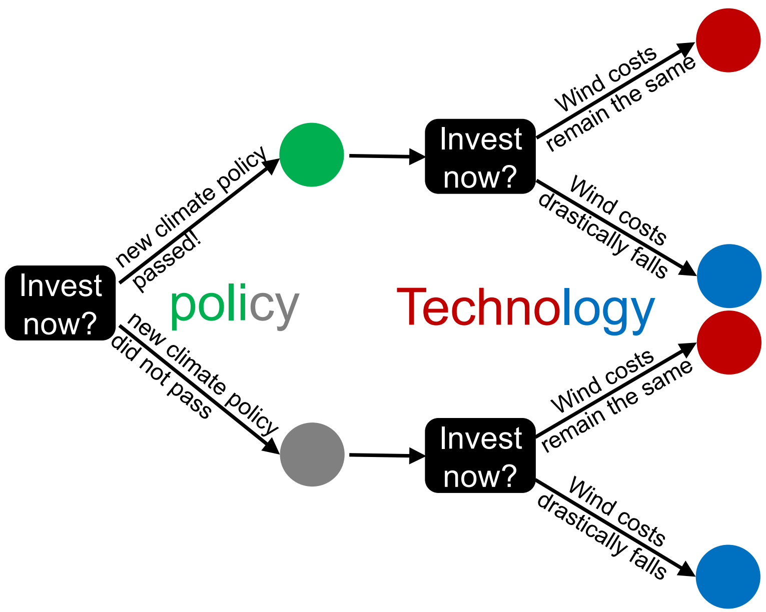


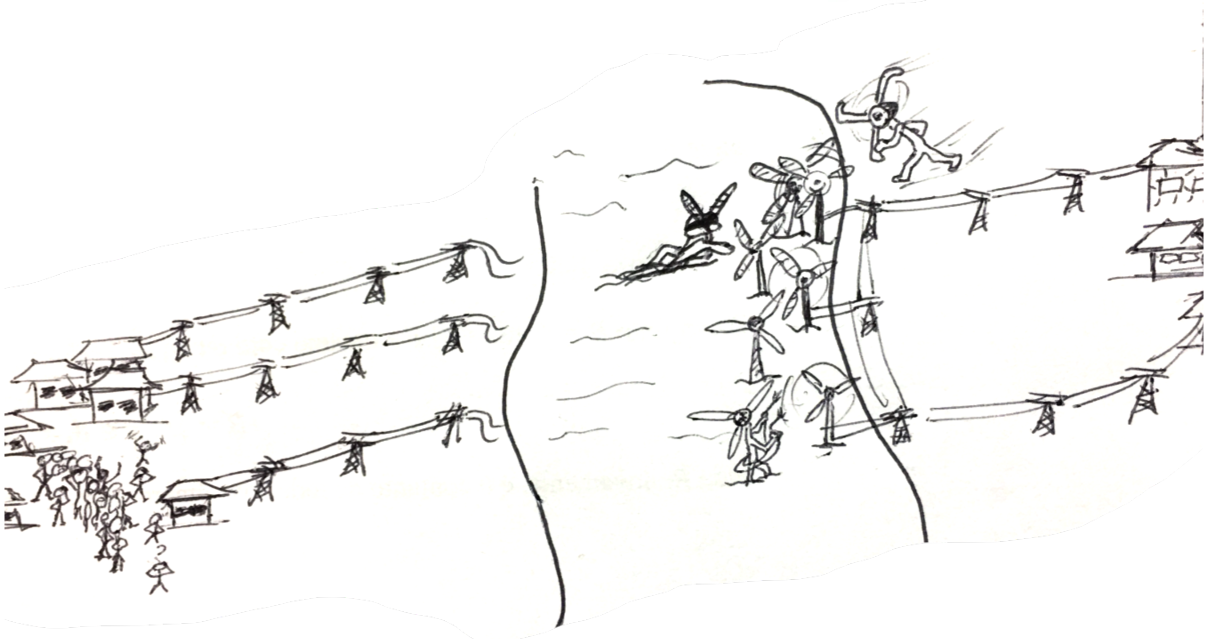
- Depending on how we describe the world, steps 1-3, the solutions will be more or less realistic (useful)…

Key concepts and best practices

The key concepts that a TEP model should consider:

- Flexibility and Adaptability against uncertainty
  - TEP must be optimized under uncertainty
  - Flexibility to consider a realistic decision setup (policy)
  - Framework capable to capture the value of decisions that allows the system to cope with many different long-run scenarios (with unconsidered ones too! But how?)





Key concepts and best practices

The key concepts that a TEP model should consider:

- Short-term generation and load variability
  - Security and reserve deliverability
  - Operational constraints and flexibilities
  - Simplifications on the operational side in TEP models often lead to very unrealistic models
  - The operational part of the model provides the cost and reliability signals for the investment part

Key concepts and best practices

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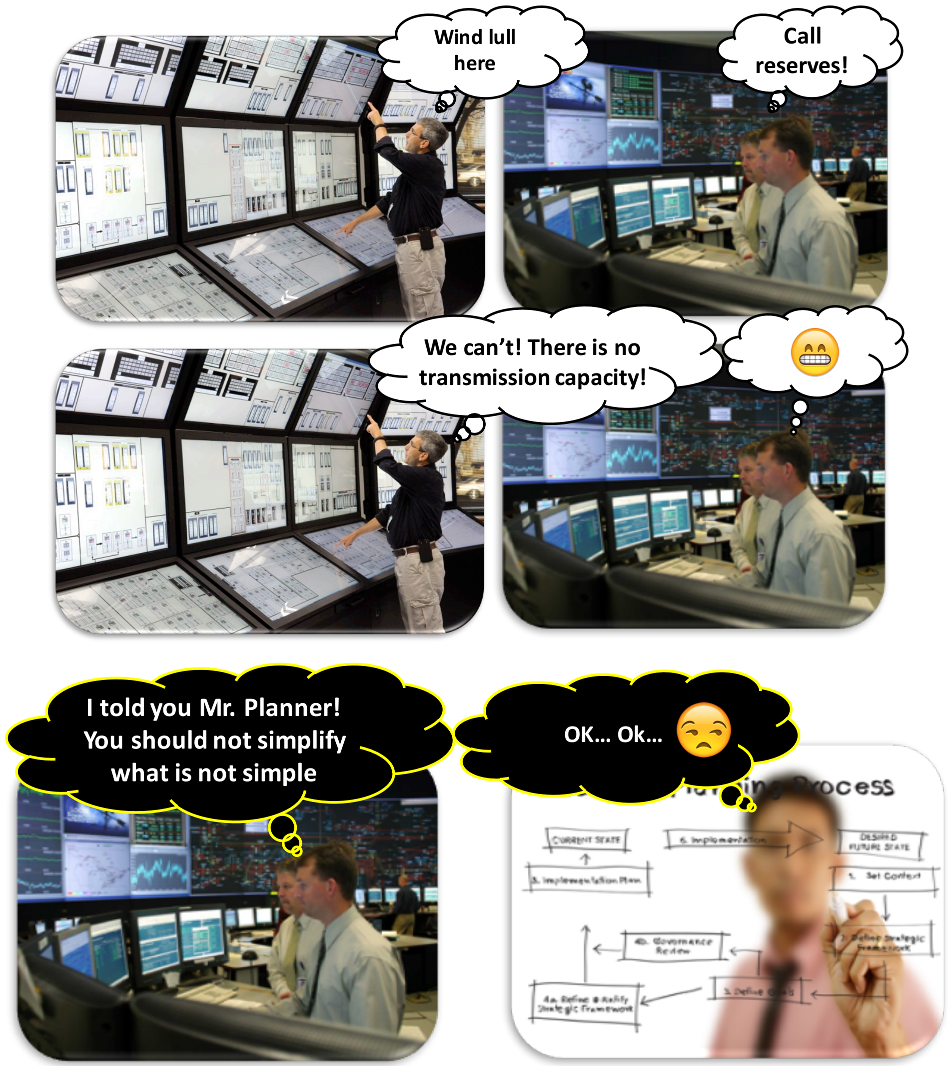

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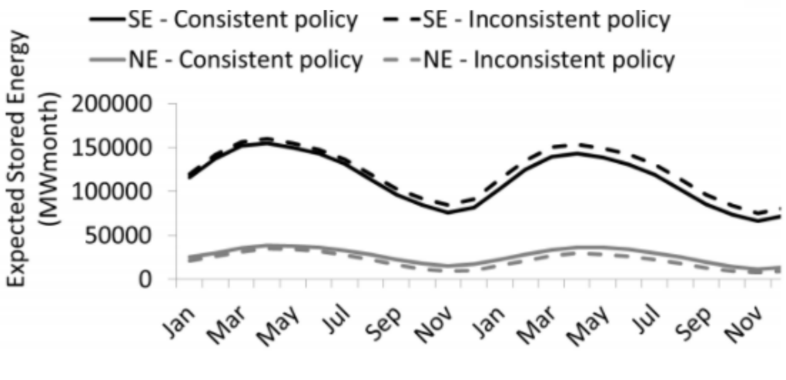
Inconsistency threats

Simplifications in KVL and n-1 security constraints

- Brazil operates the system through a two-step SDDP-based scheme
- Planning step: many simplifications to asses the future cost function (water value)
- Implementation step: makes use of tight security criteria in a meshed network

TABLE III
COST COMPARISON: INCONSISTENT VS PLANNING POLICIES (MMR$).

	GAP	Planning policy	Inconsistent policy	Consistent policy
95% CI upper bound	3,890.89	3,407.20	7,165.59	3,675.77
Sample average	3,686.43	3,303.18	6,989.61	3,566.79
95% CI lower bound	3,481.99	3,199.15	6,813.63	3,457.80



. 8. Southeastern and Northeastern stored energy.

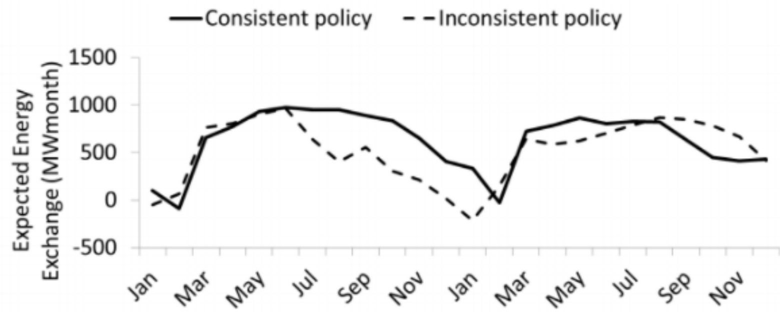


Fig. 9. Exchanged energy from the SE subsystem to the NE subsystem.

Fig. 10. Northeastern spot prices.

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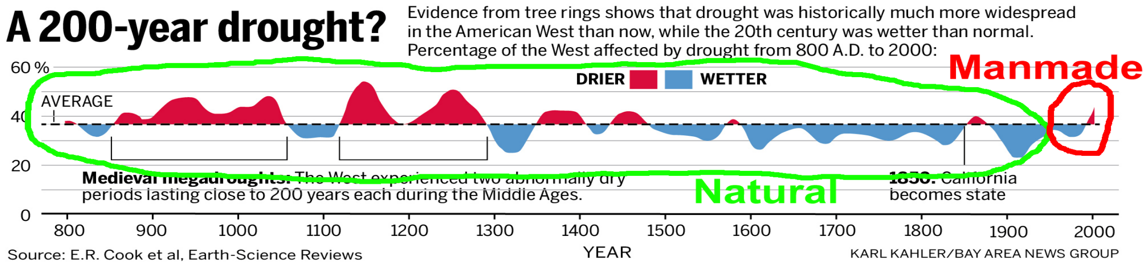
Uncertainty

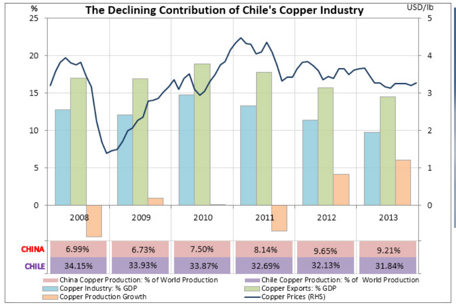
21 century TEP must account for many different types of uncertainties

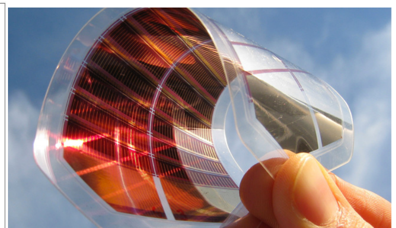
- Long-run drivers
  - Climate variations
  - Economy and Policy
  - New technologies

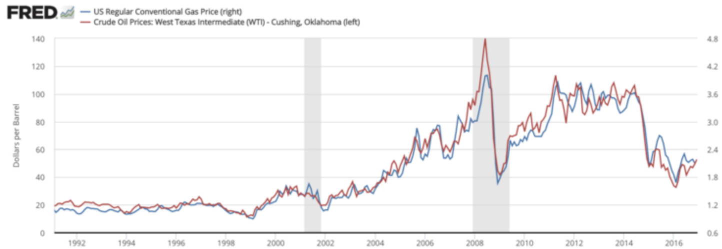
- Long-term uncertainties
  - Fuel costs
  - New generation siting
  - Electrical vehicles
  - Load growth
  - etc

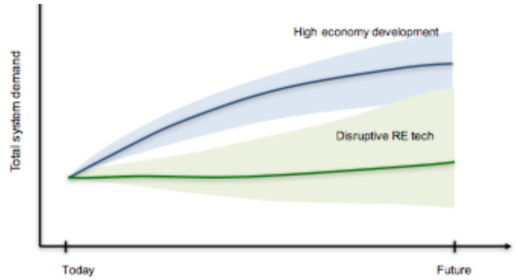
- Expert's long-term scenarios
  - We need a good process to obtain scenarios
  - We need to involve the many parties
  - Avoid partial viewpoints (bias): quite dangerous!





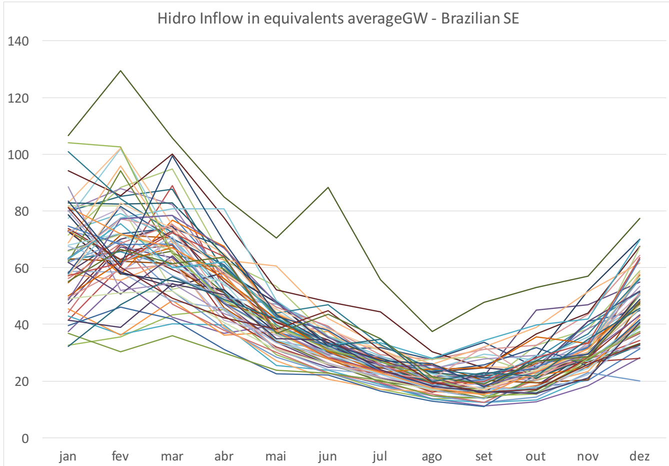




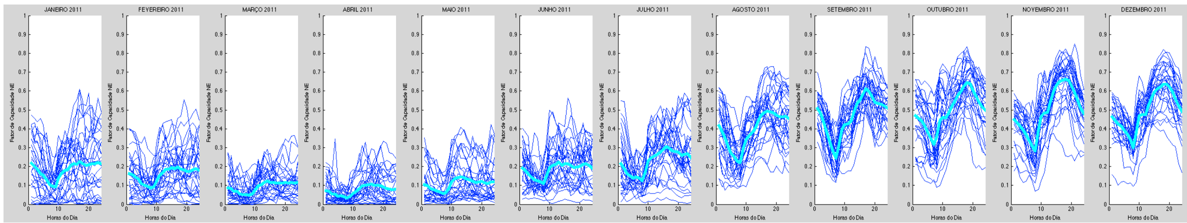


Uncertainty

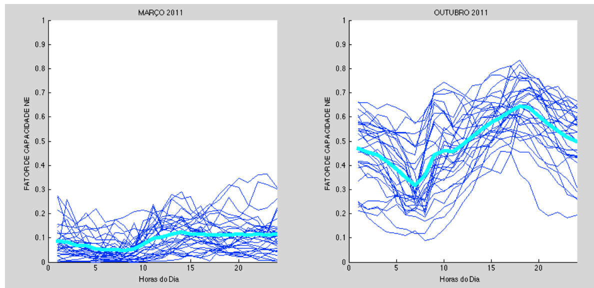
21 century TEP must account for many different types of uncertainties



- Medium-term
  - Renewables seasonal generation
  - Loads seasonal pattern
  - Commodities prices
  - etc



- Short-term
  - Renewables injections
  - Load variability
  - Contingencies
  - etc



- We need *new* statistic methods
  - Multidimensional models (dependencies)
  - Big data analytics and new methods to simulate well the stochastic processes

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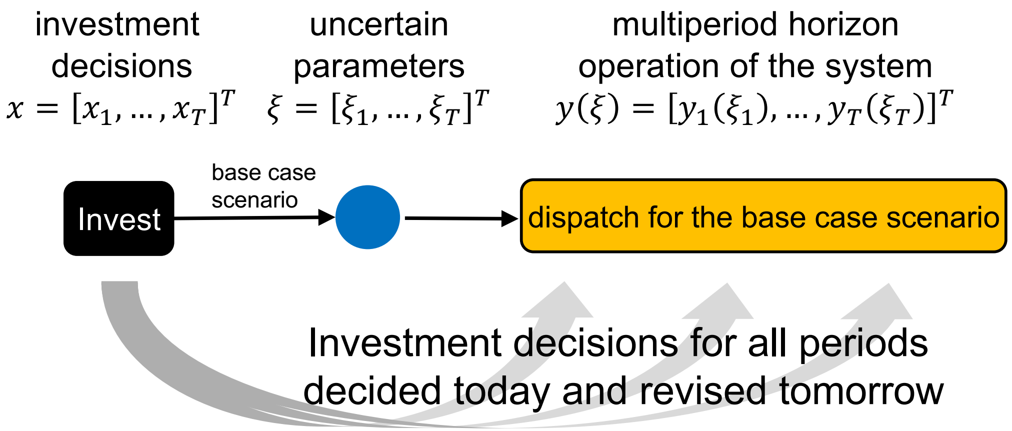
Optimization models and frameworks

Class of Static Adaptive Models

- Deterministic adaptive

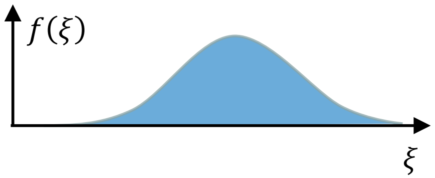


$$\underset{x}{\text{minimize}}\; C^I(x) + c^o(x, y(\xi), \xi)$$

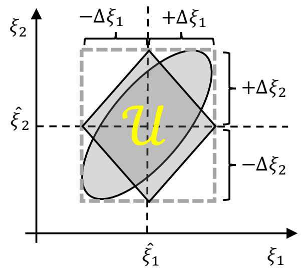
subject to:
$$Ax \leq b$$
$$Tx - Wy(\xi) \geq h(\xi)$$
$$x \in \{0,1\}^n$$

Class of Static Adaptive Models

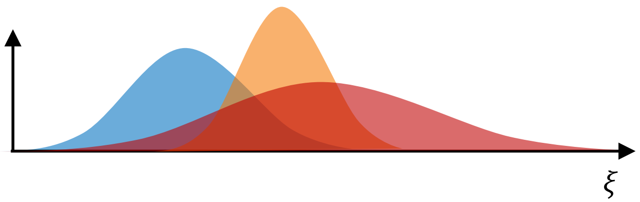
- Static adaptive
  - Two-stage stochastic

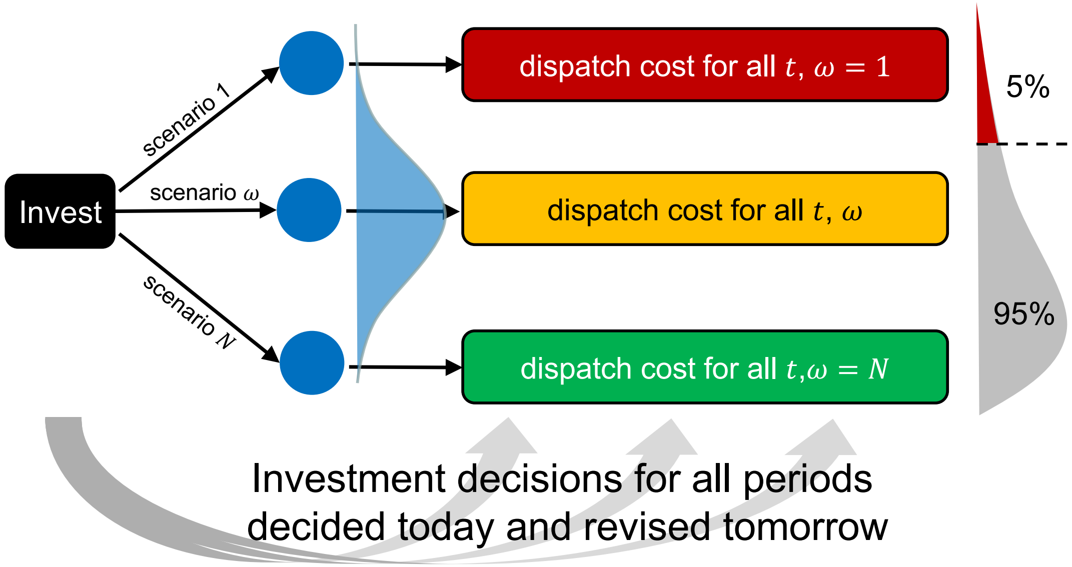


  - Two-stage robust



  - Distributionally robust





$$\underset{x}{\text{minimize}}\; C^I(x) + \rho_\xi\{c^o(x, y(\xi), \xi)\}$$

subject to: $Ax \leq b$

$$Tx - Wy\big(\xi(\omega)\big) \geq h\big(\xi(\omega)\big)\ \forall\omega \in \Omega$$

$$x \in \{0,1\}^n$$

Optimization models and frameworks

Class of Static Adaptive Models

- Static adaptive
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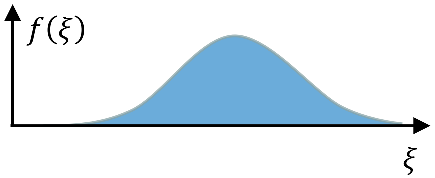

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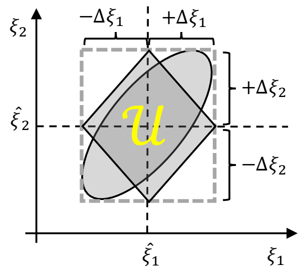
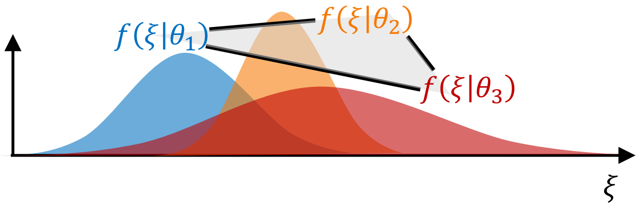
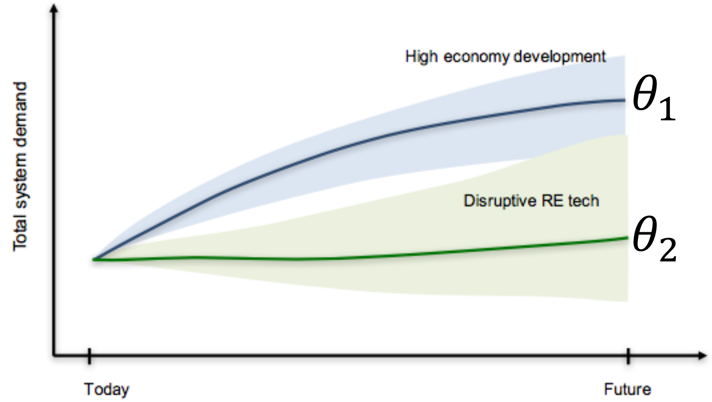


  - Distributionally robust





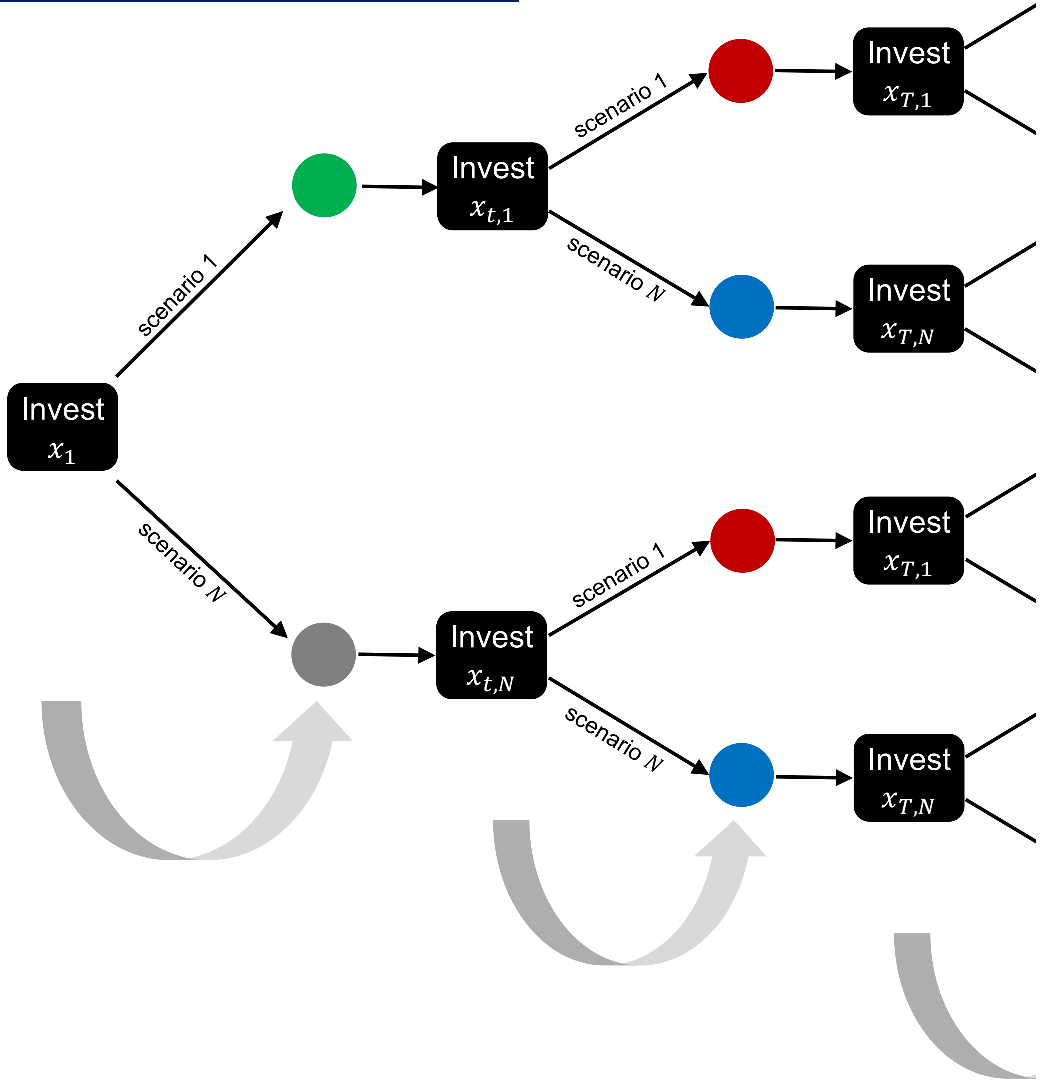
- Use for parameters of difficult description: contingencies, hourly wind and solar
- Compatible with long-run scenarios made by experts
- Worst-case solutions are robust against scenarios not considered

- Distributionally robust is a promising field
- Experts can express their views through long-run scenarios
- Statistics describes short-term uncertainties conditioned to long-term scenarios

Optimization models and frameworks

Class of Dynamic Models

- Dynamic
  - Multistage stochastic
    - Ben & Muñoz
      - Dynamic in long-term uncertainty
    - Mario Veiga Pereira
      - Dynamic in mid-term uncertainty
    - Street, Brigatto, and Valladão
      - Dynamic in mid-term uncertainty
      - Robust in short-term (contingencies)
    - Zou, Sun, Ahmed
      - Binary-state SDDP approach
  - Multistage robust
    - Álvaro Lorca and Andy Sun
      - Dynamic in short-term uncertainty



- Investment decisions follow a nonanticipative process
- In long-term studies, more than 5 years, it is crucial to go multistage!

Example of two-stage robust models

- Expanding lines and renewables to meet targets
- Co-optimization of generation, transmission, and reserve levels

- Compound security criterion:
  - n-1 and n-2 with zero load sheading
  - n-3 with no more than 2.5% load sheading
- With correlation between renewables generation

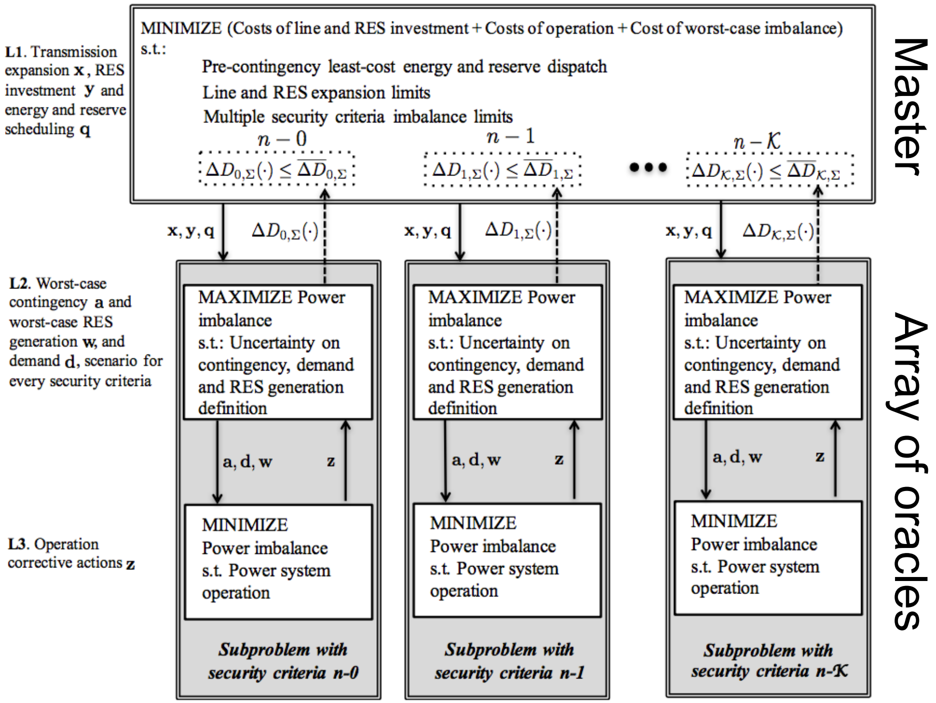


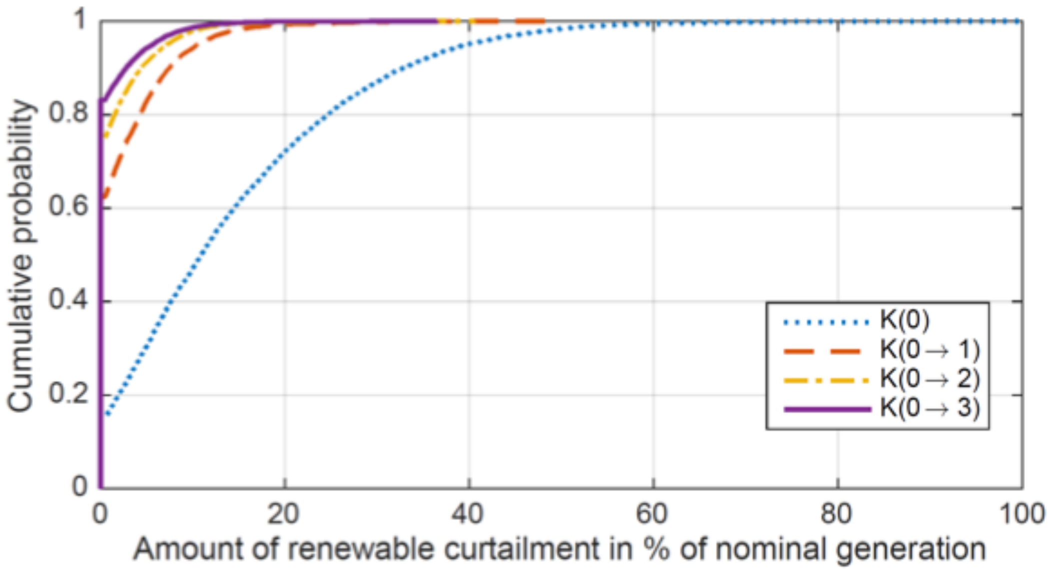
Fig. 1: Three-level robust TEP framework

TABLE IV: Out-of-sample Monte Carlo Simulation Test for the Chilean Power System

Security Criteria	$K(0)$	$K(0 \to 1)$	$K(0 \to 2)$	$K(0 \to 3)$
LOL Interval	LOL Probability			
=0%	11.77%	85.72%	93.72%	96.88%
(0-1]%	7.65%	2.94%	2.22%	0.87%
(1-2]%	15.99%	4.35%	1.92%	1.10%
(2-3]%	15.44%	2.94%	1.10%	0.60%
(3-4]%	13.84%	1.86%	0.56%	0.24%
(4-5]%	10.25%	1.12%	0.23%	0.19%
(5-10]%	21.81%	1.04%	0.25%	0.12%
>10%	3.25%	0.03%	0.00%	0.00%
Expected LOL	3.49%	0.34%	0.12%	0.06%
CVaR of the LOL	11.13%	4.20%	2.16%	1.23%
Expected Total Costs [K$]	410.01	268.82	269.19	272.46
CVaR of the Total Costs [K$]	746.52	442.48	361.11	330.38

Example of two-stage robust models

Wind spillage is mitigated while increasing security



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Conclusions

Models need to consider

- Complex interactions between transmission assets, new generation, and reserves
- Flexibility and Adaptability
- Short-term generation and load variability
  - The value of operational flexibility can only be captured if short-term uncertainties and constraints are considered

Models need to consider

- Robust and distributionally robust
  - Use for parameters of difficult description: contingencies
  - Compatible with long-run scenarios made by experts
  - Worst-case solutions are robust against scenarios not considered
- Stochastic
  - Use for parameters with good statistical properties: inflows
  - Representing dynamic decisions allows for capturing the value of postpone investments

Publications used in this presentation

Reliable Renewable Generation and Transmission Expansion Planning: Co-Optimizing System's Resources for Meeting Renewable Targets

Alexandre Moreira, *Student Member, IEEE,* David Pozo, *Member, IEEE,* Alexandre Street, *Member, IEEE,* and Enzo Sauma, *Senior Member, IEEE*

***Abstract*—The current renewable-driven generation expansion wave, pushed by high renewable targets, is not accompanied by the same movement in the transmission expansion planning (TEP) side. In this context, new techniques are needed to balance the cost of relying in expensive reserve resources and the cost of building new lines to ensure least-cost reserve deliverability and foster new renewable projects. The situation is worsened in the presence of contingencies, where the interaction between the optimal reserve siting and deployment, the amount of renewable curtailment, the construction of new lines, and the selection of candidate renewable sites to be developed became even more complex. This paper presents a two-stage min-max-min model for co-optimizing the expansion of the transmission system and renewable generation capacity to meet renewable targets under high security standards and renewable uncertainty. In order to account for realistic reserve needs and its interaction with the expansion plan, correlations between renewables injection as well as generation and transmission (GT) outages are accounted for in a worst-case fashion. In order to ensure security within a flexible framework, the concept of compound GT $n-K$ security criteria is presented. Three case studies are proposed to illustrate the applicability of the proposed model. A case study with realistic data from the Chilean system is presented and solutions obtained with different level of security are tested against a set of 10,000 simulated scenarios of renewable injections and system component outages.**

***Index Terms*—generation and transmission security criterion, renewable generation and transmission expansion planning, renewable targets, reserve deliverability and siting, wind curtailment.**

Sets

I	Set of generator indexes.
I_b	Set of indexes of generators connected to bus b.
$\mathcal{L}^C$	Set of indexes of candidate transmission lines.
$\mathcal{L}^E$	Set of indexes of existing transmission lines.
$\mathcal{L}$	Set of indexes of all transmission lines, equal to $(\mathcal{L}^E \cup \mathcal{L}^C)$.
N^E	Set of indexes of existing buses.
N^{RE}	Set of indexes of candidate buses with potential renewable energy.
N	Set of indexes of buses, equal to $(N^E \cup N^{RE})$.

Parameters

Γ^D	Conservativeness parameter.
Γ^W	Conservativeness parameter.
Σ^D	Estimated nodal demand covariance matrix.
Σ^W	Estimated nodal renewable generation covariance matrix.
$\overline{\Delta D}_{K,\Sigma}$	Maximum level of system power imbalance for an $n-K$ security criterion.
C_l^{Cap}	Cost per MW of candidate lines.
C^{RE}	Construction cost of new node with potential renewable energy.
C_K^I	Cost of imbalance under the worst-case contingency having K contingencies.

Assessing the Cost of Time-Inconsistent Operation Policies in Hydrothermal Power Systems

Arthur Brigatto, *Student Member, IEEE,* Alexandre Street, *Senior Member, IEEE,* and Davi M. Valladão

***Abstract*—The current state-of-the-art method used for medium- and long-term planning studies of hydrothermal power system operation is the stochastic dual dynamic programming (SDDP) algorithm. The computational savings provided by this method notwithstanding, it still relies on major system simplifications to achieve acceptable performances in practical applications. In contrast with its actual implementation, simplifications in the planning stage may induce time-inconsistent policies, and consequently, a sub-optimality gap. In this paper, we extend the concept of time inconsistency to measure the effects of modeling simplifications in the SDDP framework for hydrothermal operation planning. Case studies involving simplifications in transmission lines modeling and in security criteria indicate that these source of time inconsistency may result in unexpected reservoir depletion and spikes in energy market spot prices.**

***Index Terms*—Hydrothermal Power System Operation Planning, Stochastic Dual Dynamic Programming (SDDP), Time Inconsistency.**

tractability issues prevent ISOs from introducing this level of detail in the medium/long-term operative plans drawn by the SDDP policy. In this scenario, short-term decisions, which make use of the information obtained from long-term studies utilizing the cost-to-go (or recourse) function, are made with inaccurate (inconsistent) information about the future system operation and its own decision process. Therefore, implemented decisions are generally likely to deviate from those obtained in the planning stage, which is the definition of time inconsistency (see [14]–[16]). According to [14], time inconsistency induces to sub-optimality in the decision process that can be measured by the inconsistency gap.

Time consistency of optimal policies is conceptually defined by [14]: "*a policy is time consistent if and only if the future planned decisions are actually going to be implemented.*" The most commonly cited and analyzed sources of time inconsistency are those induced by nonlinearities in the probability

Co-optimization of Energy and Ancillary Services for Hydrothermal Operation Planning Under a General Security Criterion

Alexandre Street, *Senior Member, IEEE,* Arthur Brigatto, *Student Member, IEEE,* and Davi M. Valladão

***Abstract*—One of the most used methods for long-term hydrothermal operation planning is the Stochastic Dual Dynamic Programming (SDDP). Using this method, the immediate and future water opportunity cost can be balanced and an economic-dispatch policy defined for multiple reservoirs under inflow uncertainty. In this framework, equipment outages and reserve deliverability are generally disregarded, despite their strong impact on the operative plan. However, recent advances in robust**

Deterministic security criteria, such as $n-K$, have been widely explored in the recent literature (see [2], [4], [5], [7]–[11]). Because of their relevance to current industry practices, recent studies of robust optimization applied to power systems have addressed this subject within short-term operational problems (see [2], [4], [11]). For example, to address an $n-2$ security criterion, contingency-constrained models must ensure

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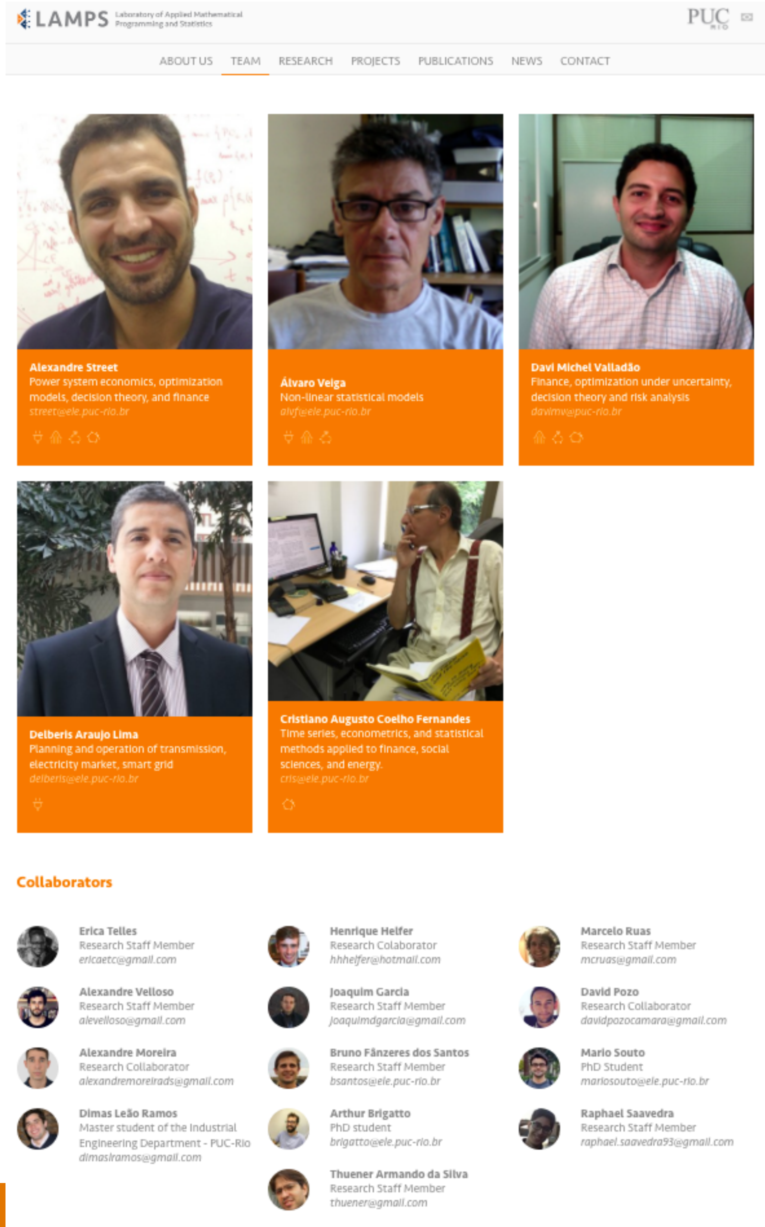

Some interesting publications

Co-optimization of Energy and Ancillary Services for Hydrothermal Operation Planning Under a General Security Criterion
Alexandre Street, Arthur Brigatto, Davi Valladão. IEEE Transactions on Power Systems. 2017. [Download]
READ MORE

Assessing the Cost of Time-Inconsistent Operation Policies in Hydrothermal Power Systems
Arthur Brigatto, Alexandre Street, Davi Valladão, "Transactions on Power Systems", 2017. [Download]
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