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Stochastic co-optimization of renewable-driven reserves, storage and flexibility in power system planning and operation

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PSR

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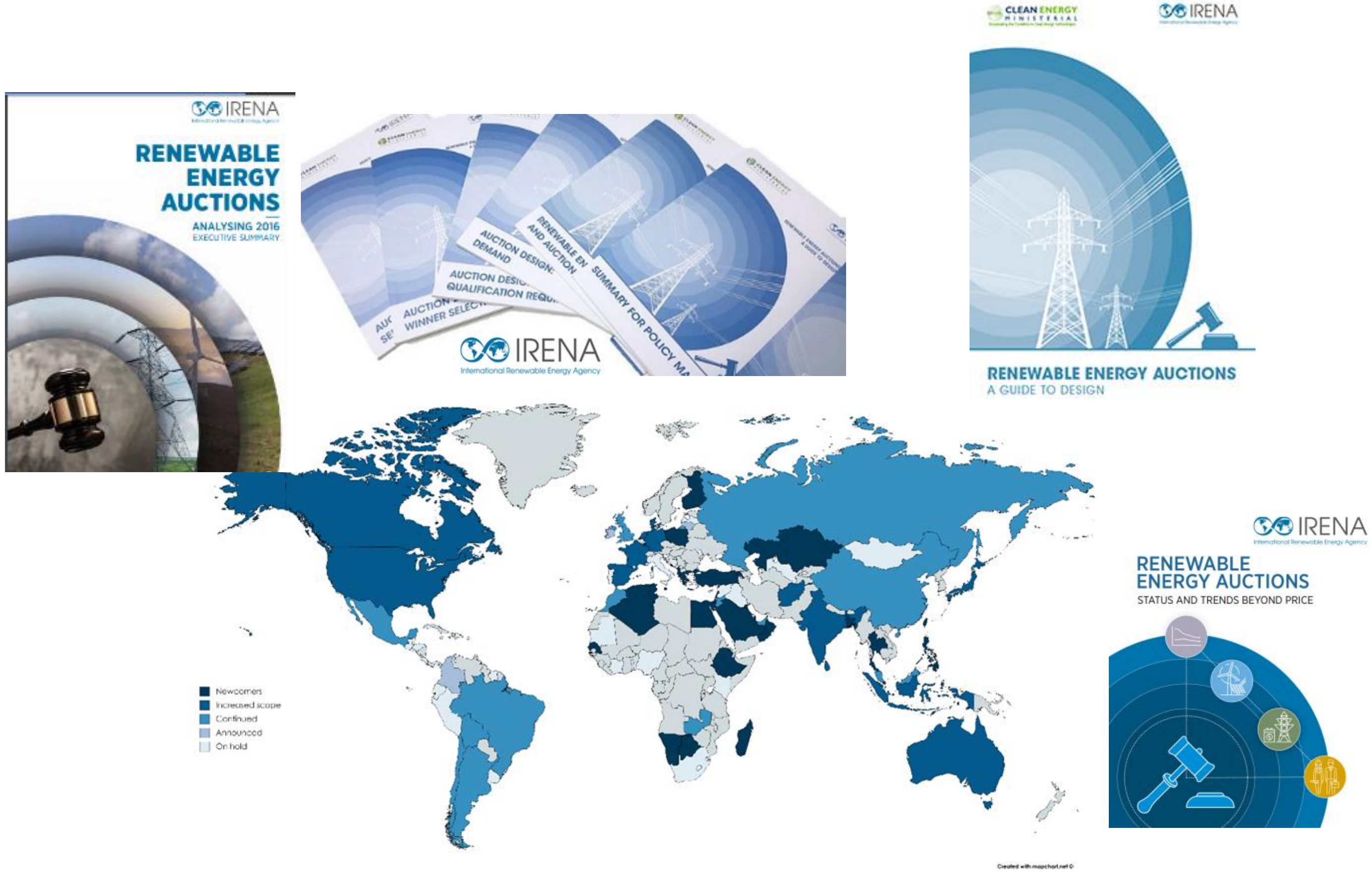
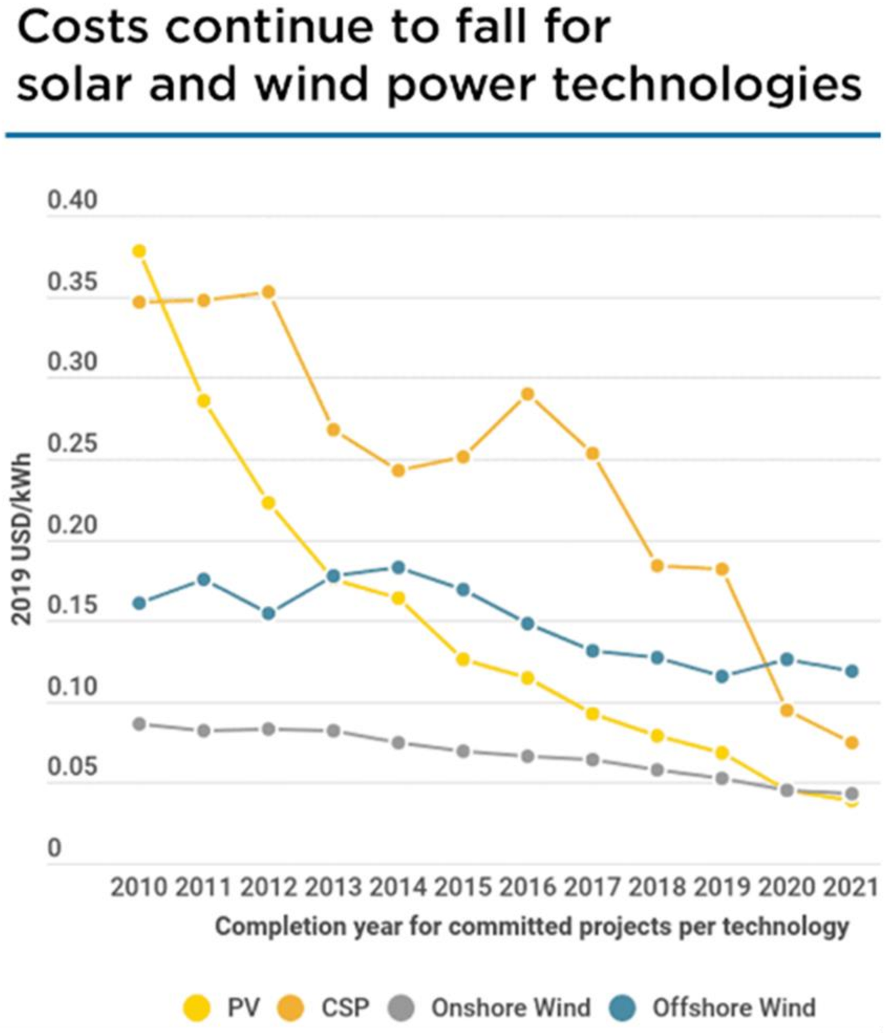
Introduction

Decarbonization: the renewable revolution

- Initial motivation: **energy policy** and climate change
- Currently: **economically** motivated, cheaper expansion





Fuente: IEA & Irena (2016, 2019)

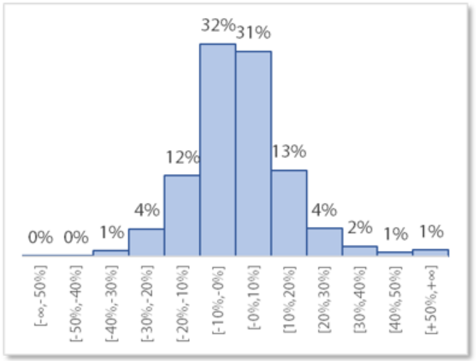
Great modelling **challenges**

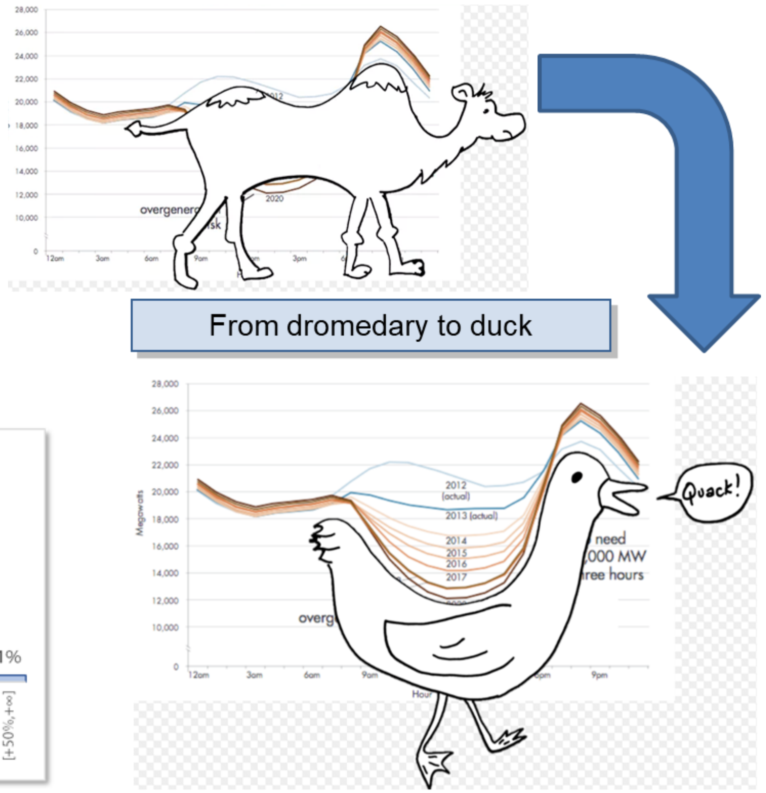
▸ Need to combine long-term view of expansion with short-term view of operation

- Hourly time steps (or even smaller)
- Unit commitment decisions
- Startup costs
- Minimum down-time and up-time
- Ramping constraints
- Hydraulic constraints in river basin
- Variability of renewables, inflows and demand (uncertainties)
- Energy, capacity and reserve requirements

Hourly generation of a wind plant in Brazil

Hourly variation





Statistical tools are essential to represent the uncertainty and variability of the renewables

- Operating Reserve: needed to guarantee security of supply

The "new world" of the 3Ds: decarbonization, decentralization and digitization

- Generators located in the distribution
- Consumers provide generation services
- Multiplicity of new actors
- Consequences:
  - Change in the operation of the distribution network
  - Need for regulatory adjustments

Electric Power Systems Research

Volume 211, October 2022, 108445

A methodology for improved TSO-DSO coordination in grid operation planning

Jan Ringelstein [a], Mike Vogt [a], Ataollah Moghim Khavari [b], Roberto Ciavarella [c], Marialaura Di Somma [c], Giorgio Graditi [c]

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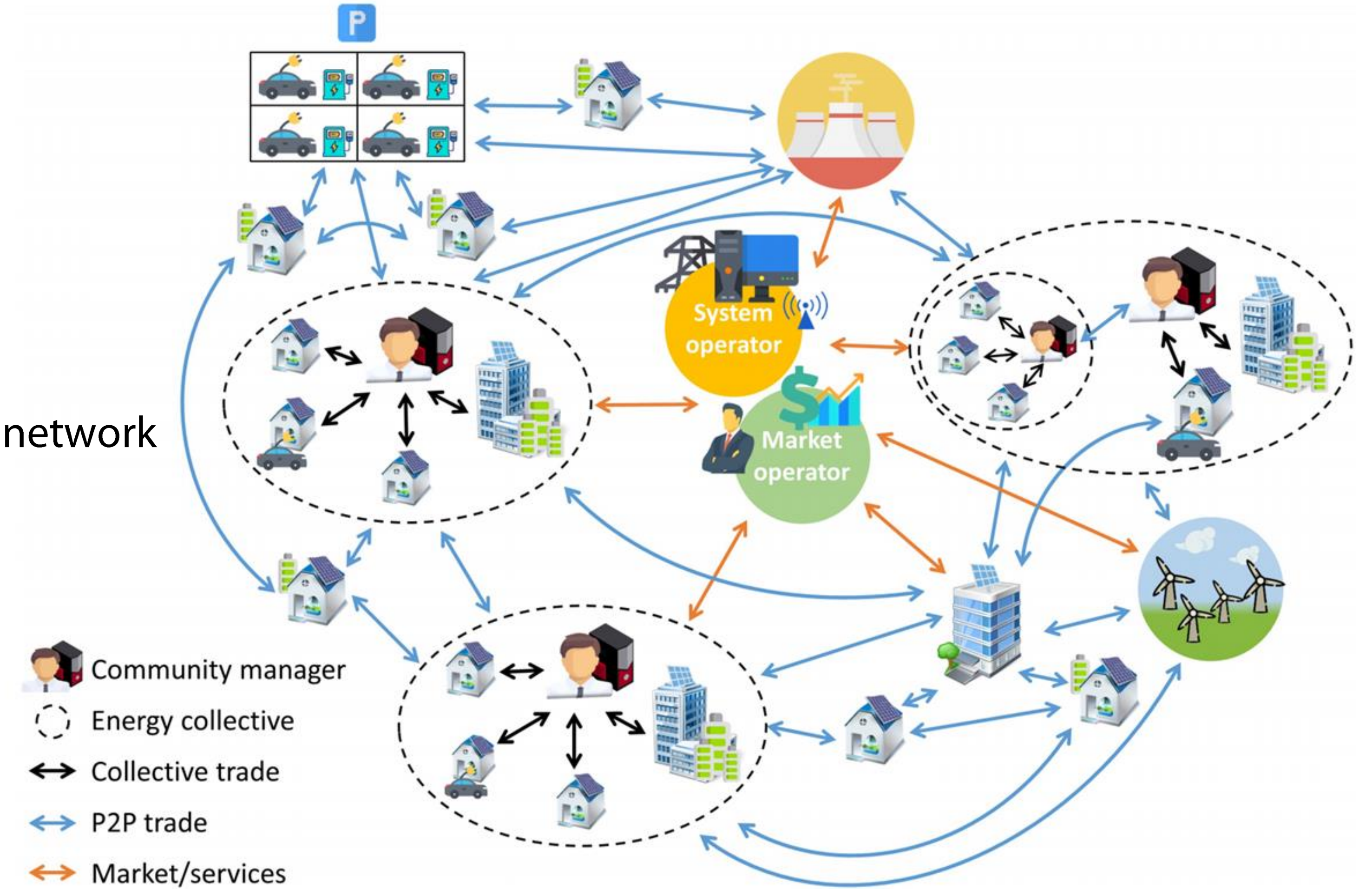


Strong wholesale and retail integration

Stochastic modeling of renewables

Stochastic modeling of renewables

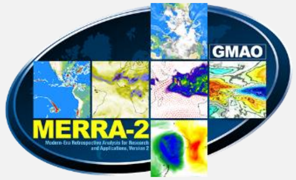
Data
Simulate renewable historical with reanalysis data

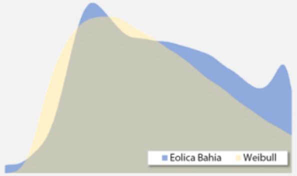
→

Scenarios
Stochastic modeling of renewables and hydro (with spatial correlation)

Input data

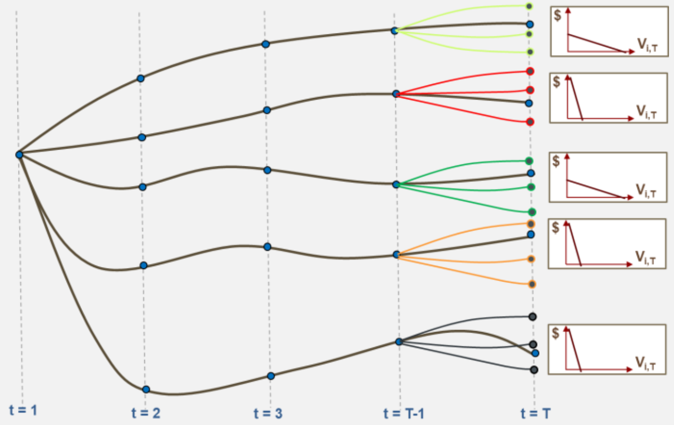
Renewable Modeling





Renewable generation scenarios

Stochastic Production Costing

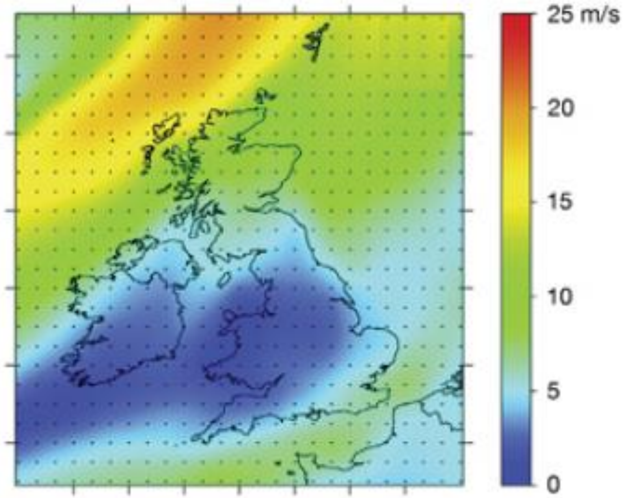


The power curve of the turbine

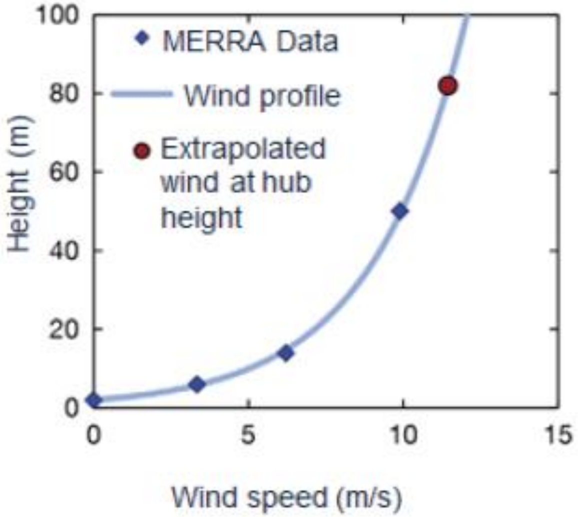
The height of the turbine

The coordinate of the plant (to download the wind speed data)

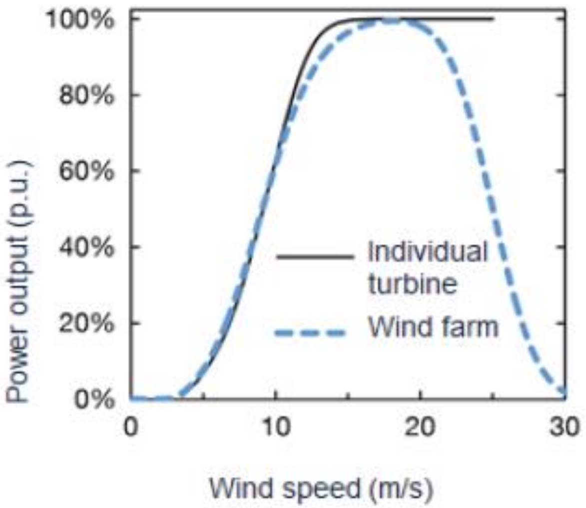
DOWNLOAD WIND SPEED DATA



EXTRAPOLATE WIND SPEED TO THE PLANT HEIGHT



CALCULATES THE POWER OUTPUT USING THE TURBINE POWER CURVE

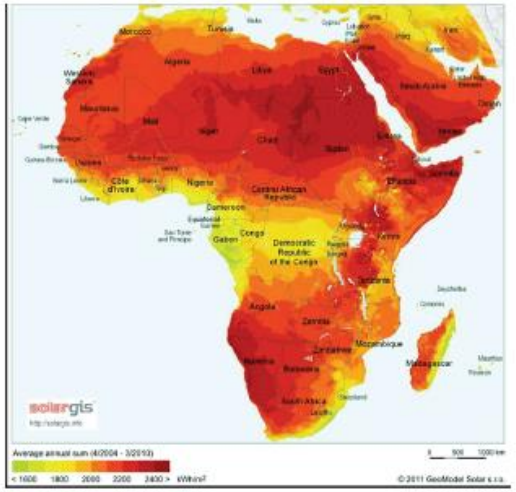


The tracking system of the panel

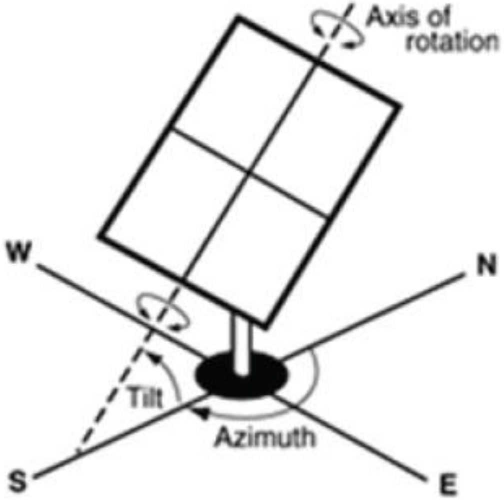
The inclination angle of the panel

The coordinate of the solar plant

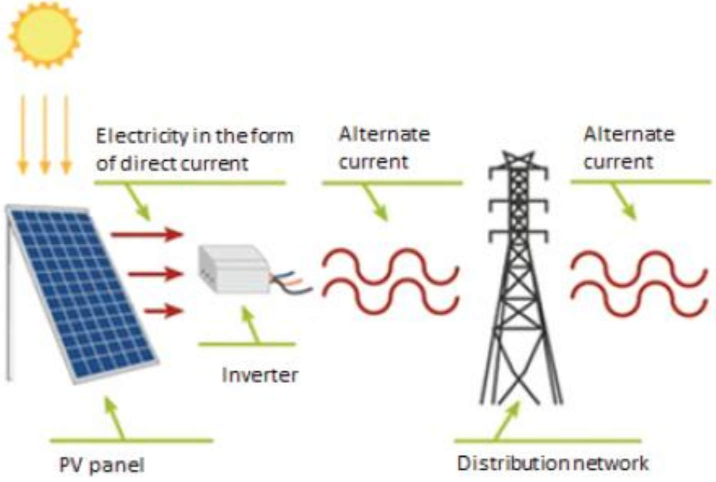
DOWNLOAD SOLAR IRRADIATION DATA



ESTIMATE POWER OUTPUT CONSIDERING EFFICIENCY AND TRACKING SYSTEM



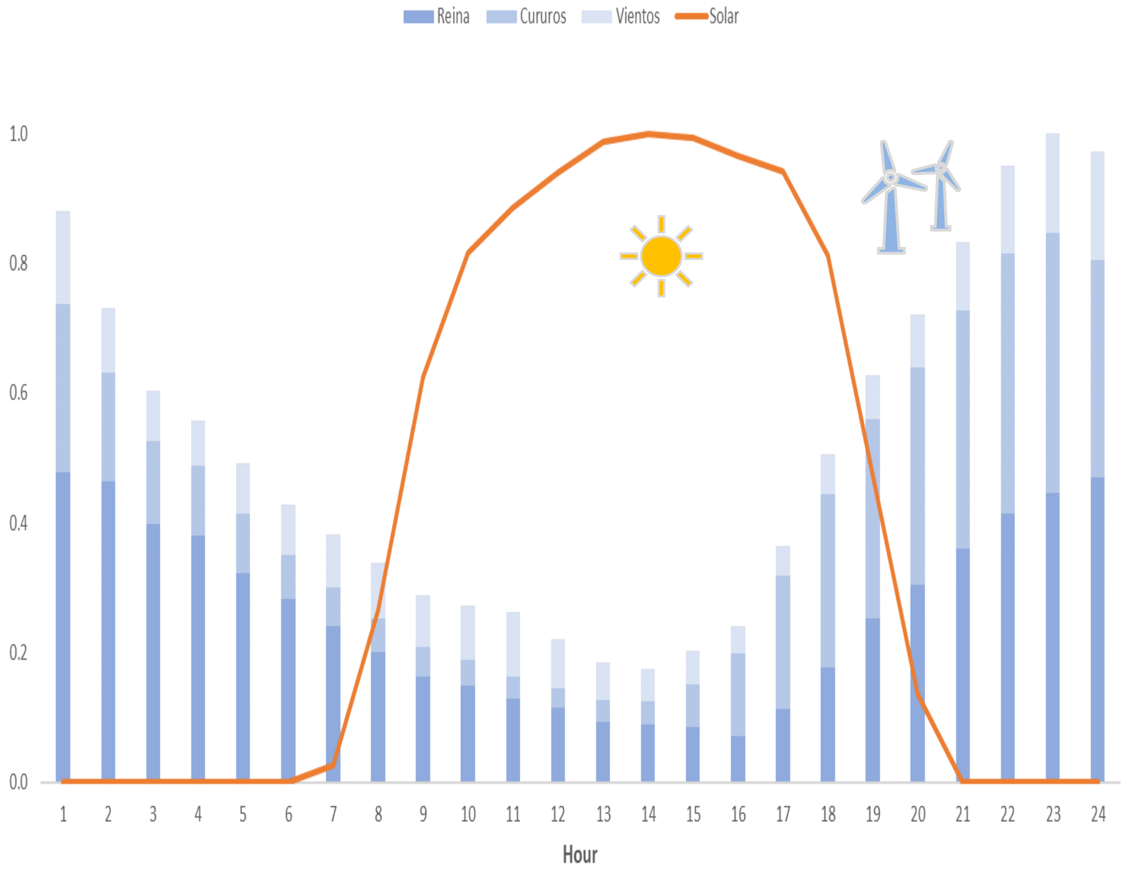
DC -> AC CONVERSION



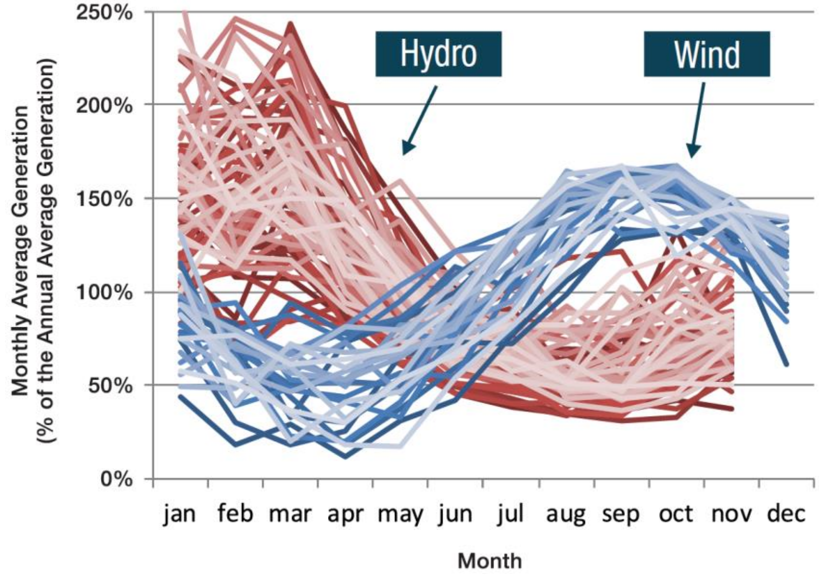
Capturing spatial & temporal correlations

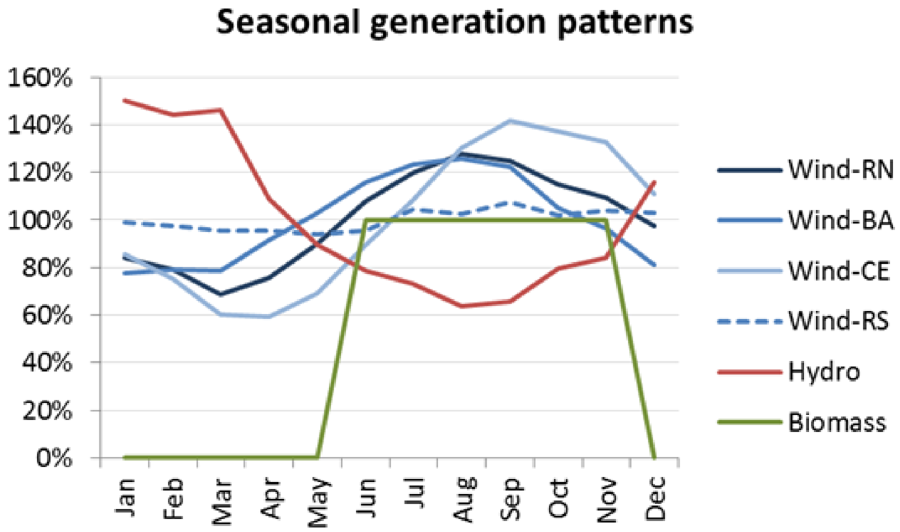
Intraday

Hourly complementarity and correlation between renewables



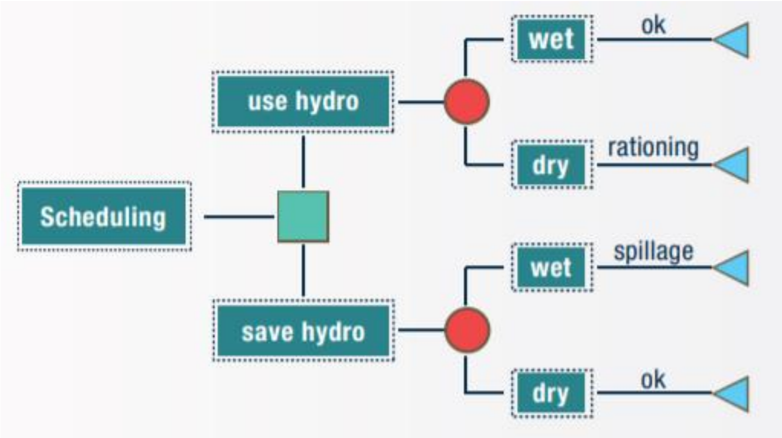
Monthly complementarity and correlation between renewables

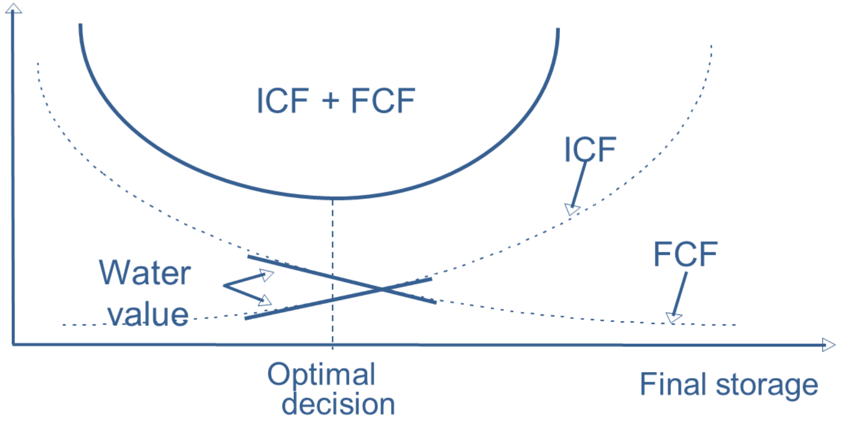




Multistage stochastic optimization methodologies for electrical system planning and operation

Stochastic production costing simulations: SDDP Algorithm





Hydroelectric plants

- Detailed representation for each reservoir
- Storage and flow rate limits through turbines, spillways, head effect, infiltration and others;
- Stochastic inflow model representing seasonality, time and spatial correlations
- Modeling of specific climatic phenomena (such as El Niño), etc.
- Ramping constraints

Thermoelectric plants

- Unit commitment constraints
- Fuel availability
- Fuel contracts (including take-or-pay clauses)
- Thermal efficiency curves
- CO_2 and other pollutants emission
- Ramping constraints

Variable Renewable Energy *(VRE)*

Time Series Lab Model

- Definition of VRE historical generation through global reanalysis database
- Stochastic VRE power production model, generating future synthetic scenarios with hourly resolution
- VRE scenarios are temporally and specially correlated with hydro inflows

Transmission Network

- Kirchhoff laws
- Power flow limits
- Quadratic losses
- Security constraints
- Limits on export and import among electric areas, sum of flow constraints and others;

Natural Gas Network

- Gas production and transportation constraints
- Production capacity in the fields
- Pipeline flow limits and losses

Batteries and others fast response storage devices

- Storage capacity
- Charge/discharge capacities
- Efficiencies
- Ramping constraints.

- The objective of this tool is to minimize the sum of costs for purchase and transportation of fuels for thermal plants, pollutant emission costs, hydro and thermal plants' O&M costs, transmission wheeling rates, cost of energy not supplied and other penalties.

SDDP Algorithm: uncertainties that can be represented

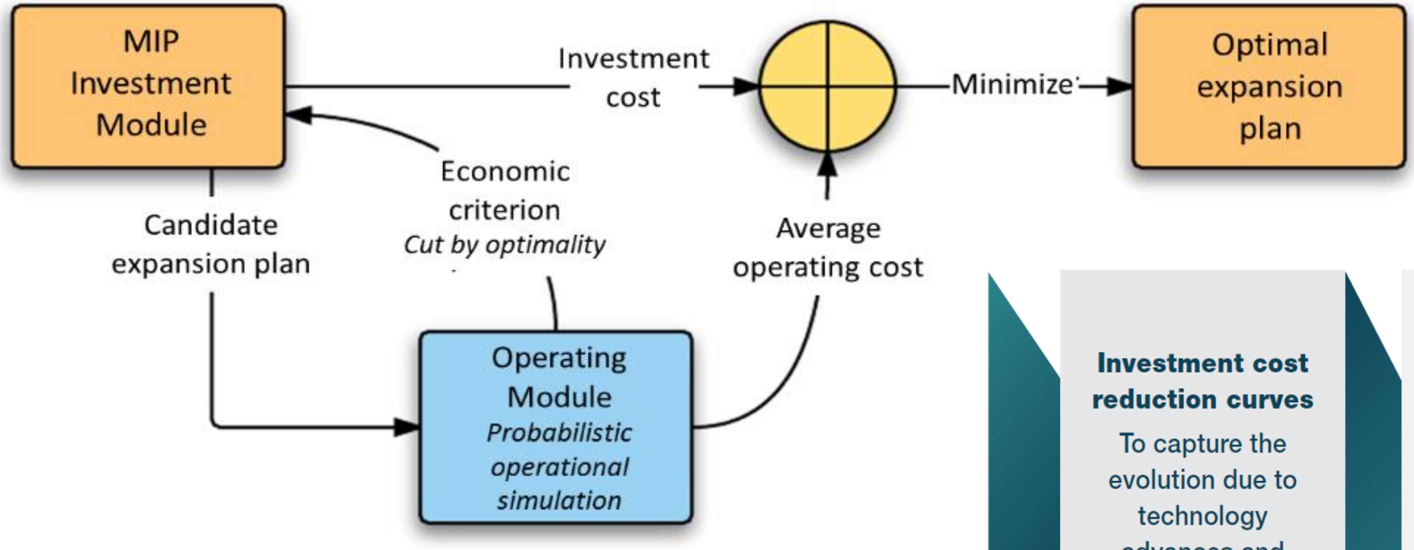
- Hydro inflows and renewable generation (wind, solar, biomass etc.)
  - Multivariate stochastic model (PAR(p))
    - Inflows: macroclimatic events (El Niño, La Niña), snowmelt and others
    - Climate change impact
    - Spatial correlation of wind, solar and hydro
- Load uncertainty
  - Annual load growth rates
    - Markov chains/AR model
  - Demand scenarios
  - Within-stage variability
    - Monte Carlo sampling
- Uncertainty on fuel costs
  - Fuel cost scenarios
  - Markov chains

    (hybrid SDDP/SDP model)
- Wholesale energy market prices
  - Markov chains
- G&T equipment outages
  - Monte Carlo sampling

Solution Algorithm:
Stochastic Dual Dynamic Programming (SDDP) ➔ global industry standard, with over 1.200 citations in the scientific/engineering literature

Multistage stochastic capacity expansion planning

- This tool determines the least-cost sizing and timing decisions for construction, retirement and reinforcement of generation capacities, transmission network and natural gas pipelines.
- This model optimizes the **trade-off** between **investment costs** to build new projects and the expected value of **operative costs**



Investment cost reduction curves
To capture the evolution due to technology advances and other factors

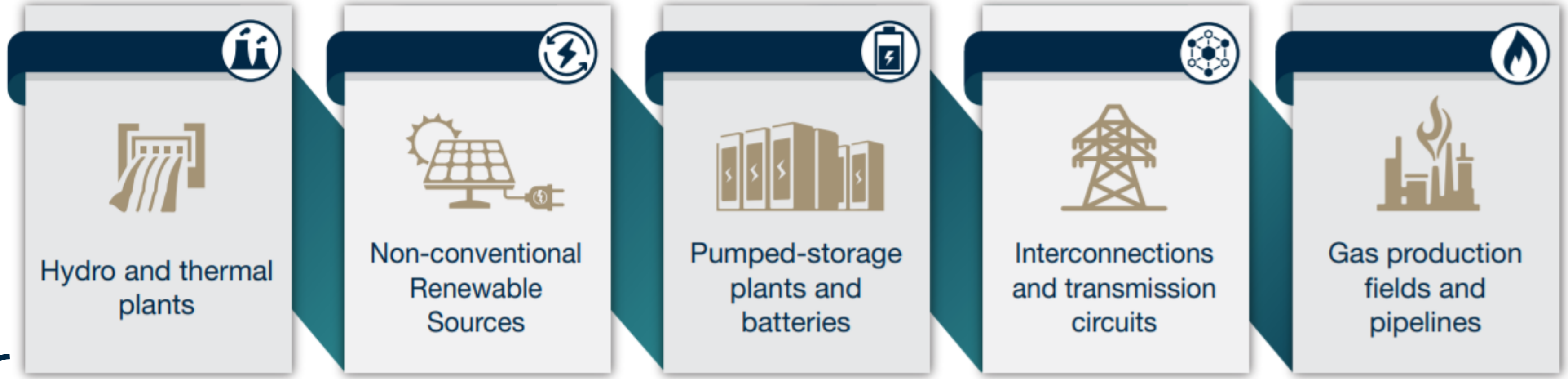
Environmental criteria
Clean energy certificates, emission costs and caps

Governmental energy policies
Related to decarbonization policies and penetration target of renewables

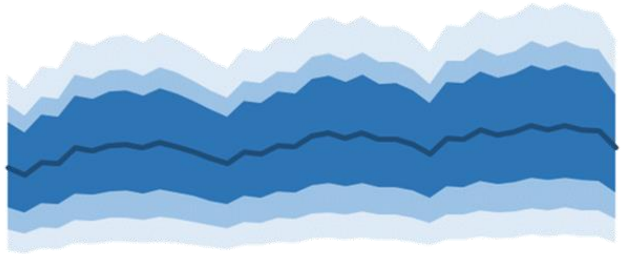
Firm energy and firm capacity constraints
To enforce system policies for the security of supply

Multistage stochastic capacity expansion planning

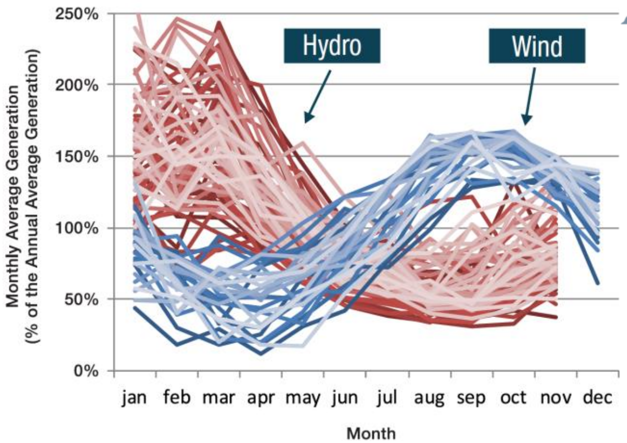
- Several types of projects are available to be contemplated by the model:



Probabilistic scenarios with the effect of **regional patterns**



Captures the effect of **regional patterns** and **correlation** to hydro production

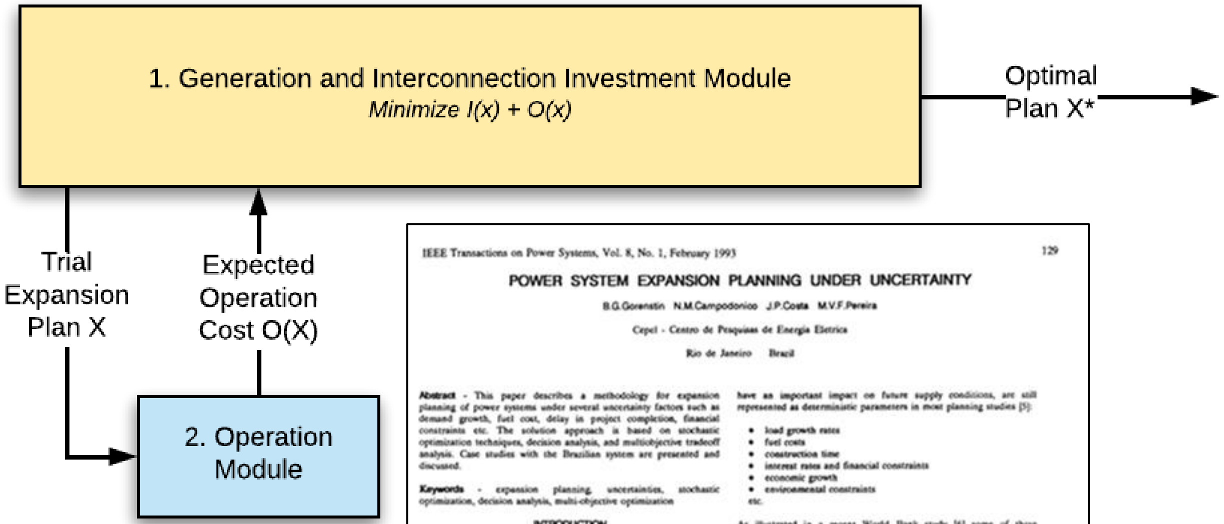


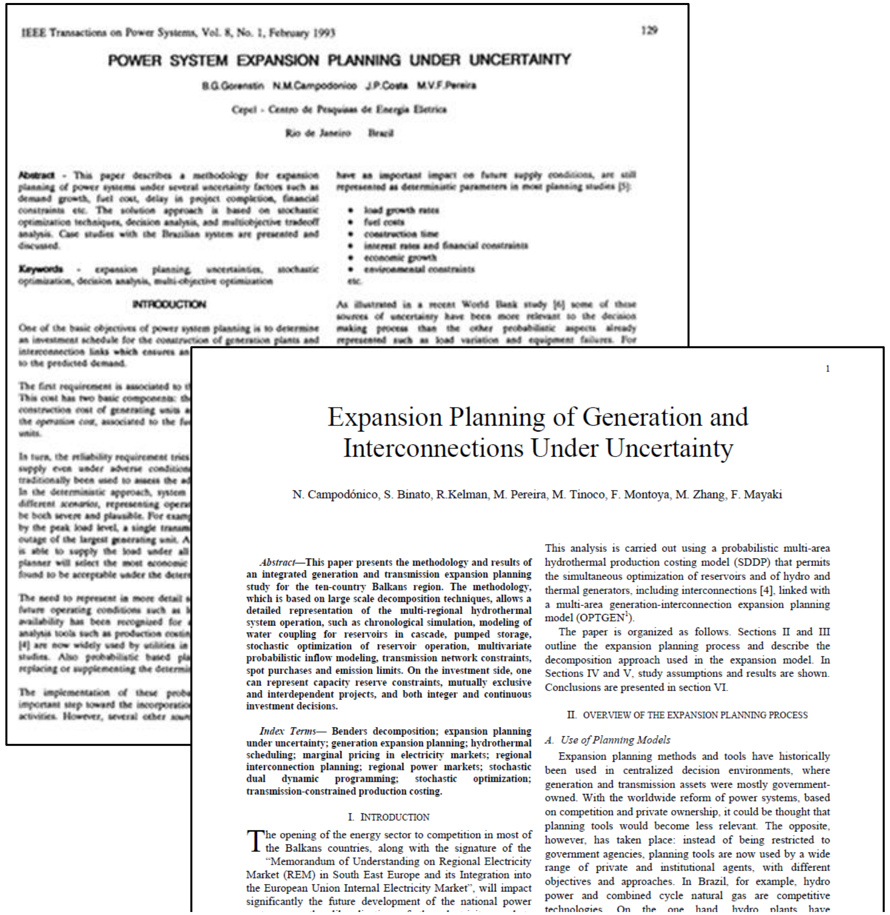
Captures the effect of **daily patterns** and **intermittency**

How to ensure efficiency, reliability, flexibility, and resilience in the energy transition

Planning 1.0: Economic Efficiency + Energy Policy Guidelines

- Minimize total costs to the consumer (investment + expected value of the operating costs)
  - Renewable variability (hydroelectric, wind, biomass, solar), demand (e.g., effect of temperature etc.)
- Energy policy guidelines
  - Nuclear programs, etc.
  - "New old criteria": CO_2 emission budgets, renewable penetration targets, etc.
  - Desired energy mix





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POWER SYSTEM EXPANSION PLANNING UNDER UNCERTAINTY

B.G.Gorenstin N.M.Campodonico J.P.Costa M.V.F.Pereira

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Rio de Janeiro Brazil

Abstract - This paper describes a methodology for expansion planning of power systems under several uncertainty factors such as demand growth, fuel cost, delay in project completion, financial constraints etc. The solution approach is based on stochastic optimization techniques, decision analysis, and multiobjective tradeoff analysis. Case studies with the Brazilian system are presented and discussed.

Keywords - expansion planning, uncertainties, stochastic optimization, decision analysis, multi-objective optimization

INTRODUCTION

One of the basic objectives of power system planning is to determine an investment schedule for the construction of generation plants and interconnection links which ensures an ...

have an important impact on future supply conditions, are still represented as deterministic parameters in most planning studies [5]:

- load growth rates
- fuel costs
- construction time
- interest rates and financial constraints
- economic growth
- environmental constraints

etc.

As illustrated in a recent World Bank study [6] some of these sources of uncertainty have been more relevant to the decision making process than the other probabilistic aspects already represented such as load variation and equipment failures. For

1

Expansion Planning of Generation and Interconnections Under Uncertainty

N. Campodónico, S. Binato, R.Kelman, M. Pereira, M. Tinoco, F. Montoya, M. Zhang, F. Mayaki

Abstract—This paper presents the methodology and results of an integrated generation and transmission expansion planning study for the ten-country Balkans region. The methodology, which is based on large scale decomposition techniques, allows a detailed representation of the multi-regional hydrothermal system operation, such as chronological simulation, modeling of water coupling for reservoirs in cascade, pumped storage, stochastic optimization of reservoir operation, multivariate probabilistic inflow modeling, transmission network constraints, spot purchases and emission limits. On the investment side, one can represent capacity reserve constraints, mutually exclusive and interdependent projects, and both integer and continuous investment decisions.

Index Terms— Benders decomposition; expansion planning under uncertainty; generation expansion planning; hydrothermal scheduling; marginal pricing in electricity markets; regional interconnection planning; regional power markets; stochastic dual dynamic programming; stochastic optimization; transmission-constrained production costing.

I. INTRODUCTION

The opening of the energy sector to competition in most of the Balkans countries, along with the signature of the "Memorandum of Understanding on Regional Electricity ...

This analysis is carried out using a probabilistic multi-area hydrothermal production costing model (SDDP) that permits the simultaneous optimization of reservoirs and of hydro and thermal generators, including interconnections [4], linked with a multi-area generation-interconnection expansion planning model (OPTGEN[1]).

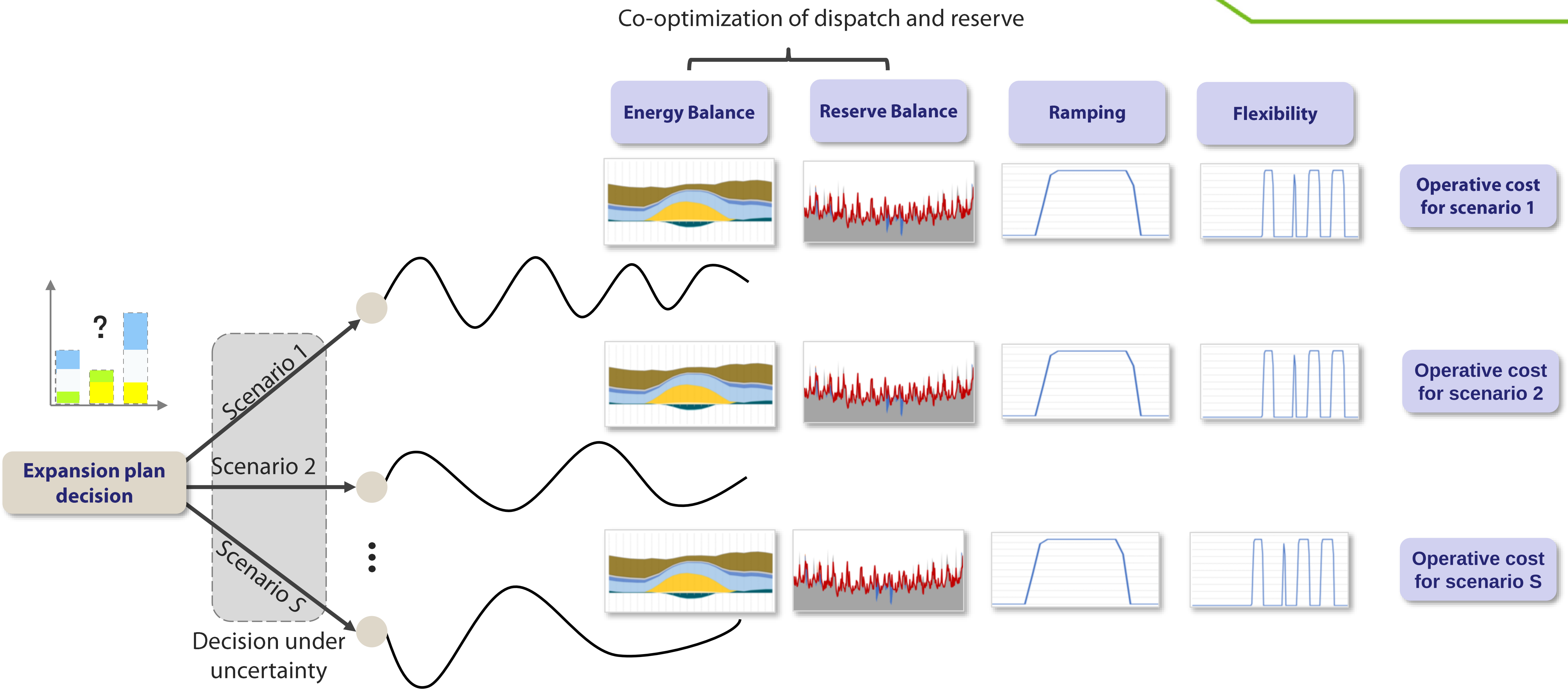
The paper is organized as follows. Sections II and III outline the expansion planning process and describe the decomposition approach used in the expansion model. In Sections IV and V, study assumptions and results are shown. Conclusions are presented in section VI.

II. OVERVIEW OF THE EXPANSION PLANNING PROCESS

A. Use of Planning Models

Expansion planning methods and tools have historically been used in centralized decision environments, where generation and transmission assets were mostly government-owned. With the worldwide reform of power systems, based on competition and private ownership, it could be thought that planning tools would become less relevant. The opposite, however, has taken place: instead of being restricted to government agencies, planning tools are now used by a wide range of private and institutional agents, with different ...

Example 1.0: Business as Usual

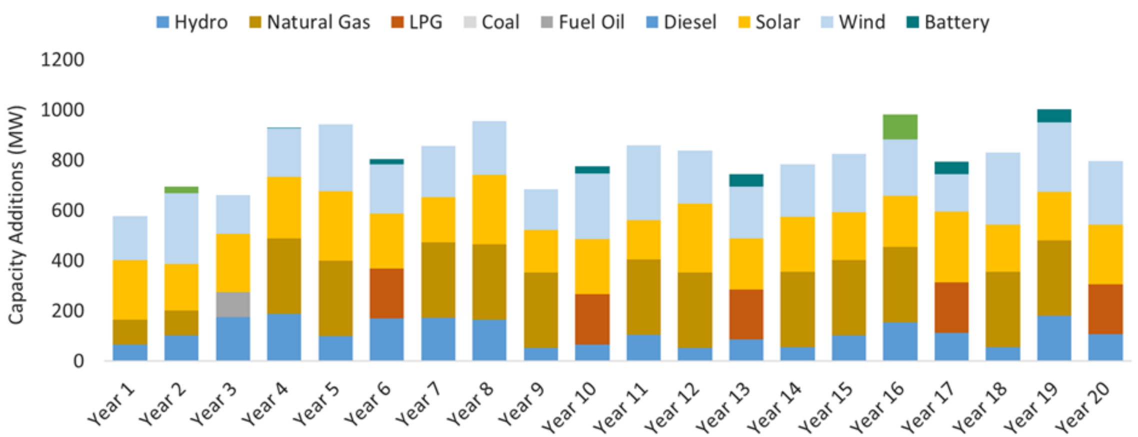


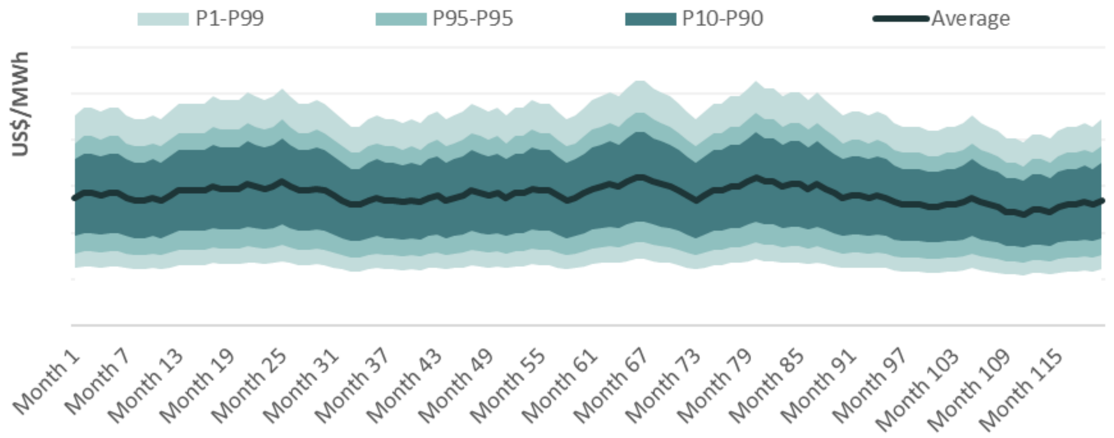
Minimize **Investment Cost** + **Operative Cost**

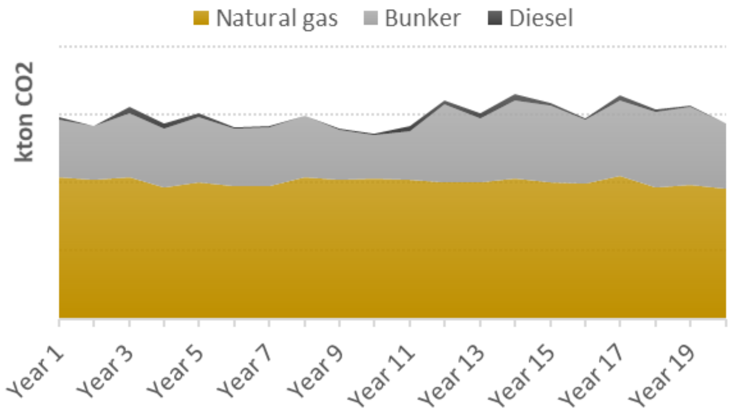
Subject to: **Energy Policy Constraints**

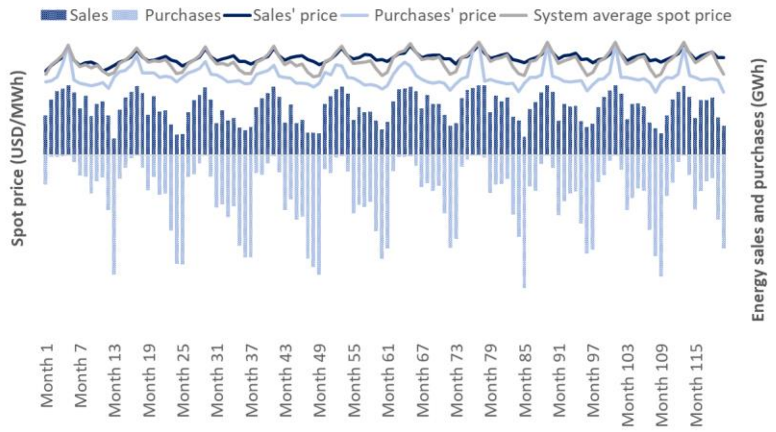
Example 1.0: Business as Usual

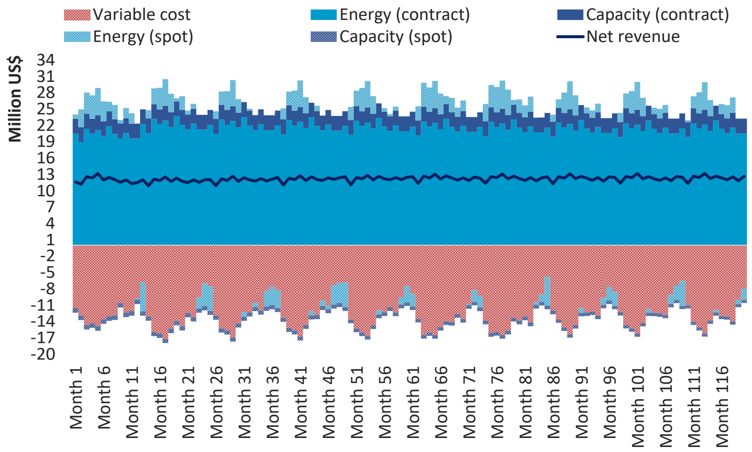
- Typical results to be evaluated are: system expansion, spot prices (with dispersion), emissions, generation, captured prices and revenues.





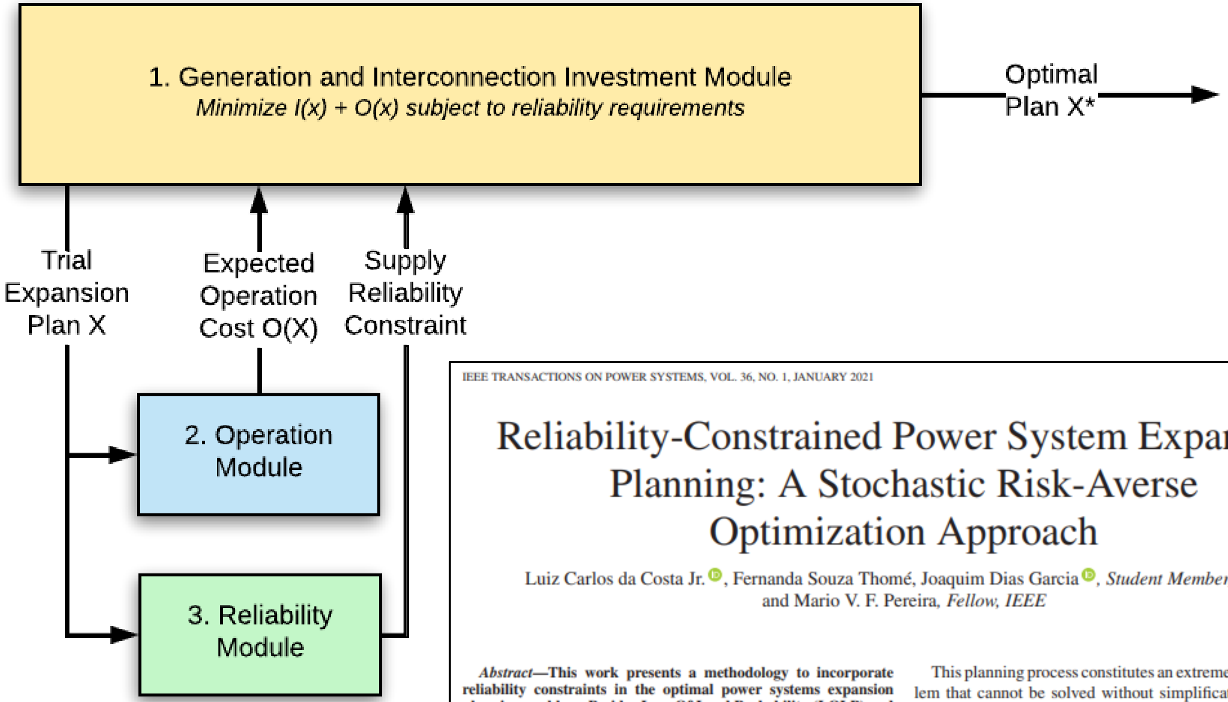


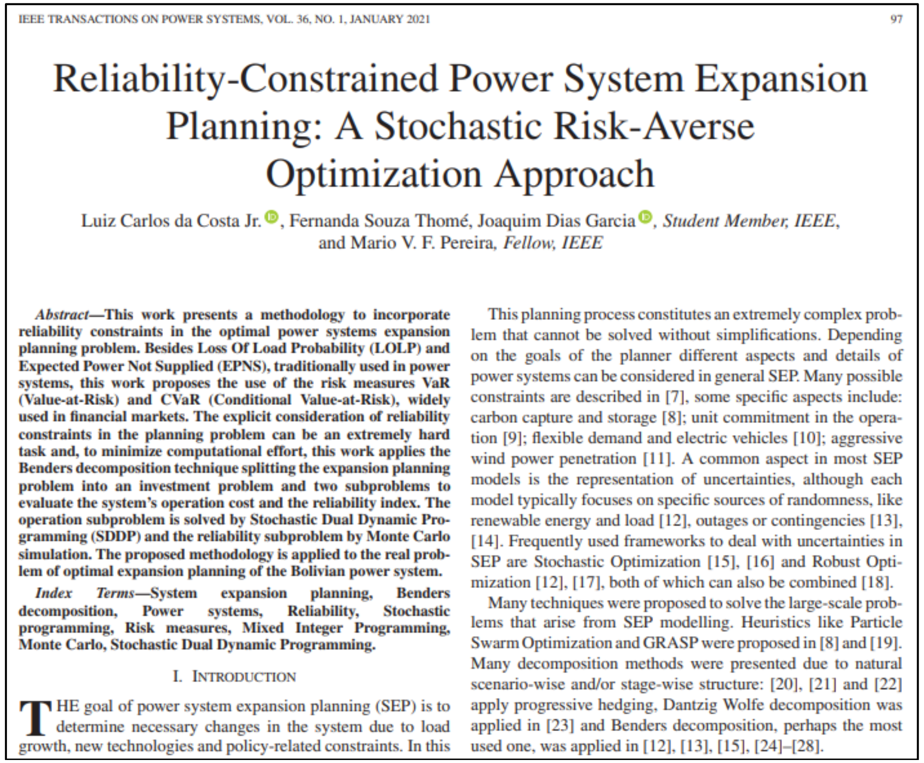




Planning 2.0: 1.0 + Reliability

- Security of supply under a wide range of conditions ("known unknowns")
- Addition of a reliability criterium (e.g., EPNS <= 1%)
- Supply reliability & resource adequacy
  - G&T forced outages
  - Composite generation and transmission reliability





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Reliability-Constrained Power System Expansion Planning: A Stochastic Risk-Averse Optimization Approach

Luiz Carlos da Costa Jr., Fernanda Souza Thomé, Joaquim Dias Garcia, *Student Member, IEEE*, and Mario V. F. Pereira, *Fellow, IEEE*

***Abstract*—This work presents a methodology to incorporate reliability constraints in the optimal power systems expansion planning problem. Besides Loss Of Load Probability (LOLP) and Expected Power Not Supplied (EPNS), traditionally used in power systems, this work proposes the use of the risk measures VaR (Value-at-Risk) and CVaR (Conditional Value-at-Risk), widely used in financial markets. The explicit consideration of reliability constraints in the planning problem can be an extremely hard task and, to minimize computational effort, this work applies the Benders decomposition technique splitting the expansion planning problem into an investment problem and two subproblems to evaluate the system's operation cost and the reliability index. The operation subproblem is solved by Stochastic Dual Dynamic Programming (SDDP) and the reliability subproblem by Monte Carlo simulation. The proposed methodology is applied to the real problem of optimal expansion planning of the Bolivian power system.**

***Index Terms*—System expansion planning, Benders decomposition, Power systems, Reliability, Stochastic programming, Risk measures, Mixed Integer Programming, Monte Carlo, Stochastic Dual Dynamic Programming.**

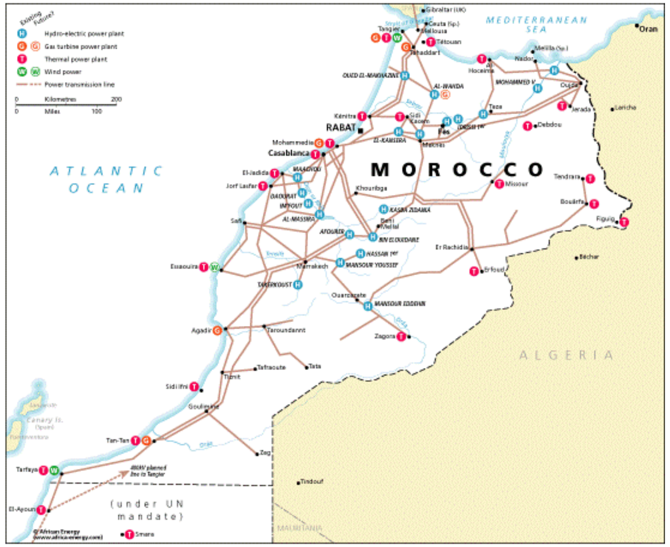
I. Introduction

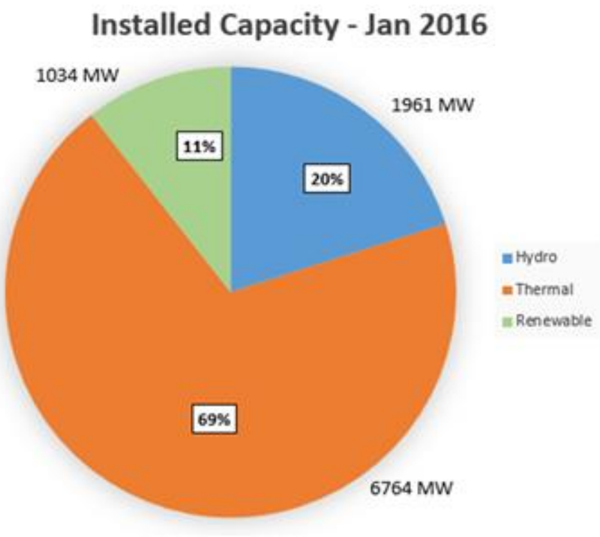
THE goal of power system expansion planning (SEP) is to determine necessary changes in the system due to load growth, new technologies and policy-related constraints. In this

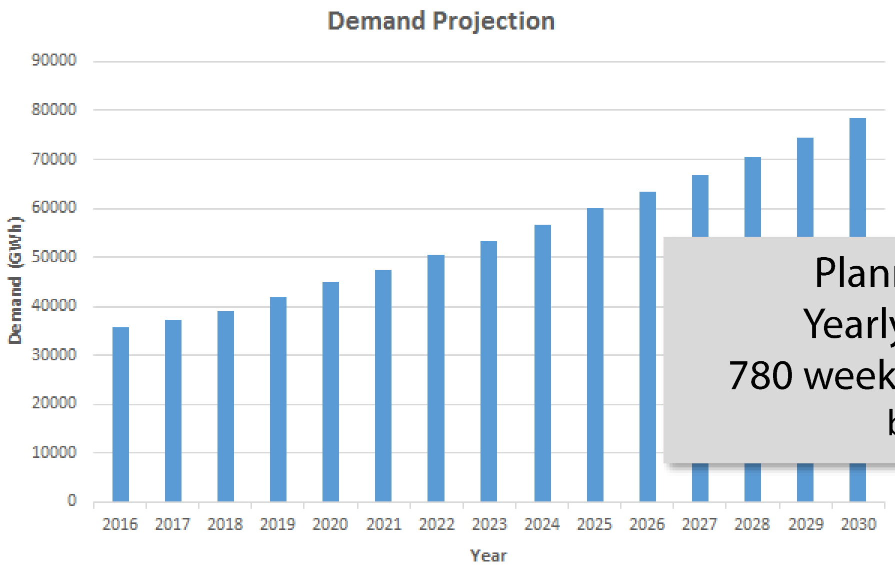
This planning process constitutes an extremely complex problem that cannot be solved without simplifications. Depending on the goals of the planner different aspects and details of power systems can be considered in general SEP. Many possible constraints are described in [7], some specific aspects include: carbon capture and storage [8]; unit commitment in the operation [9]; flexible demand and electric vehicles [10]; aggressive wind power penetration [11]. A common aspect in most SEP models is the representation of uncertainties, although each model typically focuses on specific sources of randomness, like renewable energy and load [12], outages or contingencies [13], [14]. Frequently used frameworks to deal with uncertainties in SEP are Stochastic Optimization [15], [16] and Robust Optimization [12], [17], both of which can also be combined [18].

Many techniques were proposed to solve the large-scale problems that arise from SEP modelling. Heuristics like Particle Swarm Optimization and GRASP were proposed in [8] and [19]. Many decomposition methods were presented due to natural scenario-wise and/or stage-wise structure: [20], [21] and [22] apply progressive hedging, Dantzig Wolfe decomposition was applied in [23] and Benders decomposition, perhaps the most used one, was applied in [12], [13], [15], [24]–[28].

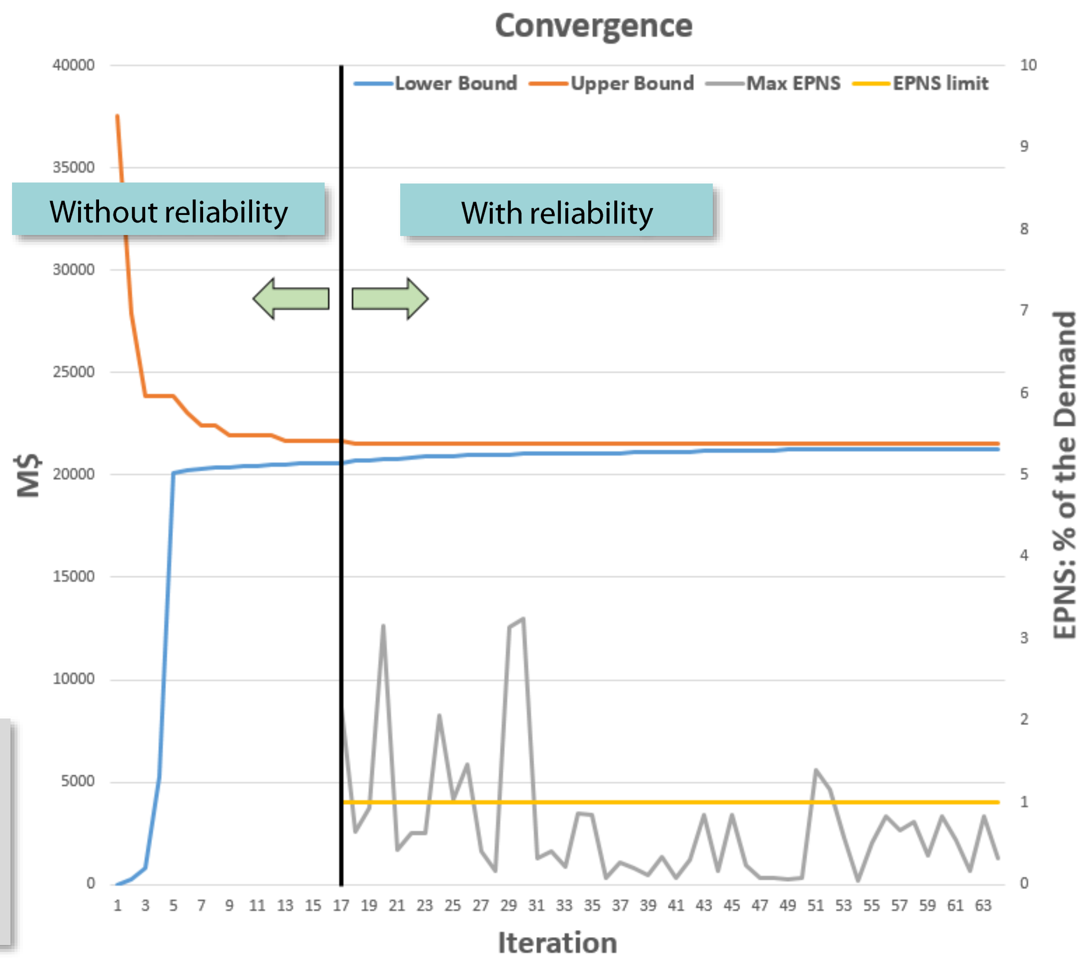
Example 2.0: Moroccan expansion plan





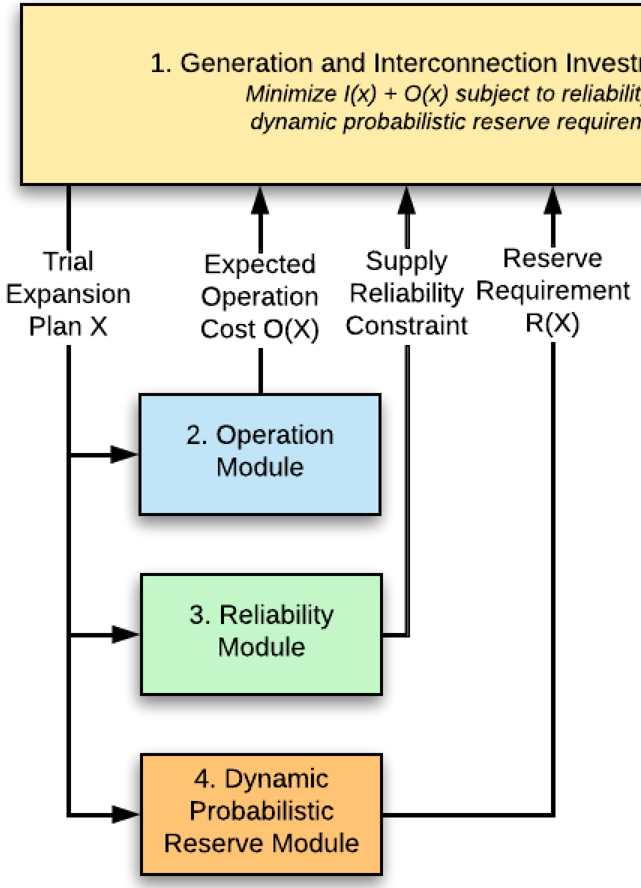


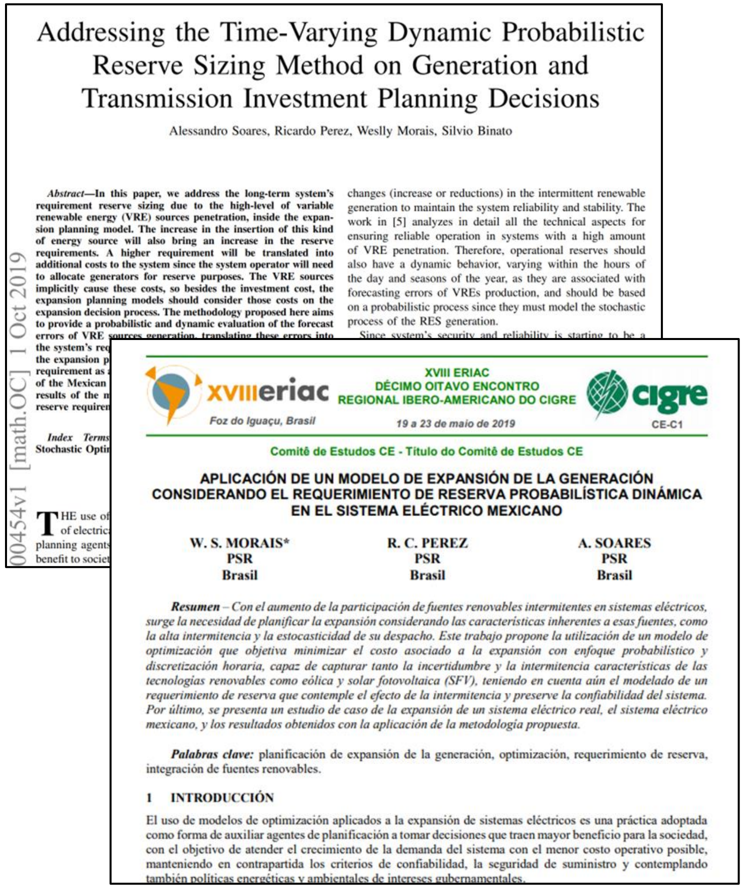
Planning horizon: 15 years
Yearly investment decisions
780 weekly operation stages (21 load blocks in each stage)



Planning 3.0: 2.0 + Co-optimization with Flexibility (Dynamic Probabilistic Reserve – DPR)

- The reserve requirement must be a decision variable for the expansion planning model
  - The DPR requirement will be co-optimized together with the investment decisions in an embedded way (endogenously)
- In other words, the model will select renewable plants considering the indirect cost that those plants will bring to the system by increasing the reserve requirements
  - The model may select, for example, specific renewable plants that, together, reduce the reserve requirement (Portfolio effect)
  - Wind parks that have a negative correlation coefficient (or high complementarity)
  - Solar plants that are not very close to each other (reducing the impact of the cloudy days)





Addressing the Time-Varying Dynamic Probabilistic Reserve Sizing Method on Generation and Transmission Investment Planning Decisions

Alessandro Soares, Ricardo Perez, Weslly Morais, Silvio Binato

Abstract—In this paper, we address the long-term system's requirement reserve sizing due to the high-level of variable renewable energy (VRE) sources penetration, inside the expansion planning model. The increase in the insertion of this kind of energy source will also bring an increase in the reserve requirements. A higher requirement will be translated into additional costs to the system since the system operator will need to allocate generators for reserve purposes. The VRE sources implicitly cause these costs, so besides the investment cost, the expansion planning models should consider those costs on the expansion decision process. The methodology proposed here aims to provide a probabilistic and dynamic evaluation of the forecast

changes (increase or reductions) in the intermittent renewable generation to maintain the system reliability and stability. The work in [5] analyzes in detail all the technical aspects for ensuring reliable operation in systems with a high amount of VRE penetration. Therefore, operational reserves should also have a dynamic behavior, varying within the hours of the day and seasons of the year, as they are associated with forecasting errors of VREs production, and should be based on a probabilistic process since they must model the stochastic process of the RES generation.

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APLICACIÓN DE UN MODELO DE EXPANSIÓN DE LA GENERACIÓN CONSIDERANDO EL REQUERIMIENTO DE RESERVA PROBABILÍSTICA DINÁMICA EN EL SISTEMA ELÉCTRICO MEXICANO

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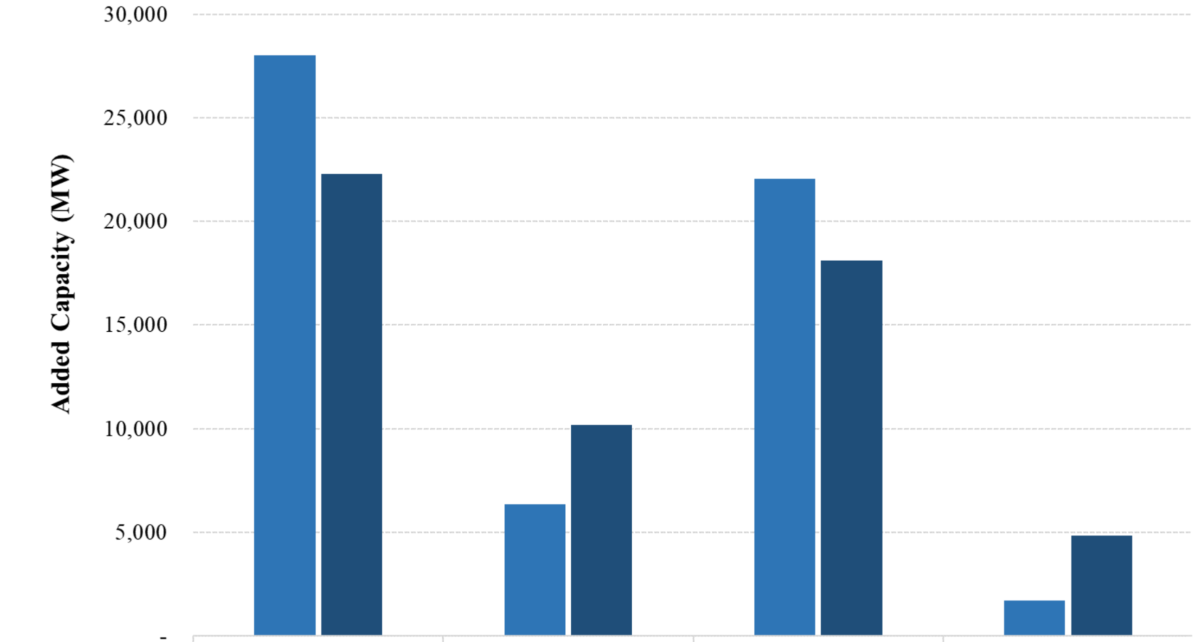
Resumen *– Con el aumento de la participación de fuentes renovables intermitentes en sistemas eléctricos, surge la necesidad de planificar la expansión considerando las caracteristicas inherentes a esas fuentes, como la alta intermitencia y la estocasticidad de su despacho. Este trabajo propone la utilización de un modelo de optimización que objetiva minimizar el costo asociado a la expansión con enfoque probabilístico y discretización horaria, capaz de capturar tanto la incertidumbre y la intermitencia características de las tecnologias renovables como eólica y solar fotovoltaica (SFV), teniendo en cuenta aún el modelado de un requerimiento de reserva que contemple el efecto de la intermitencia y preserve la confiabilidad del sistema. Por último, se presenta un estudio de caso de la expansión de un sistema eléctrico real, el sistema eléctrico mexicano, y los resultados obtenidos con la aplicación de la metodología propuesta.*

Palabras clave: planificación de expansión de la generación, optimización, requerimiento de reserva, integración de fuentes renovables.

1 INTRODUCCIÓN

El uso de modelos de optimización aplicados a la expansión de sistemas eléctricos es una práctica adoptada como forma de auxiliar agentes de planificación a tomar decisiones que traen mayor beneficio para la sociedad, con el objetivo de atender el crecimiento de la demanda del sistema con el menor costo operativo posible, manteniendo en contrapartida los criterios de confiabilidad, la seguridad de suministro y contemplando también políticas energéticas y ambientales de intereses gubernamentales.

Example 3.1: Expansion of the Mexican System

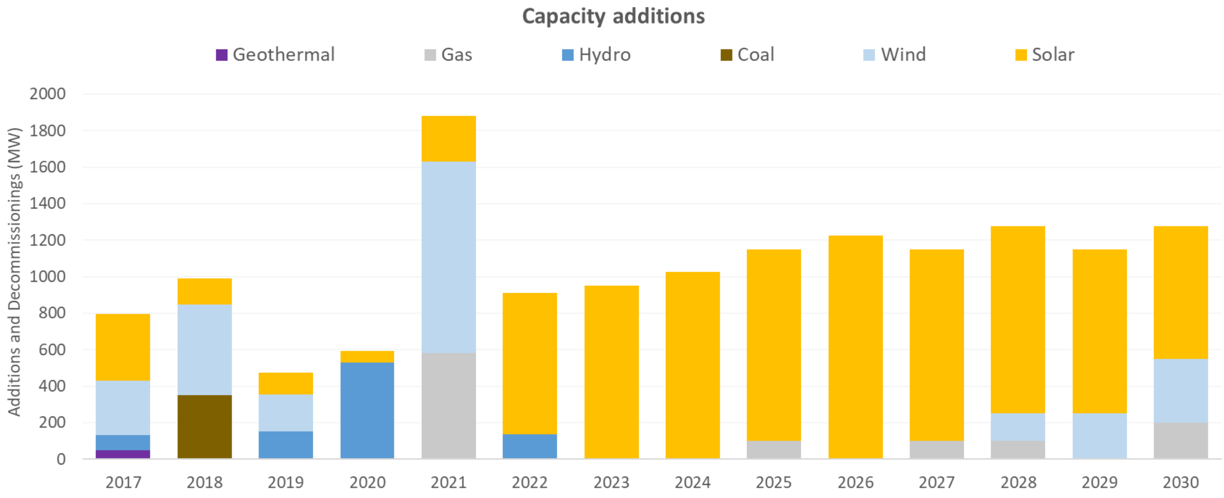


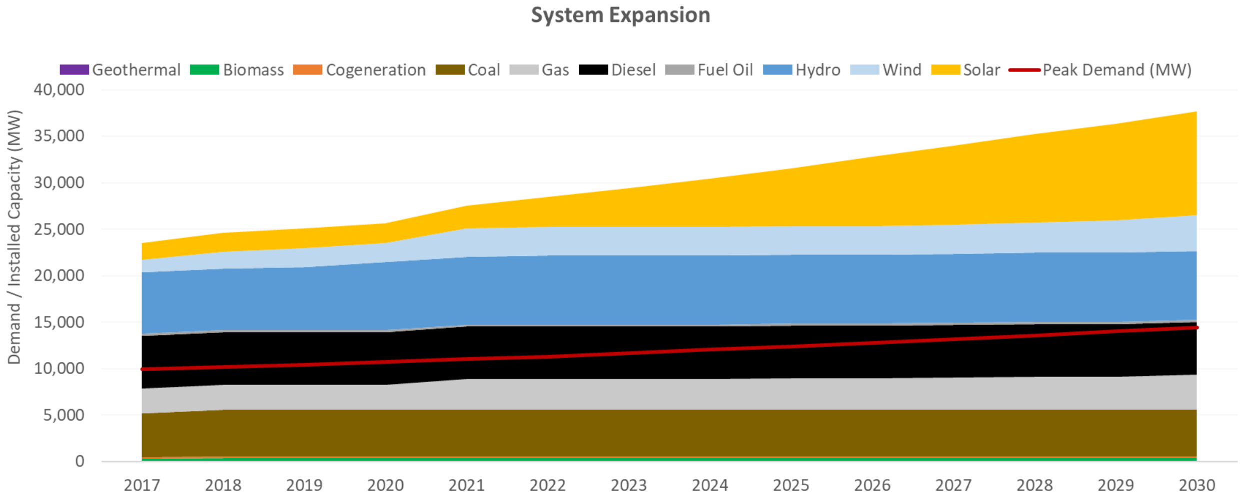
Reserve	Wind	CCGT	Solar	OCGT
Demand	28,032	6,322	22,057	1,709
D + Intermittency	22,303	10,168	18,096	4,838

- The idea of the Dynamic Probabilistic Reserve (DPR) is to contemplate not only demand fluctuations and the failure of the biggest generating unit while calculating the 2ary Reserve Requirement, but also the intermittency caused by renewables in an embedded way
- When the DPR is considered in the investment model, VRE participation decreases due to an increased requirement of Secondary Reserve Requirement (increased operating costs)

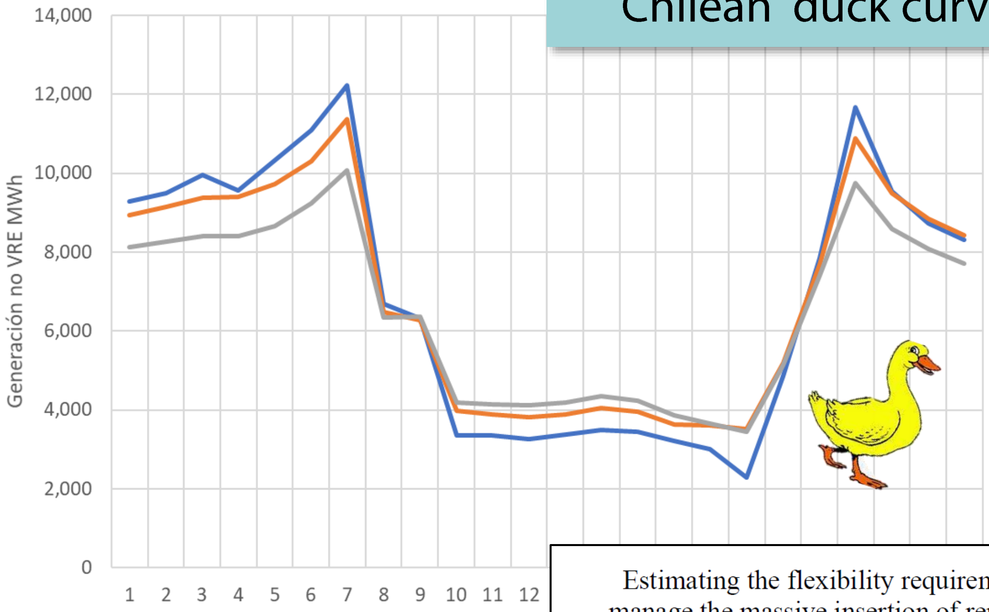
Example 3.2: Chile

- The optimal expansion plan:





Chilean "duck curve" (2030)



Estimating the flexibility requirements and cost to manage the massive insertion of renewables in Chile

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Abstract—**This paper describes the methodology, computational tools and results of a study sponsored by the Chilean Generators' Association (AGC) to quantify the investment and direct/indirect costs of providing the flexibility services (probabilistic dynamic reserve, modulation etc.) required for the efficient and secure operation of the Chilean power system under the projected massive variable renewable energy (VRE) insertion in the next decade.**

Index Terms—**Flexibility service, Operational reserve, Optimization, Power systems, Variable energy resources.**

I. Introduction

Chile's variable renewable energy (VRE) resources are among the world's competitive: the Atacama Desert has ideal insolation characteristics, whereas wind production tends to be higher in the nighttime, thus complementing the daily solar profile. Therefore, solar and wind won most of the contract auctions in the past years and should dominate the country's expansion. This massive VRE insertion motivated government and agents to assess the *flexible generation reserve* required to manage their production variability: amount, type (e.g. existing hydro and thermal, new fast gas generation, pumped storage, batteries etc.) and cost (investment cost of new capacity, additional O&M costs due to increased cycling, missed energy sales of generation allocated to reserve etc.).

the *flexibility services cost* (investment, additional O&M costs) based on detailed probabilistic hourly simulations of system operation.

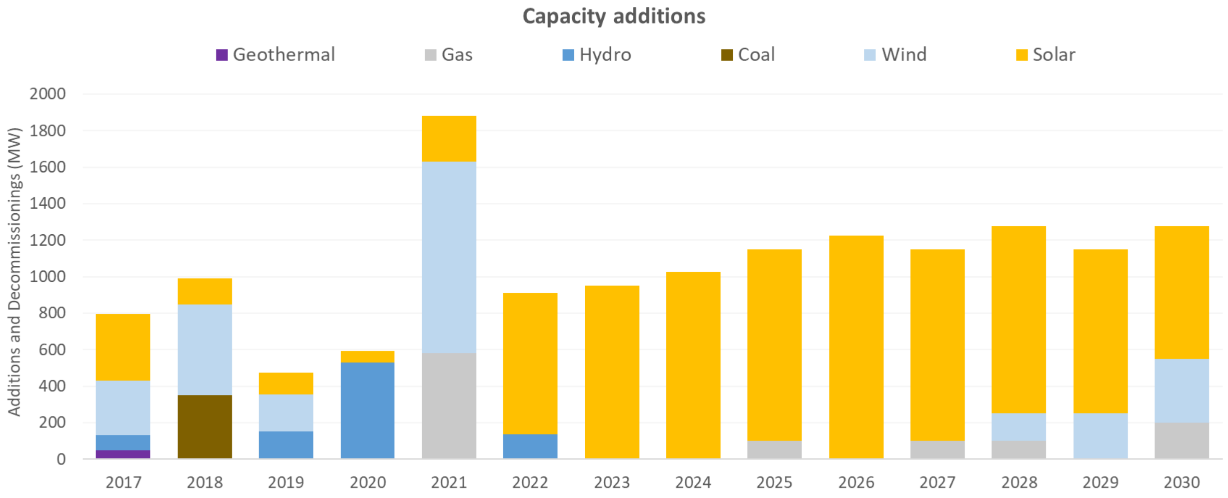
A. Related work

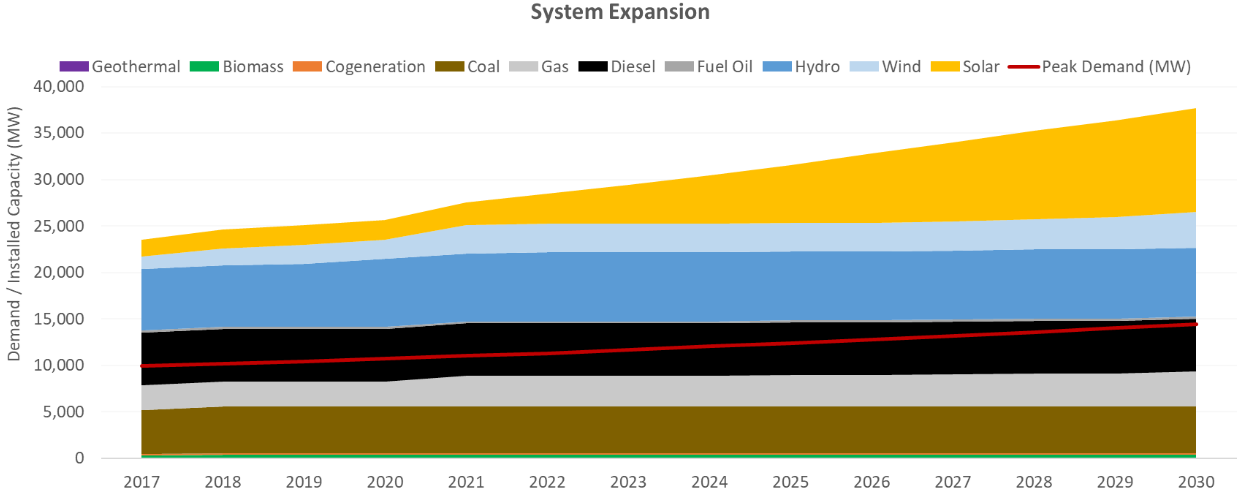
Flexibility is defined as the capability of a system to deal with unexpected changes in generation or demand while keeping a certain level of reliability at minimum cost [1],[2]. Therefore, it is an attribute of great interest when integrating a significant amount of VRE sources [6]. For example, NREL's study in [7] identifies the costs associated with flexibility services for thermal plants, such as increase on number of start-ups/cycling of generating. In [8], the start and stop costs for hydro generators are evaluated; the study in [9] quantifies the costs for German power plants considering up to 50% VRE insertion and concludes that direct and indirect start-up costs are higher than ramping-related costs. Another German study [10] quantifies the number of start-ups from 2010 to 2030 and show that they are affected by changes in the generation mix, in particular, retirement of nuclear plants.

As stated in [3], just increasing the reserve margin (peak demand minus the total installed capacity) is not enough to ensure system security in the case of VREs; in order to calculate the optimal mix of generators, reserve and flexibility, some short-term constraints such as upward/downward ramps, minimum up/down time and others must be considered. For

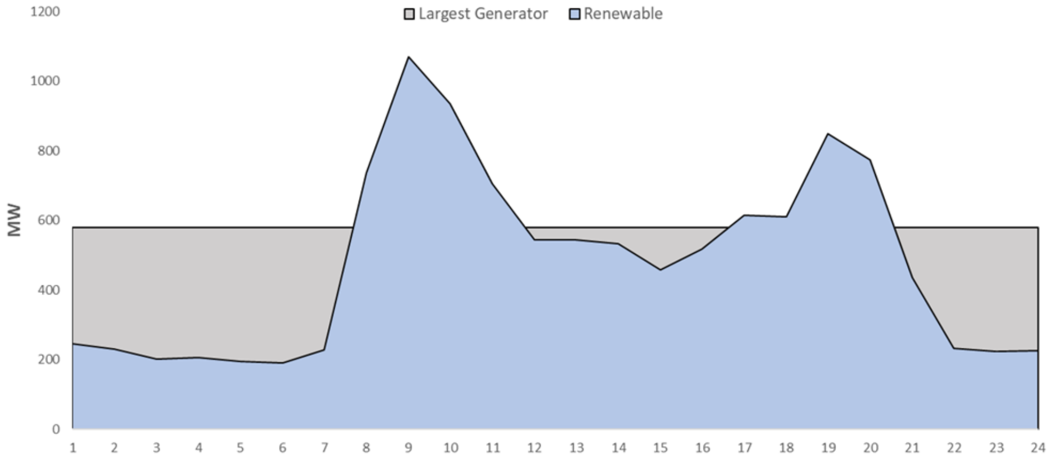
Example 3.2: Chile

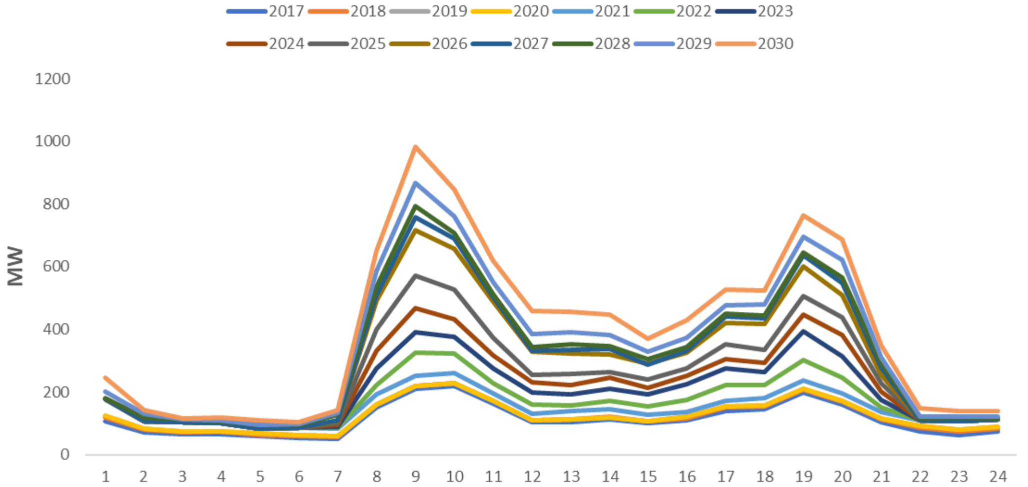
- The optimal expansion plan:





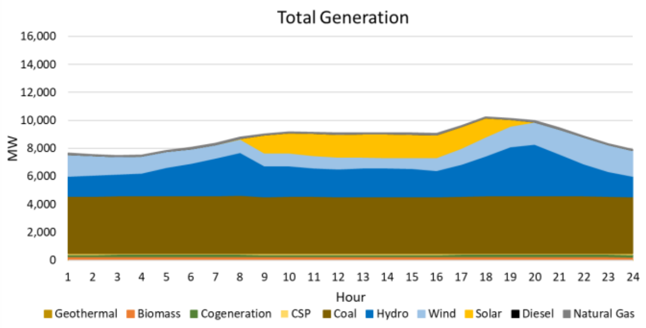
- Calculation of the Dynamic Probabilistic Reserves:

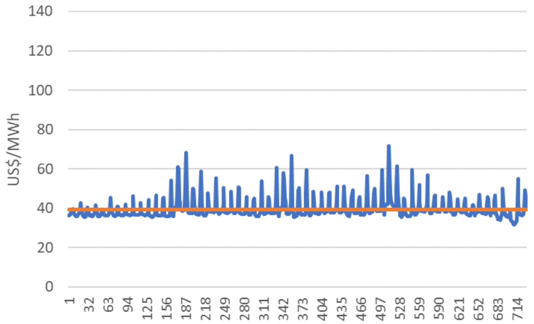




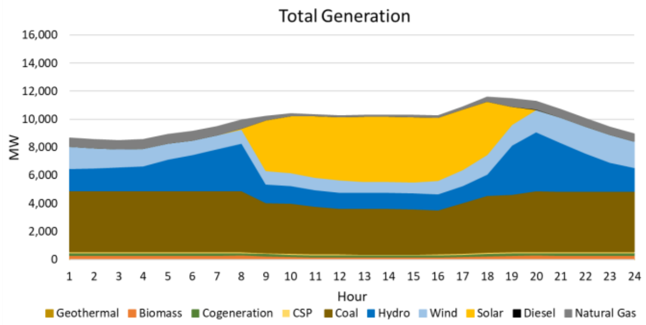
Example 3.2: Chile

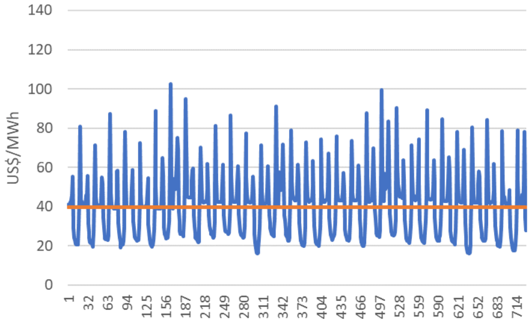
2021



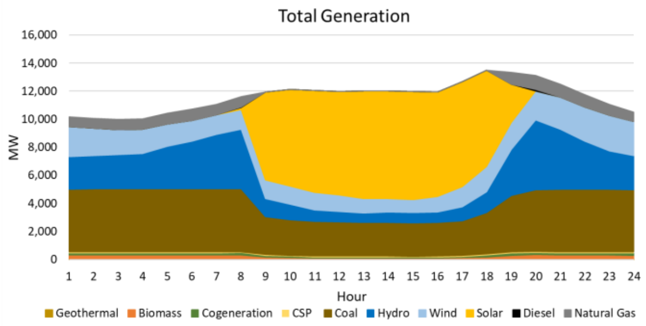


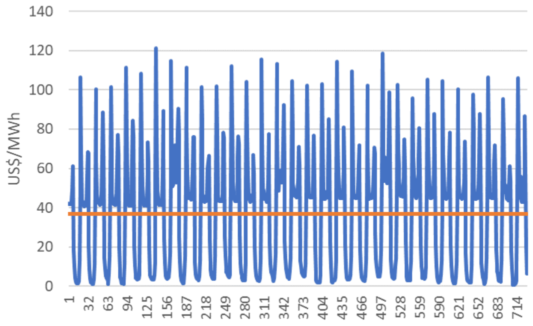
2025



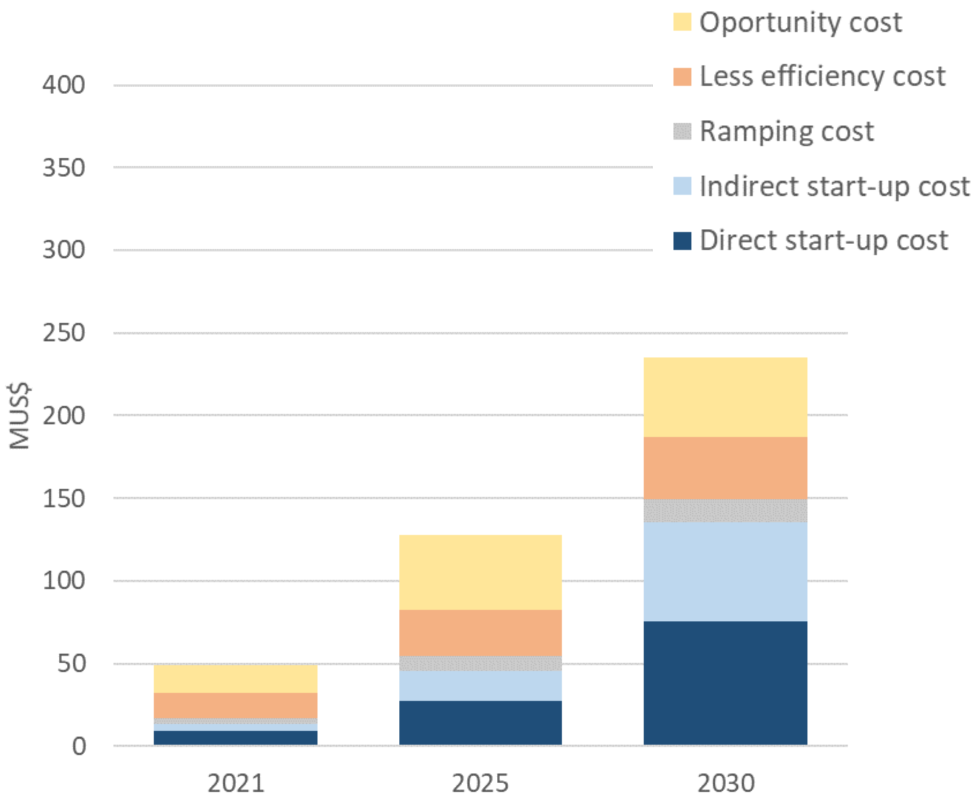


2030



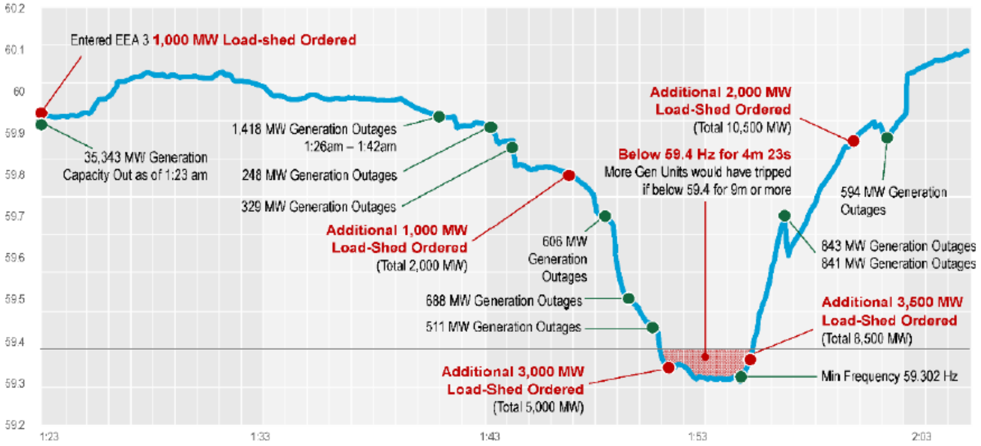


Example of the Flexibility Cost Calculation:



Looking back, what is the missing piece?

Rapid Decrease in Generation Causes Frequency Drop



Climate change is making India's brutal heat waves worse

As temperatures top 110°F, the heat could be deadly, especially to those without access to cooling.

By Casey Crownhart

April 28, 2022

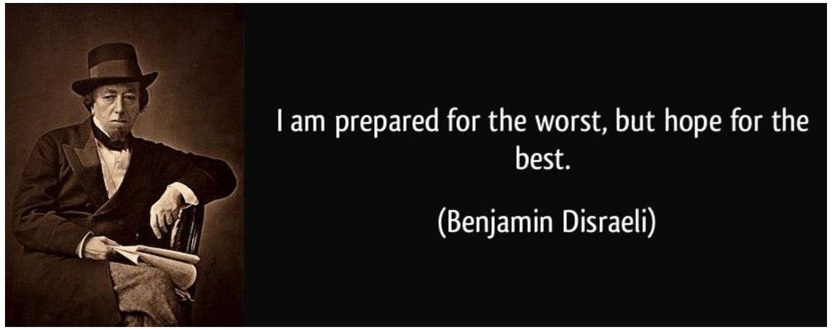
NEWS | 28 April 2022

Climate change will force new animal encounters — and boost viral outbreaks

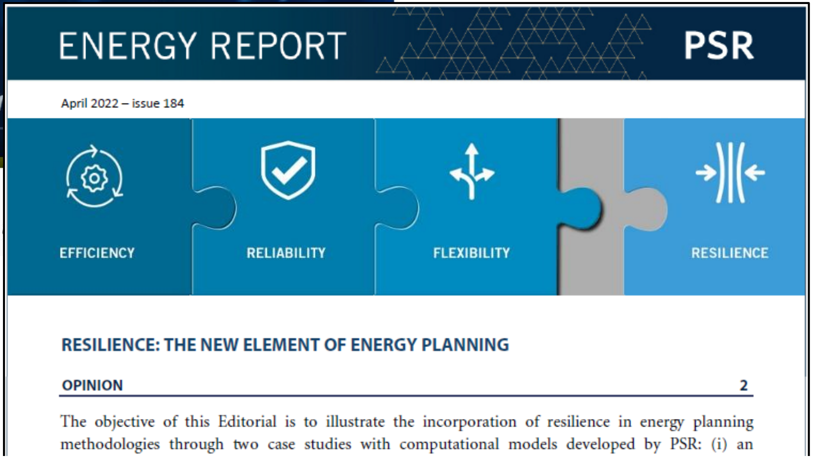
Modelling study is first to project how global warming will increase virus swapping between species.

*"The Timeline and Events of February 2021 Texas Electric Grid Blackouts", The University of Texas at Austin, July 2021.

Looking back, what is the missing piece?



Premium BR



Very hot topic at the IEEE PES GM 2022

PSOPE - Task Force on Advanced Intelligence Techniques for Resilient Power System Restoration

DETAILS

Monday, 18 July

Managing the Unexpected: Wildfire Risk in Power Infrastructure

DETAILS | DISCUSSION

18 July 15-17

PSDP Task Force on Methods for Analysis and Quantification of Power System Resilience

DETAILS | DISCUSSI

Monday, 18 July

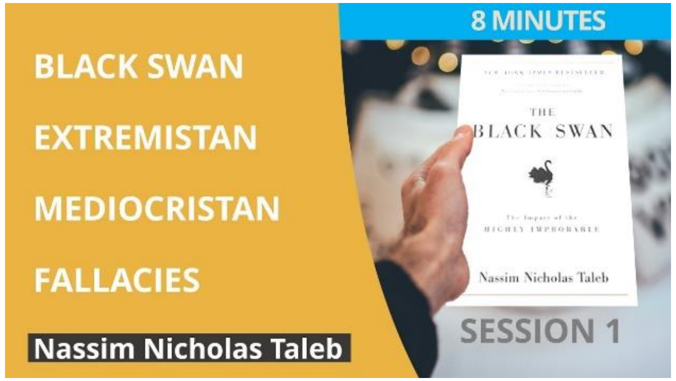
Future Reliability and Resilience Study of Electrical and Gas Systems under Extreme Weather Events

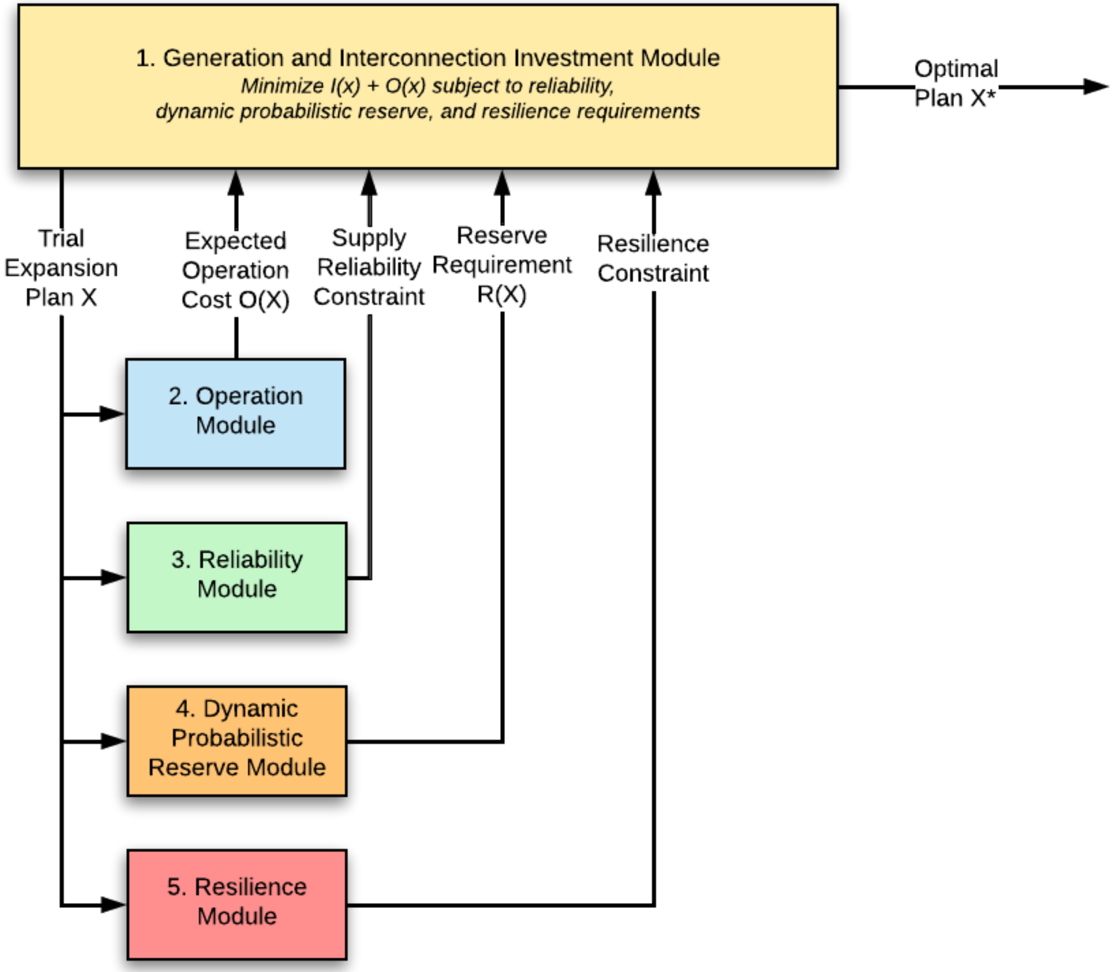
DETAILS | DISCUSSION

Monday, 18 July 17-19

Planning 4.0: 3.0 + Resilience

- Let's model now the "unknown unkowns"!
- Extreme ***scenarios*** (without assigning a specific probability):
  - Long-lasting decrease in renewable generation
  - Droughts and very severe temperatures due to climate change
  - Interruptions in fuel imports
  - Long-lasting outages of large generation trunks (e.g., due to cyber attacks, etc.)
- Resilience measures
  - Source diversification
  - Storage distribution
  - Greater self-sufficiency in each region

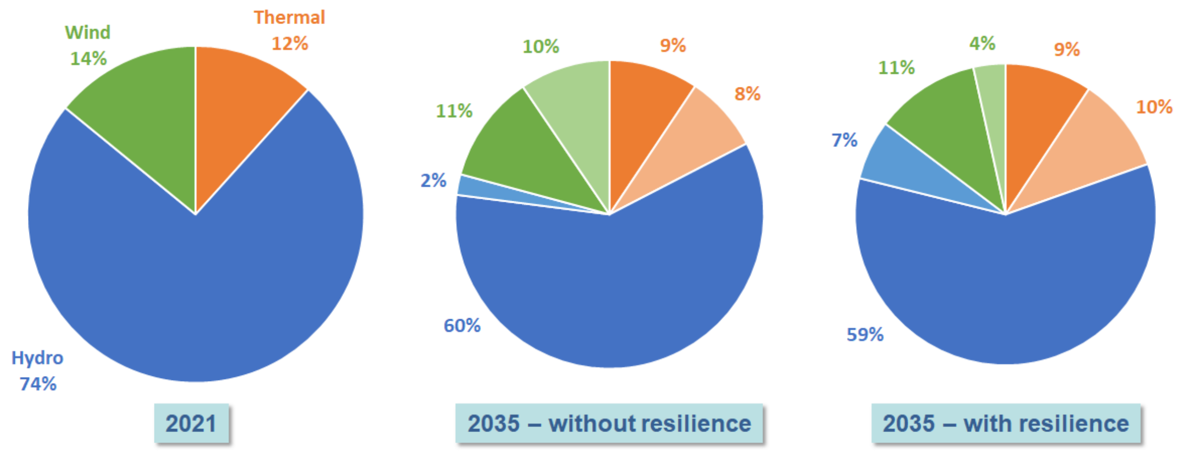




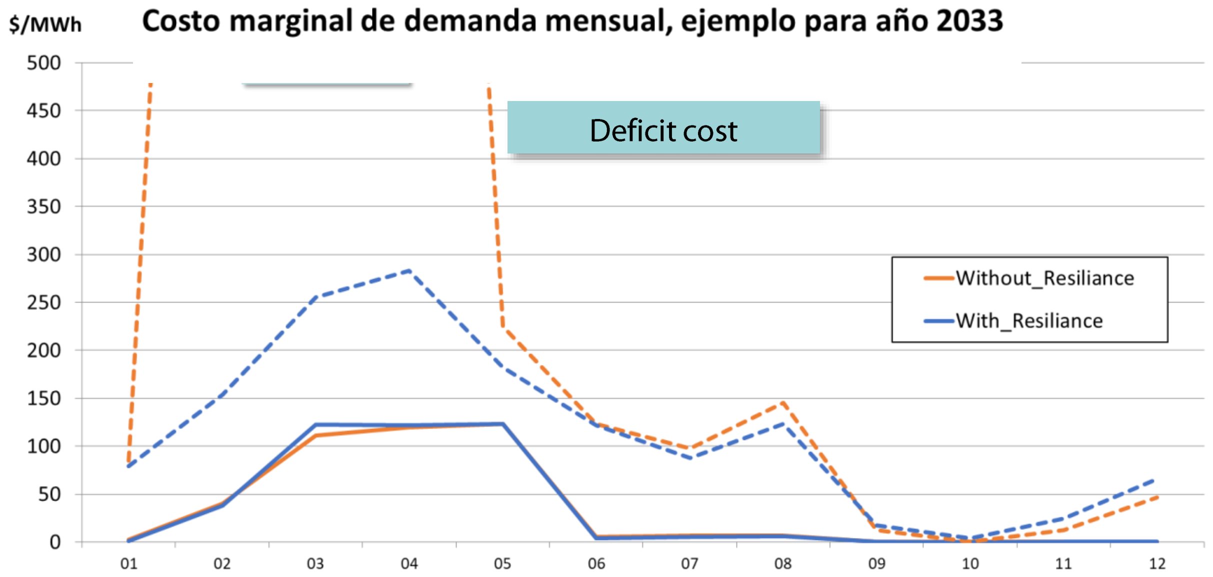
Captures high-impact low-probability events

Example 4.0: Costa Rica

- "Black swan" scenario is a severe reduction of wind



- Load Marginal Cost (2035)



Change in the mix: more diversification with less wind power

The critical event is faced with lower load marginal costs

*A single extreme scenario was considered, which is the almost total reduction of wind generation for one year. This scenario is totally artificial (we hope!) and was intended to highlight the effects of the resilience module

Summarizing everything!

- **Planning 1.0**: economic efficiency + energy policy guidelines
  - BAU: Business as Usual
  - Minimize expected total costs (investment + expected value of the operating costs) under uncertainty (variability of hydro, wind, solar, biomass production, and demand)

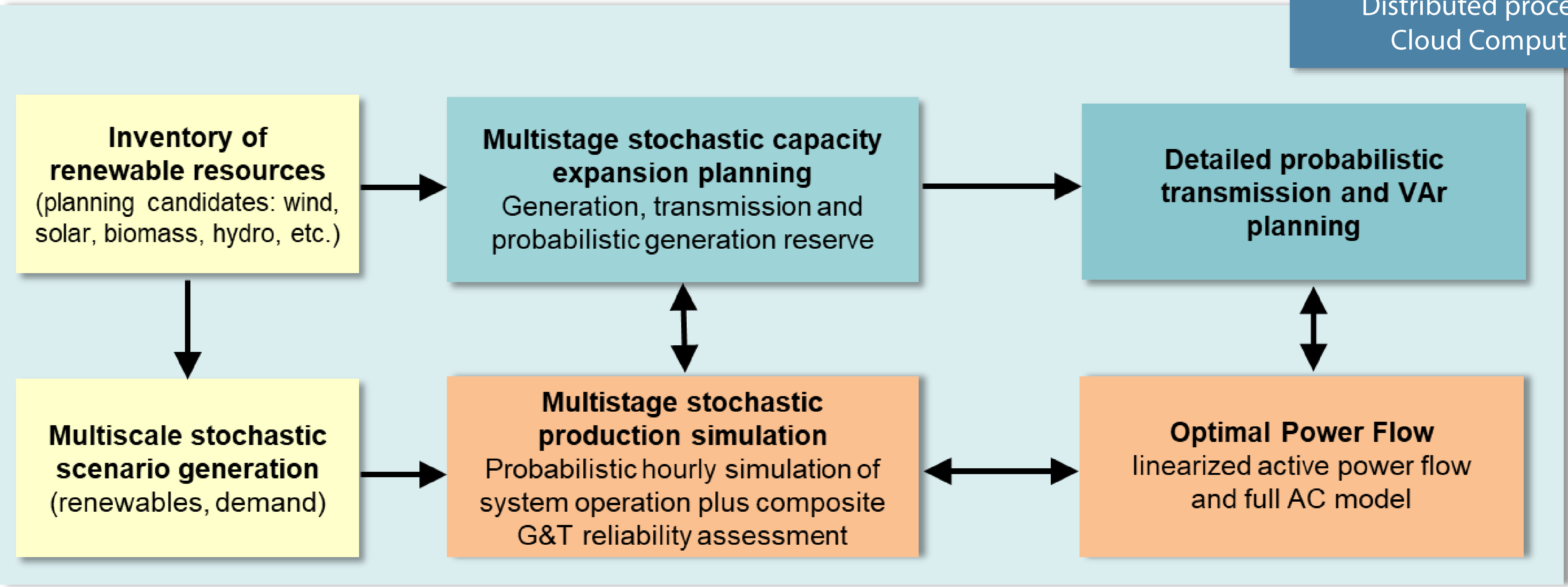
- **Planning 2.0**: (1.0) + reliability & resource adequacy
  - Security of supply considering the “known unknowns” (equipment failure, composite generation and transmission reliability)

- **Planning 3.0**: (2.0) + co-optimization with flexibility (= dynamic probabilistic reserve)
  - Contemplating: intermittency of renewables, demand fluctuations and failure of the largest generating unit
  - Considers that reserve requirements vary over time ➔ better dimensioned requirements and, consequently, the costs for the provision of these services are optimized

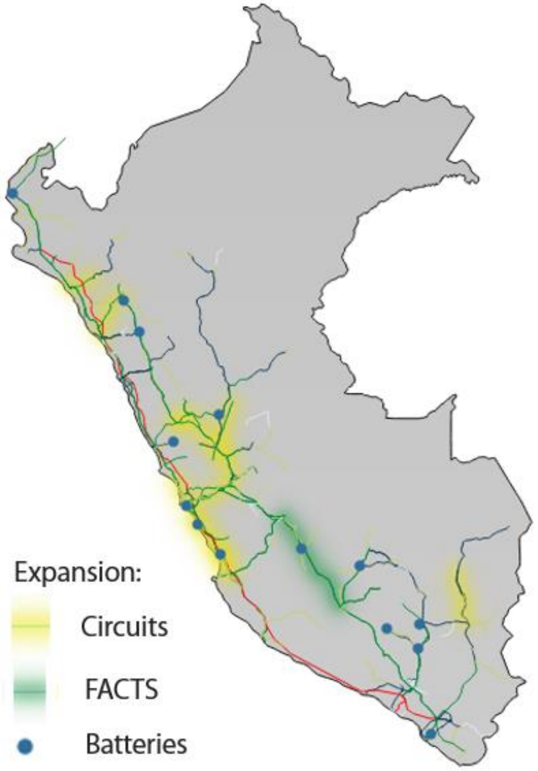
- **Planning 4.0**: (3.0) + resilience
  - Feasible supply considering the “unknown unknowns” (stochastic models are not suitable for extreme events)
  - Application examples: Geopolitical disruptions of fuel supply, very severe droughts, wind disruptions, effects of climate changes, etc.

Integrated planning with “state of the art” tools is essential

Distributed processing
Cloud Computing



Out of the scope: flexibility in transmission



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POWER FLOW CONTROLLABILITY AND FLEXIBILITY IN THE TRANSMISSION EXPANSION PLANNING PROBLEM: A MIXED-INTEGER LINEAR PROGRAMMING APPROACH

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Study Committee C1
PS2 – New System Solutions and Planning Techniques

CIGRE 2014

FACTS and D-FACTS: The Operational Flexibility Demanded by the Transmission Expansion Planning Task with Increasing RES

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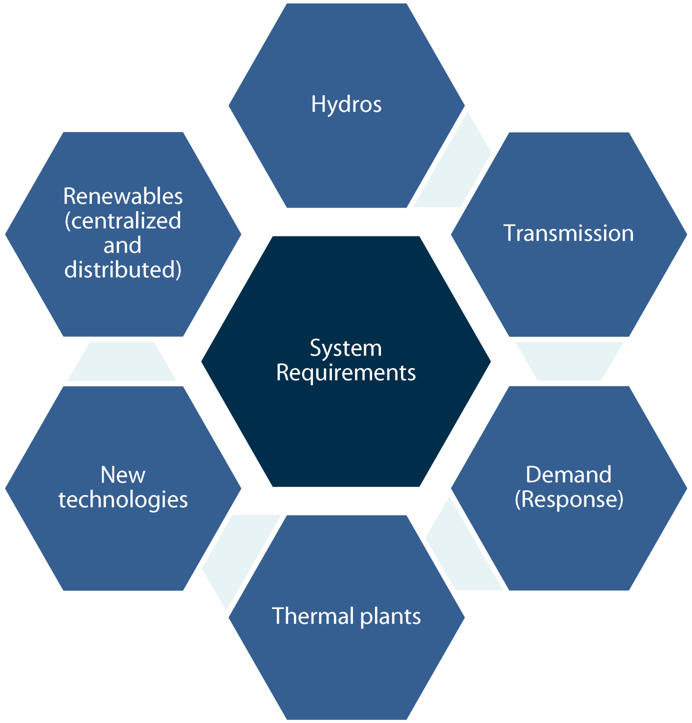
SUMMARY

There are several reasons to explain why transmission system loading is less than 100%. These reasons include: (i) reliability, (ii) uncertainties associated with the demand growth forecast and (iii) different dispatch scenarios due to Renewable Energy Sources (RES), i.e., hydroelectricity, modern biomass, wind and solar power. The combination of these facts leads to high investments in the transmission systems to meet different dispatch scenarios and low loading throughout the year.

Conclusions

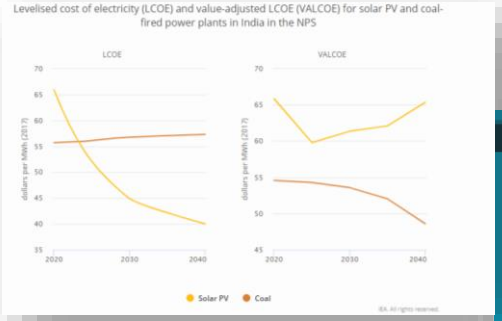
Valuation of the attributes of each technology

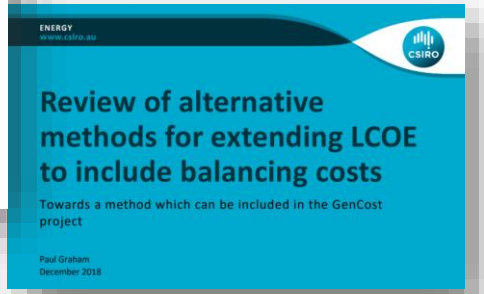
- Each technology offers a different value for the services that the system needs
- Each technology is a piece of the "puzzle" of the energy transition / decarbonization process
- The proposed planning scheme allows these values to be determined in order to compare them on the same basis, leveling the rules of the game



- Peak Demand Supply
- Portfolio Effect
- Location
- CAPEX/OPEX
- Emissions
- Modulation and seasonalization
- Robustness
- Flexibility
- Reliability
- Effects on Transmission

- CAPEX, OPEX
- Generation services (modulation, production synergies, flexibility)
- Infrastructure costs
- Effects on the transmission network
- Subsidies and incentives
- Environmental costs
- Emissions
- Resilience





In summary

- The complexity of power system planning & operation has increased substantially
- And market mechanisms are effective in promoting economic efficiency, but they are not adequate to ensure the reliability of supply under a wide range of uncertainties
- The reason is that reliability is a systemic attribute, that is, it requires an integrated vision of all supply and demand resources
- Recent disruptive events: economic decoupling of the United States and China; pandemic; extreme temperatures and flooding; and the invasion of Ukraine has also increased the importance of this integrated vision: in addition to reliability, it becomes necessary to ensure the resilience of energy systems
- The importance of enhanced planning schemes is going to grow considerably
- Fortunately, suitable computational tools are available in the market 😉

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Questions? Thanks!

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