Analytics Report PSR

ISSUE 1 **JULY 2025**

The Analytics Report (AR) is a PSR publication that presents our latest advancements in energy analytics, focusing on models (methodologies and applications), high-performance computing, and research. Each edition offers a detailed look at how PSR is continuously innovating in the field of energy analytics, showcasing the development and application of advanced tools and techniques. The report provides a platform for sharing insights and bleeding-edge research that drive decision-making and enhance understanding in the energy sector.

Special Issue

Lately in PSR

Highlights from the PSR User Meeting in May 2025 and launching of SDDP 18.

inBrief

Case Studies

Discover applications of PSR tools focusing on addressing curtailment challenges in Brazil and supporting the planning of large-scale hydropower projects in Central Asia.

inSight

Grid Enhancing Technologies

A study from Colombia explores how Grid Enhancing Technologies can improve power system flexibility and efficiency by optimizing the use of existing infrastructure and delaying investments in new transmission lines.

inDepth

A New Framework to Assess Reliability, Flexibility, and Resilience of Power Systems

Introducing SINAIS. A framework for power system performance indicators estimation for analysis of interconnected systems.

inNovation

PSR and Academic Research

Highlights of PSR's contributions to the academic field include participation in international conferences, collaborative research efforts, and scientific publications, showcasing how its modeling tools are embedded in advanced studies on energy systems.

SPECIAL ISSUE

Luiz Carlos da Costa Junior

PSR User Meeting

From May 18th to 22nd, PSR hosted the 2025 edition of its Global User Meeting in Búzios, Brazil. With over 170 participants from 20 countries across 4 continents, the event confirmed its role as a unique space for global dialogue on energy analytics. Attendees included clients, government agencies, system operators, consultancies, and research institutions. The entire PSR modeling and software development team was also present, enabling deep technical interaction and reinforcing the company's commitment to fostering collaboration and engagement with its clients.

This year's agenda was structured around three core themes. The first focused on navigating the energy transition, exploring how systems can remain resilient and flexible amidst rising renewable penetration, new energy carriers such as hydrogen, and growing geopolitical uncertainty. The second examined how energy planning must incorporate the impacts of climate change, moving beyond historical assumptions to probabilistic modeling of resource availability. The third emphasized the role of transmission infrastructure in supporting system flexibility and renewable integration, especially under increasing curtailment and congestion challenges.

Strategic opening: global challenges, SDDP 18 and PSRCast previews

The opening roundtable, led by PSR's leadership — Mario Veiga Pereira (Founder and Chief Innovation Officer), Raphael Chabar (Executive Director), and Luiz Augusto Barroso (CEO) — welcomed international guests Rob West (Thunder Said Energy) and Ricardo Motta (CENACE Mexico). The session provided a global overview of the forces shaping the energy sector: from geopolitical instability and supply chain pressures to the evolving role of analytics in infrastructure investment and adequacy planning. These discussions laid the foundation for a technical program that reflected both strategic vision and methodological depth.

A key milestone of the event was the exclusive preview of **SDDP 18**, PSR's unified platform for integrated energy planning. The new version brings together four modules — SDDP, OptGen, CORAL, and OptMain — into a single modeling environment, enabling consistent and transparent analyses across time horizons and planning layers. A detailed overview of SDDP 18 is presented in a dedicated section of this *Analytics Report*.

Participants also had access to the sneak peek of **PSRCast**, PSR's new deep learning-based platform for generating climate-informed resource availability scenarios. Built on global climate models and neural architectures, PSRCast produces high-resolution probabilistic forecasts for hydro inflows and renewable generation. The platform offers multi-timescale capabilities — from daily to multi-decadal horizons — and is being integrated with PSR's modeling platform to support short- and long-term planning under structural climate shifts.

Modeling challenges and global applications

Over the following days, sessions addressed emerging modeling needs and innovations. Topics included the representation of climate non-stationarity in resource forecasting, the balance between model detail and computational scalability, and the development of large-scale datasets for complex systems such as those in Europe and the United States. Additional sessions focused on flexibility-enabling technologies, energy storage, transmission planning, and the integration of generation and grid expansion under increasing uncertainty.

A central feature of the event was the series of case studies shared by PSR's clients. These presentations illustrated how tools like SDDP, OptGen, NCP, OptMain, and CORAL are being applied to tackle complex challenges across planning and operation. Highlights included expansion and adequacy assessments in hydro- and non-hydro-dominated systems, storage and hydrogen integration in renewable-rich regions, and climate-informed modeling of future scenarios.

Institutions from North and Latin America, Europe, and Oceania presented projects on topics such as system reliability in isolated grids, renewable curtailment reduction, automation of calibration processes, and the use of stochastic optimization to support policy and investment decisions. The diversity of applications reflected the adaptability of PSR's models across different regulatory structures, system topologies, and energy transitions.

Live tools, technical immersion, and hands-on learning

Beyond the plenary sessions, the agenda included practical workshops and demonstrations. Attendees participated in mini courses on modeling automation (PSR Factory), result visualization (PSRIO), renewable scenario generation (Time Series Lab), and high-performance computing (PSR Cloud). These sessions provided an opportunity for users to test new functionalities and discuss technical details directly with the teams who develop and support the tools.

Live tool demonstrations were available throughout the week, creating continuous opportunities for clarification, feedback, and exploration of modeling configurations.

Connecting people and modeling cultures

The presence of PSR's full technical team enabled participants to clarify methodologies, validate modeling strategies, and provide direct input on tool evolution. More than a conference, the event functioned as a collaborative forum — where real-world problems were discussed with the developers who build the solutions.

Individual meetings between clients and PSR staff complemented the technical sessions, offering space for in-depth, personalized dialogue. These one-on-one conversations strengthened the trust-based relationship between PSR and its user community and reflected the company's commitment to active listening and long-term collaboration.

Networking also played a central role. Against the stunning backdrop of Búzios, attendees had the opportunity to connect in a relaxed and inspiring setting — exchanging perspectives on modeling choices, uncertainty treatment, and system-specific adaptations. These interactions helped strengthen a shared analytical culture across institutions and geographies.

Looking ahead

The 2025 PSR User Meeting confirmed the increasing convergence of global energy challenges and the growing demand for robust, transparent, and scalable modeling frameworks. Planning is already underway for the next edition — and we hope to see you there.

SDDP 18: Integrated Platform for Multi-scale Energy Planning

Released in July 2025, SDDP 18 introduces a significant evolution in scope. Built upon PSR's well-known **Stochastic Dual Dynamic Programming** algorithm, the platform now integrates modules for operation (SDDP), expansion (OptGen), reliability (CORAL), and maintenance scheduling (OptMain) enabling consistent planning across multiple horizons and decision layers.

This shared framework allows the joint evaluation of operational policies, investment portfolios, capacity adequacy, and planned outages, all within a unified modeling environment. The approach also extends to multi-energy systems, allowing the co-optimization of electricity, natural gas, hydrogen, biomass, water, and synthetic fuels under uncertainty.

Transmission modeling was enhanced with support for AC/DC elements, FACTS devices, N-k security constraints, and integration with external tools. These improvements enable spatially detailed studies and evaluation of Grid-Enhancing Technologies (GETs) like DLR and power flow control.

Usability was also a focus in this release. A redesigned interface, centralized data structure, georeferenced visualization, and automated dashboards via PSRIO aim to simplify workflows. Integration with the PSR Factory Python API to automate data preparation and streamline execution workflows, and contextual documentation via the PSR Knowledge Hub further support productive and reproducible modeling.

A platform for planning and collaboration

The platform now offers a unified environment for configuring, executing, and analyzing models. Shared data structures support seamless transitions between operation, expansion, reliability, and maintenance studies.

Tabular editing, georeferenced visualization, and customizable dashboards improve transparency and analysis. PSRIO enables automated result reporting, while the PSR Factory Python API allows scripted workflows. The embedded Knowledge Hub provides integrated documentation and guidance.

Energy supply chains and co-optimization of carriers

SDDP 18 includes explicit modeling of energy supply chains — integrating producers, converters, storage, transport, and demand elements. This enables planners to represent infrastructure interactions and identify synergies across electricity and fuel sectors, such as Power-to-X strategies or coordinated storage across carriers.

Enhanced power network modeling

New features allow for realistic power flow modeling in systems with high renewable penetration. These include AC/DC components, FACTS devices, N-k dispatch constraints, and improved loss modeling. Compatibility with tools like PSS®E and support for GETs expand the platform's applicability to modern grid planning.

OptMain: Optimal Maintenance Scheduling

OptMain is a new module that optimizes maintenance schedules using risk-based criteria. It replaces simplified derating with explicit modeling of outages, respecting constraints such as ramp limits, precedence rules, and critical periods. OptMain supports planners and system operators in aggregating, coordinating, or rescheduling maintenance with consistency across operation and expansion contexts.

Other modeling improvements

Key updates include dynamic solver convergence for MIP problems, unit-based modeling of all power plants, multi-block generation offers, improvements in generic variable and constraint support, hourly maintenance for renewables and DC links, Markov-based uncertainty representation, and integration of user-defined DLR scenarios.

Final remarks

SDDP 18 consolidates its position as a flexible and robust platform for integrated energy planning. By combining advanced modeling capabilities with improved usability and automation, this version supports technically consistent studies — from national policy to operational coordination — across sectors and timeframes. For more details, visit the **SDDP 18 Release Site**.

CASE STUDIES

Analysis of Curtailment in Brazil: A Perspective Using PSR Tools

Lucas Okamura

The increasing penetration of renewable energy sources, particularly wind and solar, brings complex global challenges for electric grid management. In Brazil, energy curtailment—the deliberate reduction of generation—has become increasingly critical, driven by the rapid expansion of variable renewable energy (VRE) sources. This report synthesizes the leading causes of curtailment within the Brazilian power system and details how sophisticated modeling tools can analyze, forecast, and manage this growing phenomenon. Recent historical data reveal a continuous upward trend in curtailment, underscoring the urgent need for robust analytical frameworks. The findings highlight that the mismatch between the pace of renewable integration and the demand growth, plus the expansion of transmission infrastructure, is exacerbating the problem. Methods that account for stochastic simulation and provide hourly granularity and detailed network representation are indispensable for understanding and mitigating curtailment, ultimately contributing to a more resilient and efficient energy transition.

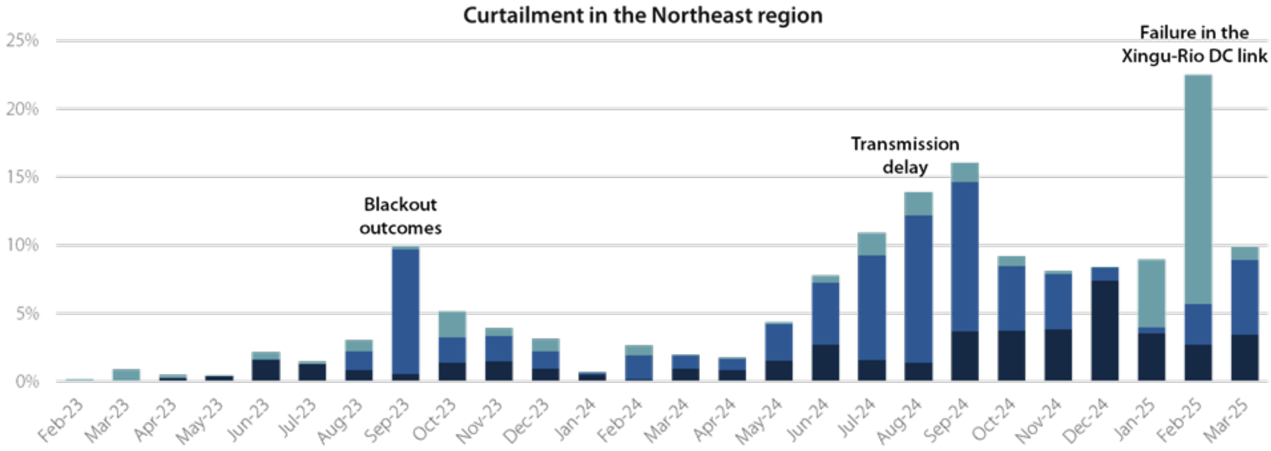
Understanding Curtailment in the Brazilian Context

Renewable curtailment, defined as the deliberate reduction of energy generation from renewable sources like wind and solar, has become common in modern power systems. This practice is particularly pronounced in Brazil due to the rapid integration of intermittent renewable sources. Three distinct yet interconnected factors primarily drive the phenomenon, each contributing to the necessity of limiting output from these generators.

Firstly, Energy Balance issues arise when the available supply from inflexible generation sources exceeds the prevailing demand of the system. To maintain the equilibrium required for grid stability, a reduction in production becomes imperative. This imbalance is increasingly common as the share of VRE grows. Secondly, Electrical Reliability concerns frequently necessary curtailment when transmission networks experience congestion. Such bottlenecks can occur at various points, compelling a reduction in generation to ensure the safety and stability of the entire network. This speaks directly to the principle that there is "no transition without transmission," emphasizing the crucial role of robust grid infrastructure in accommodating new generation. Lastly, External Unavailability refers to an external outage outside the immediate generation complex. These external factors can force a decrease in generation to adapt to new system topologies or address unforeseen limitations within the broader energy infrastructure.

Brazil's energy landscape has indeed transformed, marked by the extensive integration of wind farms and, more recently, solar plants, both distributed and centralized. This surge was fueled by decreasing investment costs for these technologies and various governmental incentives, including net metering policies, transmission tariff discounts, and exemptions from specific sectoral charges. For instance, in 2024, the system added around 14 GW of installed capacity, of which 99% is composed of wind and solar power plants. However, a critical divergence has emerged: the expansion pace of the transmission network and the growth in energy demand have demonstrably lagged behind the rapid uptake of renewable generation capacity. This mismatch has invariably led to a surplus energy supply, which drives an increasing trend in renewable curtailment. Historical data from 2023 through 2025, presented below, illustrate this upward trajectory, with notable peaks directly linked to transmission delays throughout 2024, where total curtailment in the northeast region within a month reached 15% of the total potential generation.

Projecting Curtailment Using PSR Tools



The robust forecasting and analysis of future curtailment in the Brazilian power system is underpinned by a four-step methodology developed by PSR. This structured approach ensures a comprehensive and detailed projection, moving from foundational assumptions to granular simulation and actionable insights.

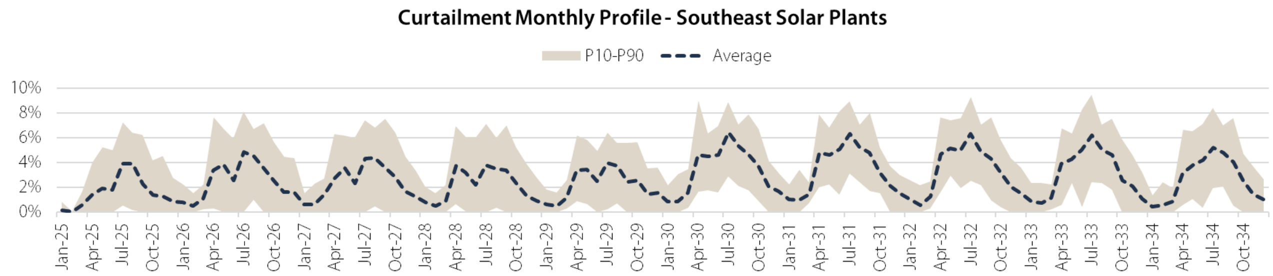
The initial step involves the definition of key assumptions. These assumptions serve as the bedrock for all subsequent projections and significantly influence the accuracy of curtailment forecasts. This encompasses a demand forecasting process, which accounts for multifaceted factors such as national economic growth and the introduction of disruptive new technologies, including electric vehicles, data centers, and the nascent green hydrogen production sector. Concurrently, the evolution of the supply mix is carefully considered, incorporating projections for the decommissioning of older thermal power plants, distributed generation penetration, which exhibits a distinct dynamic when compared to centralized projects, expected capacity auctions, and indicative generation expansion plans often derived from long-term expansion planning models, such as PSR’s OPTGEN. Given Brazil's substantial reliance on hydropower, an accurate representation of Inflows is pivotal, drawing upon recent hydrological trends that, unfortunately, indicate below-average long-term inflows. Finally, transmission expansion assumptions meticulously model the projected growth of inter-regional interconnection capacity and the necessary regional network reinforcements for future years.

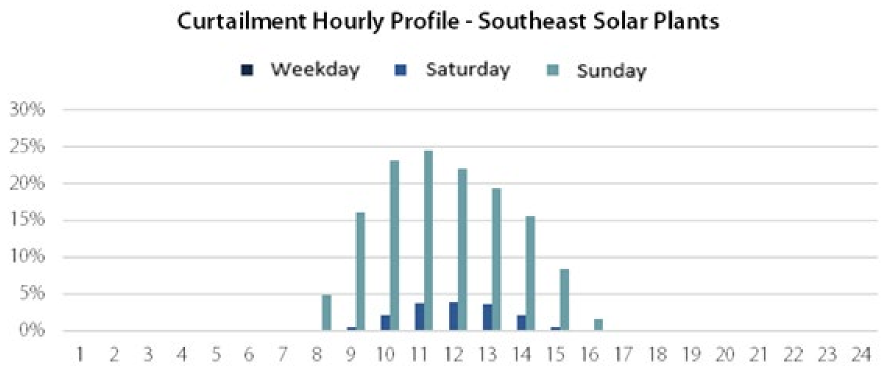
The second step focuses on database development, which presents a significant integration challenge. The primary objective is to unify an aggregated energy case, representing the overall generation system, with a highly detailed network representation into a single, cohesive database. Firstly, a specialized converter seamlessly imports data from the official NEWAVE model into PSR's SDDP environment. Once this base is established, the previously defined assumptions are systematically incorporated. This includes the integration of detailed VRE profiles using PSR’s Time Series Lab (TSL) tool. Distributed generation is also modelled, alongside individual centralized power plants. Demand is meticulously detailed with hourly projections, reflecting the time-varying nature of consumption. At this point, the “Energy Case” is settled.

Subsequently, network data from official sources, such as the PAR/PEL configuration provided by ONS, which encompasses a network of approximately 13,000 buses and 17,000 branches, is imported and converted into the SDDP format. Subsequent modifications fine-tune this data, defining load distribution across various buses, establishing connections between generators and the network, and codifying all relevant interconnection constraints. This intricate process culminates in an "Integrated Generation and Transmission (G&T) Case", a unified and comprehensive database that harmonizes generation and transmission information.

The third step is simulation, which predominantly centers around the SDDP model. This stage involves two distinct but sequential executions. Initially, the "Energy Case" is utilized to calculate the optimal operating policy[1] and define the water values for all hydro plants. Then, hourly simulations are conducted, using the "Integrated G&T Case", incorporating the detailed generation and transmission representations established in the preceding database development phase. The TSL, fully integrated with SDDP, plays a vital role by providing the necessary hourly production scenarios for both wind and solar plants. This integration is paramount for the stochastic simulations designed to address the inherent uncertainty and variability of renewable generation.

Finally, the fourth step involves analyzing the results of the SDDP execution. The stochastic simulation enables the assessment of the probability distribution of curtailment levels. For example, looking 10 years ahead on a monthly scale, the average total curtailment for a specific group of solar power plants located in the southeastern region of the system can reach approximately 6% of their potential generation, as presented in the figure below. However, under specific scenarios, this value may approach 10%. Also, when analyzing the results with hourly resolution, it becomes evident that curtailment is concentrated during daylight hours, regardless of the technology employed, and tends to be more pronounced on weekends, when electricity demand is typically lower.





The Strategic Value of PSR Tools for Curtailment Forecasting

Curtailment forecasting is vital for the financial and economic analysis of renewable energy projects worldwide, as it can significantly impact their profitability. The in-depth analysis of curtailment within the

[1] The "Energy Case" is used for this task to mimic how the ISO calculates the policy.

Brazilian power system demonstrates the essential value and robust capabilities of the PSR tools. Their comprehensive functionalities offer a strong suite of resources for navigating the complexities introduced by the rapid expansion of renewable energy.

A key feature that stands out is the capacity for stochastic simulation. This functionality is paramount for assessing many future scenarios, effectively addressing the inherent uncertainty that defines variable renewable generation, such as wind and solar. By modeling a range of potential outcomes, these simulations provide a more realistic and resilient framework for decision-making, moving beyond deterministic approaches to embrace the probabilistic nature of renewable output.

The hourly granularity provided by these tools is another indispensable attribute. This temporal resolution is crucial for dissecting curtailment patterns at various times of day and across weekdays and weekends, offering a detailed temporal understanding. Furthermore, the detailed network representation capability is vital for accurately identifying curtailment directly caused by network congestion. The ability to pinpoint these localized bottlenecks allows for targeted investment in transmission expansion and the deployment of Grid Enhancing Technologies (GETs), essential for a more efficient, safe, and flexible operation of transmission networks.

The seamless integration with the PSR's expansion planning model (OPTGEN) further enhances the strategic utility of PSR tools. This integration facilitates the simulation of curtailment within optimized long-term future scenarios. Finally, the automated database conversion capability significantly streamlines and optimizes the entire analysis process. This efficiency gain reduces manual effort, minimizes potential errors, and accelerates the time-to-insight, enhancing overall operational and planning effectiveness.

Unlocking USD 10 billion investments in Central Asia: Powering the World's Largest Dam with OPTGEN-SDDP

João Pedro Bastos

The Central Asian power sector is undergoing a structural realignment. Against a backdrop of rising electricity demand, legacy infrastructure, and an urgent need to expand renewable generation, two World Bank-backed hydropower projects — Rogun Dam in Tajikistan and Kambarata-1 in Kyrgyzstan — stand out both in scale and systemic implications. Together, they involve over USD 10 billion in investments and are poised to reshape the regional energy landscape.

Hydropower remains one of the region's most underexploited assets. Despite significant technical potential, decades of underinvestment and coordination challenges have delayed large-scale developments. Rogun and Kambarata-1 are outliers in this context. They are not only the largest energy infrastructure projects in their respective countries but are also central to regional efforts to integrate power markets and strengthen export capacity.

Rogun Dam, currently under construction on the Vakhsh River, is projected to reach 335 meters, making it the tallest dam in the world upon completion. With 3,600 MW of installed capacity and a 13.3 billion m^3 reservoir, it will eventually generate nearly 97% of Tajikistan's current electricity demand. Full reservoir operation is expected by the end of the 2030s, with phased commissioning through the decade. Kambarata-1, on the Naryn River in Kyrgyzstan, will contribute 1,860 MW and 5.4 billion m^3 of storage, adding roughly 32% to national generation. Its commissioning is planned for 2034.

From an economic standpoint, the projects represent a substantial share of GDP: about half for Tajikistan and one-third for Kyrgyzstan. In this context, robust system modeling and export market analysis are essential — not only to inform design and financing decisions, but to ensure resilience in countries with limited fiscal space and exposure to climate and hydrological variability.

Projects Snapshot – Key Parameters

Parameter	Rogun Dam (Tajikistan)	Kambarata-1 (Kyrgyzstan)
Investment (USD billion)	6.3	5.0
Installed Capacity (MW)	3,600	1,860
Dam Height (m)	335	~275
Reservoir Volume (billion m^3)	13.3	5.4
Commissioning Year	2032 (Full by 2039)	2034
% of National GDP	~50%	~30%
% of National Installed Capacity	~70%	~45%
% of National Annual Generation	~97%	~32%

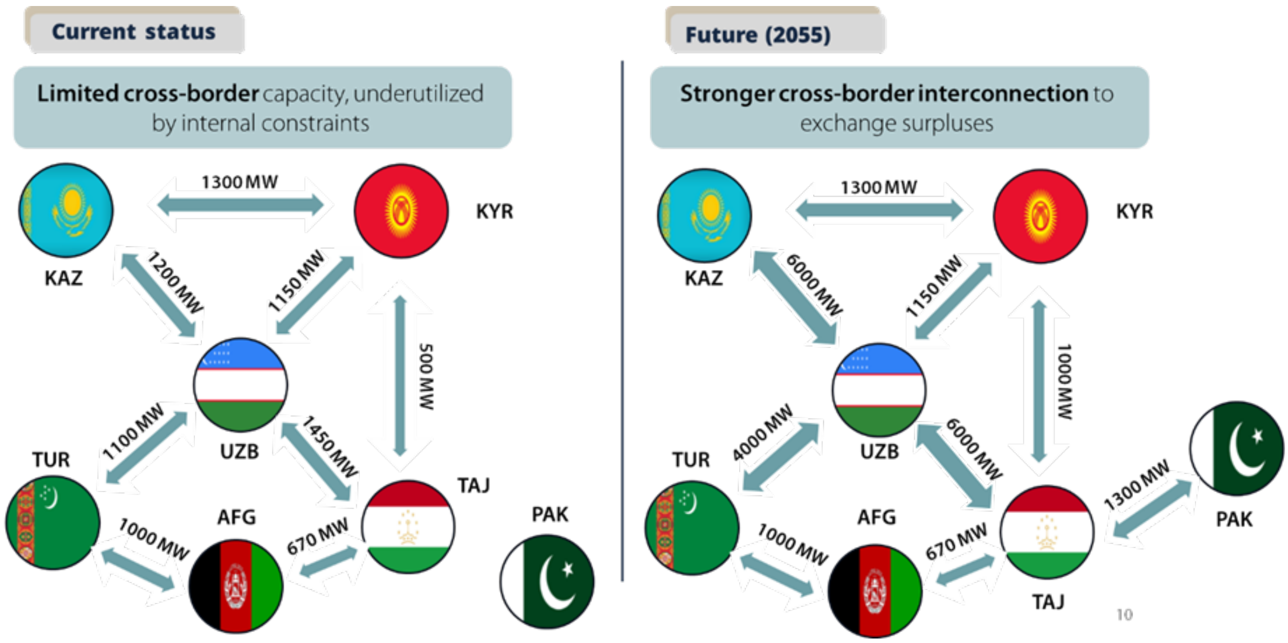
Both projects are designed to go beyond domestic energy supply. They are structured to enable regional exports to neighbors such as Kazakhstan, Uzbekistan, Afghanistan and Pakistan — an ambition that depends on expanded interconnection capacity and integrated operational planning. The modeling effort behind this strategy is detailed in the following sections.

Energy System Modeling

The long-term viability of large-scale hydropower in Central Asia hinges not only on civil works and financing structure, but on how well these assets integrate into a broader, export-oriented power system. To address this, the modeling effort by PSR covered the entire Central Asian region, with detailed datasets for Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, and simplified representations of Afghanistan, Pakistan, and southern Russia. The objective: simulate generation expansion and cross-border transmission flows under a range of hydrological, economic, and policy scenarios.

The generation database includes over 300 renewable sites — both existing and candidate — across technologies and geographies. Capacity estimates reflect spatial resource quality and project-level constraints, helping to avoid overoptimistic supply assumptions. Demand projections incorporate seasonal variation and structural economic shifts, while transmission modeling accounts for grid topology, interconnection limits, and future reinforcement scenarios.

Results point to a clear transition: from a system still heavily reliant on coal and inefficient gas plants toward one increasingly dominated by renewables and more efficient dispatchable units. In particular, Kazakhstan is set to emerge as a regional wind power exporter, supported by new nuclear capacity, while Tajikistan and Kyrgyzstan will leverage their hydro assets to supply clean firm energy to neighboring systems.



The analysis also shows that current interconnection limits are a key constraint. Transmission upgrades — especially east-west corridors and north-south links to Pakistan and Afghanistan — are required to enable efficient seasonal balancing and export flows. Hydrological diversity can be monetized only if physical exchange infrastructure is in place.

To emulate a realistic expansion from each country, their expansion plans were initially modeled independently, without assumed imports. Only then were transmission investments simulated to identify optimal reinforcements. This ensures that no country would expand their system heavily relying in their neighbors, and exchanges would be opportunistic. Final runs combined all assets into an integrated system, with full operational dispatch, investment sequencing and reliability constraints. The modeling used PSR's OPTGEN-SDDP platform, with hourly granularity, dynamic reserve margins, grid stability constraints, and probabilistic hydro inflows and renewable production.

Institutional Challenges and Regional Impact

Despite their technical appeal, both Rogun and Kambarata-1 face significant political and cooperative hurdles. Water governance in Central Asia remains highly sensitive, rooted in decades of tension over transboundary river usage. Uzbekistan, in particular, initially opposed Rogun's construction, citing concerns over downstream irrigation impacts. Progress required years of regional dialogue and international mediation, with the World Bank playing a key role in facilitating basin-level coordination.

The projects are now framed not only as energy ventures but as instruments of regional stabilization. Beyond electricity generation, they contribute to a rebalancing of water-energy linkages across the Amu Darya and Syr Darya basins. Hydropower operation planning is being aligned with seasonal water releases for agriculture, especially during summer peaks — helping to reduce friction between upstream and downstream countries.

From an energy security perspective, the new hydropower capacity provides clean, firm generation that complements the intermittent nature of solar and wind. It also stabilizes system frequency and supports synchronous grid operations across countries with weak reserve margins. This is particularly relevant in Uzbekistan and Afghanistan, where rapid demand growth and network fragilities limit system flexibility.

Economically, regional electricity trade enabled by these projects could unlock billions in net benefits. By exporting surplus hydro during the wet season and importing back during dry periods, countries can optimize seasonal exchanges and reduce thermal backup needs. For Tajikistan and Kyrgyzstan, export revenues are essential to cover debt service on the projects. For buyers like Pakistan and Afghanistan, imports offer a cheaper and cleaner alternative to inefficient thermal generation or deferred capacity investment.

The geopolitical stakes are also shifting. As regional infrastructure becomes more interdependent, incentives for cooperative behavior increase. Electricity trade acts as a stabilizer: curbing fragmentation, creating mutual dependencies, and reducing the risk of unilateral action on water flows. In this sense, energy interconnection becomes both an economic enabler and a diplomatic tool.

Final Considerations

Hydropower in Central Asia is moving from strategic potential to operational backbone. Rogun and Kambarata-1 are not isolated mega-projects, but components of a systemic shift toward renewable-based regional integration. Their success depends on more than civil works or financing terms — it requires robust modeling, transparent governance, and credible coordination platforms.

The modeling frameworks used in these projects demonstrate how technical analysis can support high-stakes decision-making in politically complex environments. By simulating long-term scenarios with OPTGEN-SDDP — accounting for realistic constraints and intertemporal dynamics — planners were able to stress-test expansion pathways and quantify trade-offs between domestic supply, exports, and system reliability.

As interconnections expand and energy systems become more intertwined, the value of integrated planning increases. Clean energy, when deployed with precision and cross-border alignment, becomes more than a climate solution — it becomes a development strategy and a vector of regional cooperation. These two hydropower projects signal the start of that transition.

GRID ENHANCING TECHNOLOGIES: A CASE STUDY IN COLOMBIA

Amanda Fernandes, Silvio Binato

Overview of Grid-Enhancing Technologies

The global energy landscape is undergoing a profound transformation, largely driven by the imperative to decarbonize and integrate a growing share of renewable energy sources such as wind and solar power. However, these changes introduce significant challenges, particularly concerning the flexibility and robustness of transmission networks to accommodate the intermittent nature of these energy sources. In this context, the need for efficient, safe, and flexible operations in electrical grids becomes critical. The North American motto "no transition without transmission," emphasizing the essential role of modernized and adaptable transmission systems in the energy transition.

Many of the technologies used in transmission networks were developed over 100 years ago. They were effective for a long time but were not designed to handle today’s reality, with renewable energy sources that depend on uncertain conditions and whose output varies with the weather, time of day, and season. Without a grid capable of adapting quickly, we face waste, overloads, and instability. That’s why Grid Enhancing Technologies (GETs) are emerging as an alternative.

GETs are modern hardware and software solutions that make the grid more flexible, efficient, and resilient by making better use of existing infrastructure and reducing the need to build new lines. In the February 2025 edition of the Energy Report, we have presented an overview of the advances of GETs, including FACTs, Dynamic Line Rating, Batteries, etc. and proposed guidelines to incorporate them into the planning of our transmission system, in order to make it more reliable, flexible and economical.

This article delves into one pivotal case study that illustrate how those innovative solutions can reshape energy infrastructure in Colombia. The study showcase how technological advancements and strategic planning are crucial in building a more resilient and adaptable energy infrastructure. The methodology applied in this case study leveraged advanced analytical tools and modeling techniques to tackle the complexities of integrating new technologies into power system planning and operation.

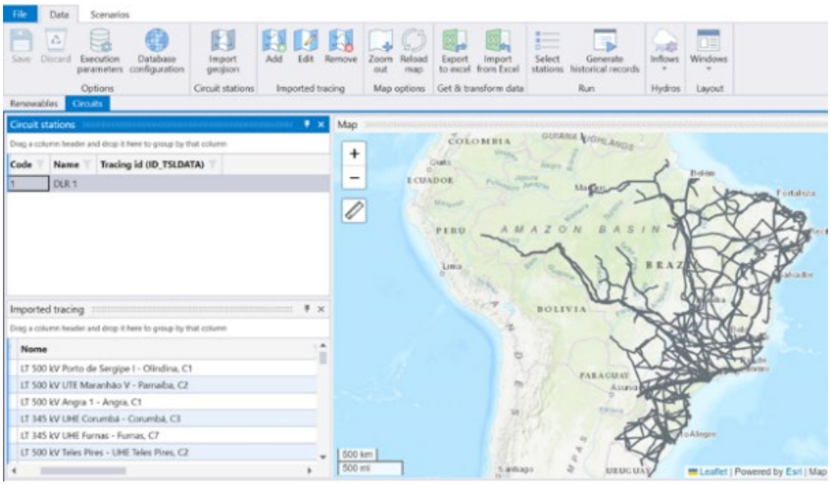
Incorporating GET in planning and operation models

GETs can play an important role in modernizing the electricity sector. Therefore, it is essential to include both traditional equipment and GETs in the same planning analysis portfolio and decide which equipment (or combination of equipment) brings the best cost-benefit to the system.

In turn, these improvements in the planning process require investing in new methodologies and more sophisticated analysis methods. On this topic, PSR has been working on three fronts in its transmission planning models and studies.

1. Operational Modeling

The SDDP stochastic operating model includes a detailed representation of the transmission networks, incorporating losses and security-constrained optimal dispatch. Additionally, advanced equipment such as batteries, Dynamic Line Rating (DLR), and FACTS are integrated into the model to simulate their impact and optimize system operation while considering transmission constraints. For DLR, through the integration with the Time Series Lab (TSL), capacity scenarios for transmission lines are generated based on the actual geographical path of each circuit.

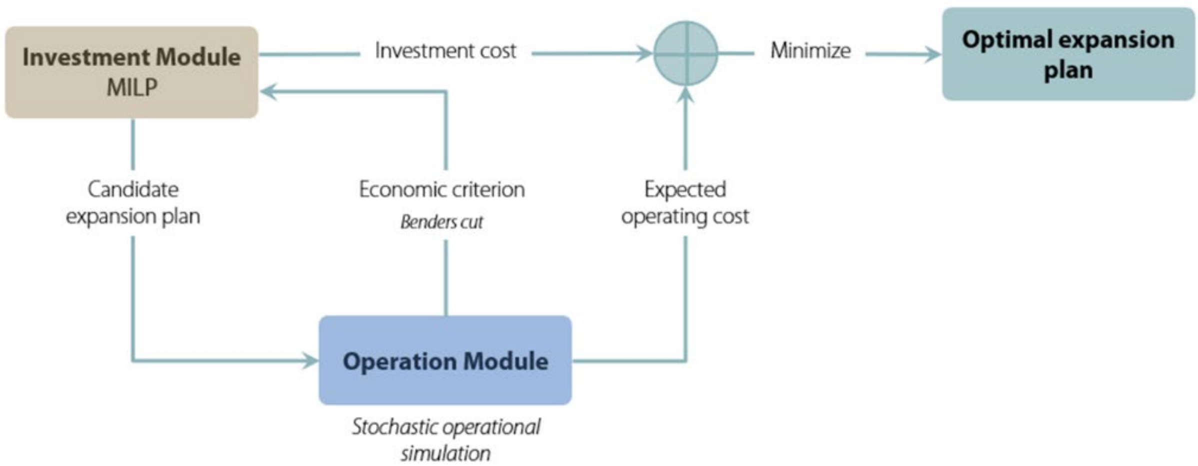


2. Candidate Screening

Methodologies were developed to estimate the marginal benefit of each technology and filter out the best candidates. This avoids analyzing an unmanageable number of equipment-location combinations by selecting only those with favorable benefit-to-cost ratios.

3. Planning Model

A Benders decomposition-based planning model is used to choose the optimal set of investments by balancing operational savings against capital costs. The decomposition scheme allows the use of separate optimization algorithms for the investment and operation module and leverages on SDDP's operating features. This process compares GETs with other traditional solutions to identify the most cost-effective transmission expansion plan.

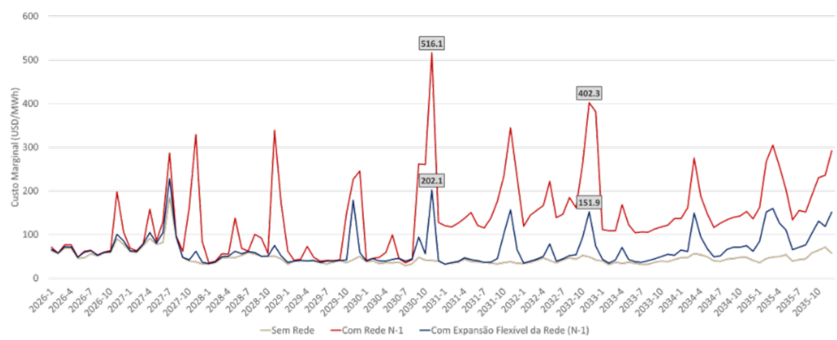


These methods and methodologies have been applied in studies of countries with strong growth and penetration of renewables, such as Colombia, Mexico, Ecuador, Central America, Bolivia and Brazil. The results of a case study with the Colombia system are presented below.

Case Study: Flexible transmission expansion in Colombia

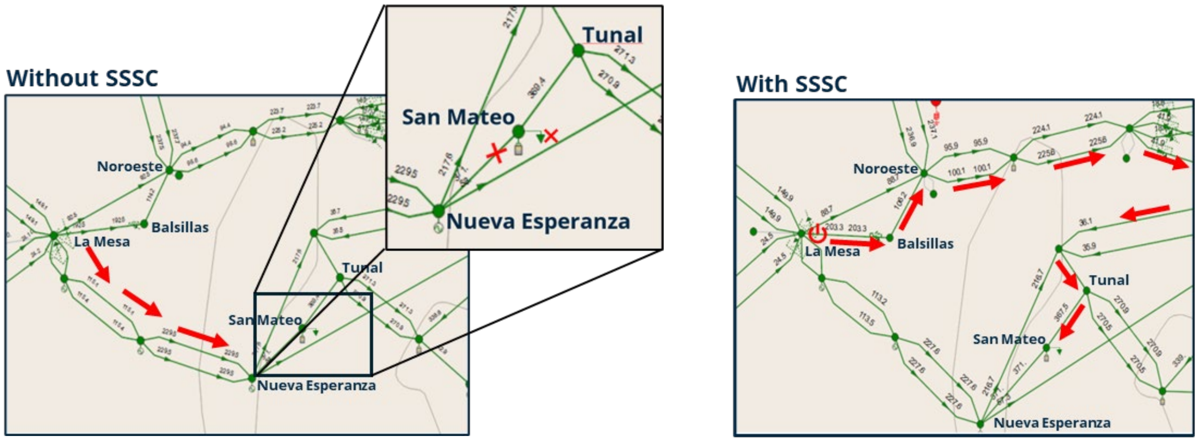
The primary objective of this case study was to determine transmission expansion plan for the Colombian transmission grid considering conventional and GETs (batteries and FACTs). The approach involved a detailed analysis of the system, using SDDP, candidate screening for FACTs and Batteries and the benders decomposition planning model to evaluate the transmission infrastructure needs of the country until 2035.

In this study, the optimal planning considered a SSSC-type FACTS equipment in addition to conventional equipment (lines and substations) to solve the problems of network restriction in this horizon. The image below presents the transmission lines, substations and FACTs that had to be deployed (left) and the estimation of the marginal costs (right) of the system before (red line) and after (blue line) the expansion of the grid. At the end of the expansion, a reduction of approximately 8% was achieved in terms of operating and investments costs.



The images below illustrate the operation of one of the SSSCs selected in this planning study. The first image depicts the power flow in a certain region of the 230 kV transmission grid without the SSSC. In this case, the flow follows the red arrows from the La Mesa substation toward the San Mateo substation to supply industrial loads in the area. However, there is a congestion issue along this section of the 230 kV network that could result in load curtailment.

The second image shows the operation of the SSSC selected by the planning model to address this issue. An SSSC was installed on the La Mesa – Balsilla transmission line and operates such that, during periods of congestion (as seen in the previous image), power flow is redirected to less-loaded 230 kV transmission lines, as indicated by the red arrows in the second image. This ensures reliable power delivery to the San Mateo region and allows continued service to local consumers.



Hence, the placing FACTS equipment in the upper ring of the San Mateo-Nueva Esperanza line successfully redirected power flow and deferred the need for conventional transmission line duplication.

This case study demonstrated how targeted technological interventions could yield substantial operational and financial benefits, offering a smart solution for managing grid constraints while deferring costly infrastructure investments.

Conclusions

The success of the energy transition is intrinsically linked to the modernization of transmission planning and operation. **Grid-Enhancing Technologies (GETs)** offer a unique opportunity to unlock the full potential of the existing infrastructure, enabling a smarter, more reliable, and flexible power system. To fully realize these benefits, it is essential to adopt advanced planning methodologies and tools capable of capturing the value of these technologies. As the electricity sector evolves, the integration of GETs into planning processes will be key to building a resilient, cost-effective, and sustainable grid that supports both current needs and future challenges

The case studies of **GETs** in Colombia underscore the critical role that innovative technologies play in enabling the energy transition and how these equipment can be part of a transmission planning analysis. In this case, the strategic integration of **Flexible AC Transmission Systems (FACTS)** has demonstrated the tangible benefits of improving grid flexibility, optimizing resource utilization, and enhancing overall system reliability.

In conclusion, the integration of **GETs** and the development of flexible, resilient, and interconnected grids will be essential for enabling a sustainable and reliable energy future. The Colombian case study serves as a valuable example of how those GETs can be incorporated in transmission planning methodologies to address the challenges of energy transition, ensuring that the systems can be capable of accommodating increasing demand and higher shares of renewable energy in the years to come. These initiatives not only offer immediate operational benefits but also set the stage for a more secure, efficient, and decarbonized energy system in the future.

A NEW FRAMEWORK TO ASSESS RELIABILITY, FLEXIBILITY, AND RESILIENCE OF POWER SYSTEMS

Mario Veiga, Silvio Binato, Amanda Fernandes

Indicators are essential tools for assessing the operation of an electric power system. They provide a clear and objective view of system operation, allowing operators and planners to ensure that system functions meet pre-established safety, reliability, and quality parameters. These indicators help identify inefficiencies, operational bottlenecks, and recurring failures—such as overloads, excessive losses, or curtailments of renewable generation—which might otherwise go unnoticed.

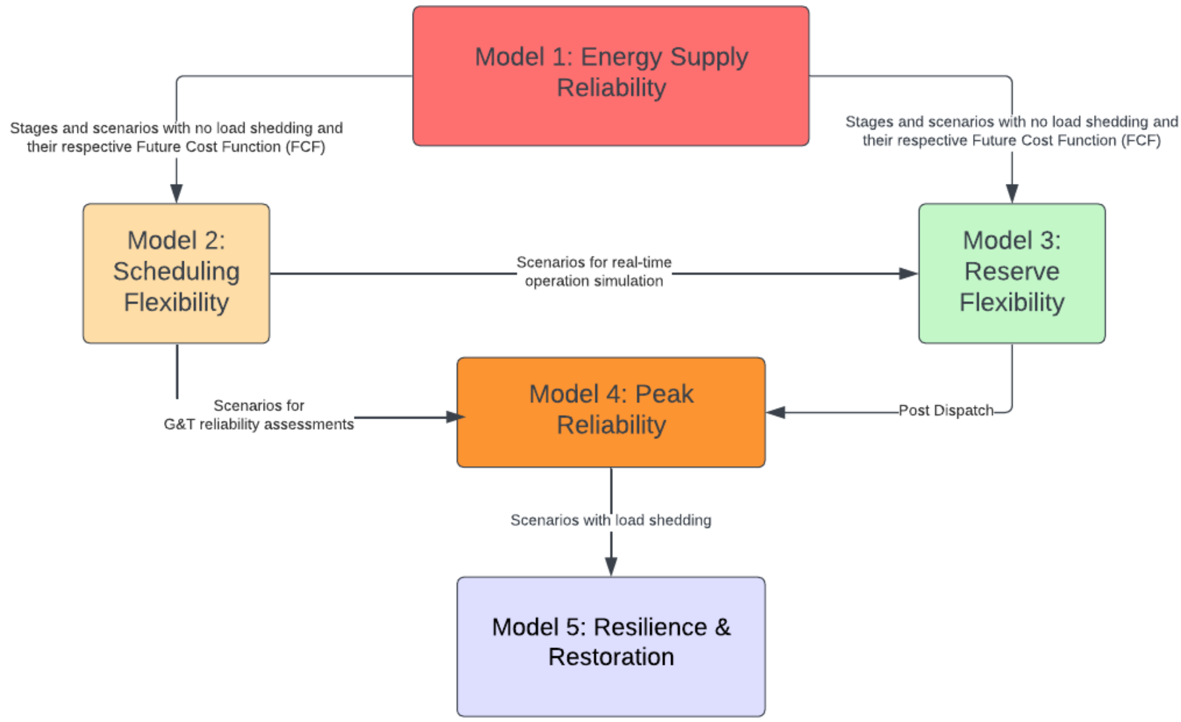
Moreover, indicators support decision-making by providing data-driven insights that guide corrective or preventive actions. Indicators are also critical for assessing whether investments, such as network reinforcements or the integration of new technologies like storage systems, are delivering the expected operational benefits.

By quantifying key attributes such as reliability, flexibility, and resilience, indicators allow for a deeper understanding of the system’s ability to compensate uncertainties or the variability in production or consumption, as well as recovering from disturbances (such as failures of generation units or transmission network circuits). In regulated environments, indicators also increase transparency and accountability among stakeholders. Ultimately, well-defined indicators are fundamental to ensure that the power system evolves in a secure, efficient, and sustainable way as it adapts to the challenges of the energy transition.

This section aims to present a detailed set of performance indicators designed to evaluate the health and operational performance of power systems. These indicators intend to address critical aspects such as reliability, flexibility and resilience, through a robust framework called SINAIS developed in collaboration with the Brazilian Power System Operator, ONS. The ultimate goal of calculating these indicators is to provide stakeholders with meaningful insights into Interconnected Brazilian System performance, support informed decision-making, and guide future improvements within the sector.

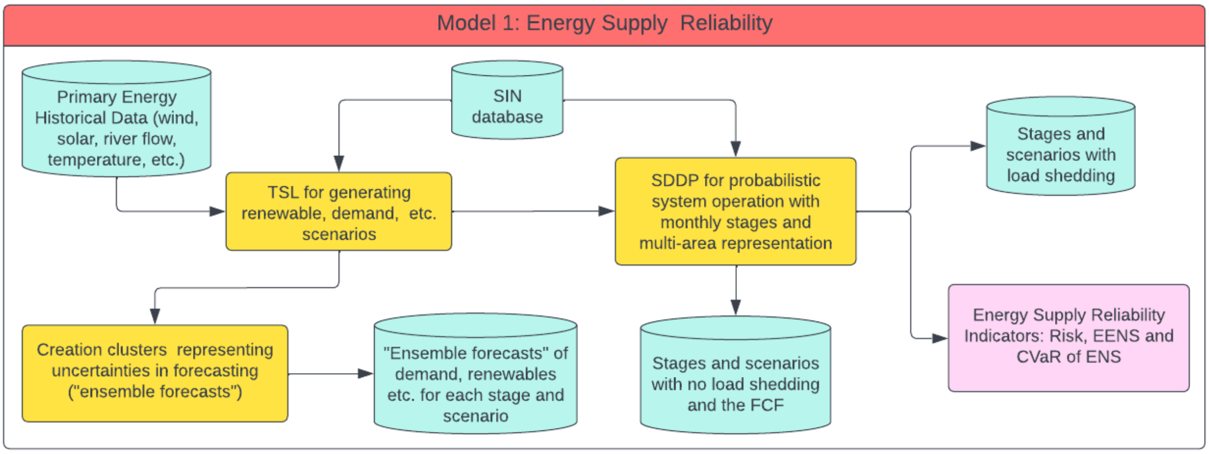
SINAIS – System of Indicators for Analysis of Interconnected Systems

The SINAIS framework designed to estimate reliability, flexibility, and resilience indicators for power systems is based on a suite of five distinct simulation models, each targeting specific performance dimensions. The first simulation model focuses on evaluating the system's energy supply security, assessing reliability metrics related to demand supply. The second one calculates day-ahead operational flexibility indicators, while the third assesses the reserve flexibility by emulating the real-time operation of the power system. The fourth model examines system performance concerning reliability during peak demand conditions. Lastly, the fifth model measures system resilience and restoration capabilities following contingencies.



Following, detailed functional specifications for each model are provided, outlining the calculation of the indicators.

Model 1: Energy Reliability Indicators



The methodology for estimating energy reliability metrics involves a combination of non-chronological and chronological simulation models using the Stochastic Dual Dynamic Programming (SDDP) approach. Initially, a multi-area, monthly-step non-chronological SDDP model with multiple load levels is applied over a horizon of interest. This model calculates the optimal operational policy considering uncertainties in renewable generation, inflows, and demand. Subsequently, a hybrid chronological SDDP simulation, with multiple load levels and weekly operational steps, is conducted. This allows capturing hourly variability while maintaining computational tractability.

Key reliability metrics derived from the SDDP results, including not only traditional indicators as the risk, and the expected value of energy not supplied (ENS) but also innovative measures as the Conditional

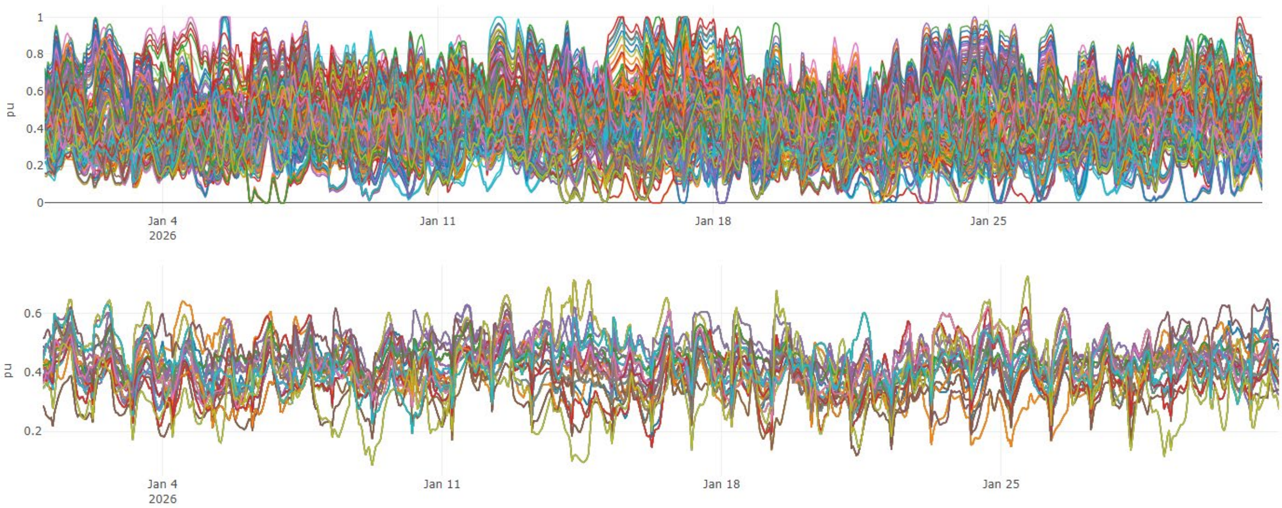
Value at Risk (CVaR) of ENS, which captures the tail risk by focusing on worst-case scenarios beyond a specific percentile.

Flexibility Indicators

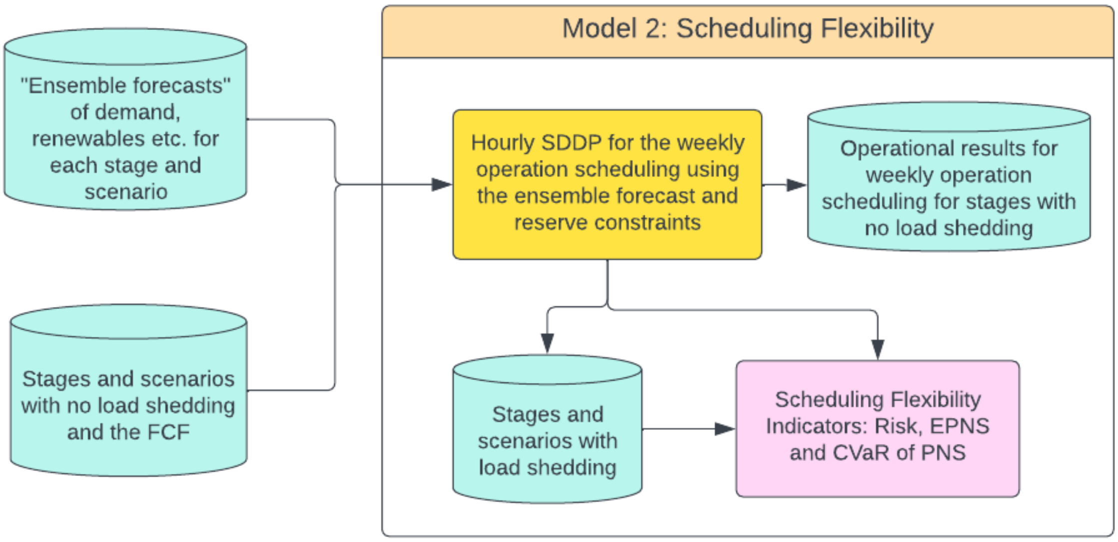
Two primary models are proposed to evaluate the operational flexibility of the electric system. The first, operational scheduling flexibility, relates to the system's ability to meet the forecasted net demand – calculated as the total demand minus the generation from non-controllable renewables – using the controllable resources represented in the simulation.

The second model, called reserve flexibility, assesses the system's ability to redispatch generation in real time, using planned operating reserves to accommodate uncertainties such as errors in demand forecasting and unpredictable renewable generation variability. To estimate these flexibility indicators, hourly dispatch problems are solved using a weekly horizon with SDDP. This results in hourly generation schedules for controllable resources and reserve allocations per generating unit.

The methodology also accounts for the creation of ensemble forecasts representing real-time prediction errors relative to scheduled values. These ensembles, particularly for renewable generation, are clustered using k-means techniques to replicate the uncertainty profile observed in historical power system operation. This approach reduces the variance in forecast scenarios while maintaining representativeness, ensuring the flexibility indicators accurately reflect operational challenges. The graph below shows the renewable generation of a plant for 200 original renewable scenarios and the renewable generation of this same plant considering the ensemble forecasts, grouped into 20 clusters.

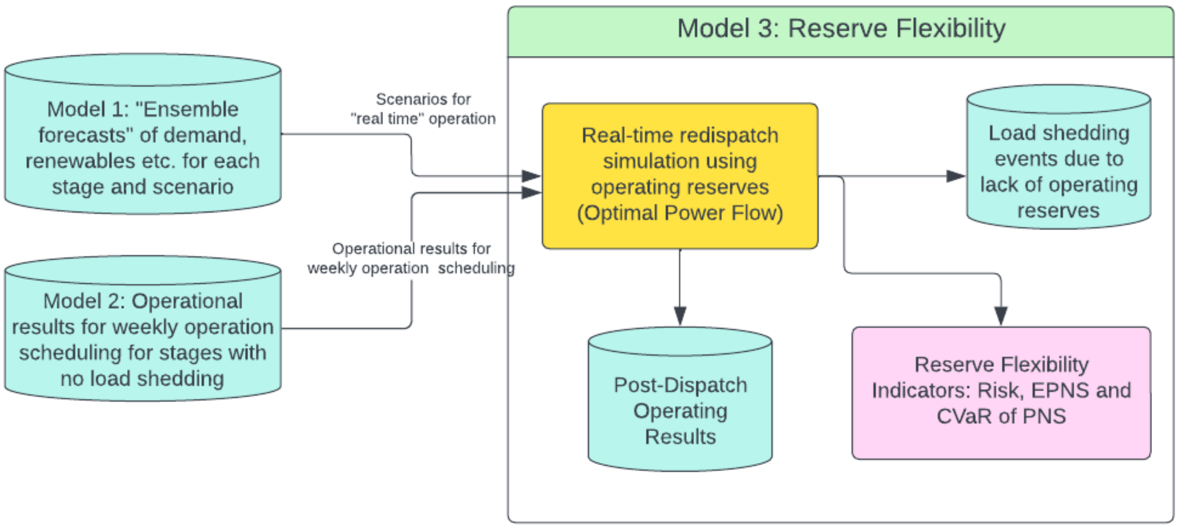


Model 2: Operational Flexibility Indicators



In this model, hourly dispatch problems are solved over a weekly horizon using SDDP. Based on the dispatch results, the upward and downward ramping available are calculated for each hour, considering the difference between the available controllable generation and the system's net demand. The indicators in this model are related to the system's ability to meet the forecasted "duck curve" (demand minus renewable generation) using controllable resources. This conceptually corresponds to a week-ahead operational scheduling.

Model 3: Methodology for Estimating Reserve Flexibility Indicators



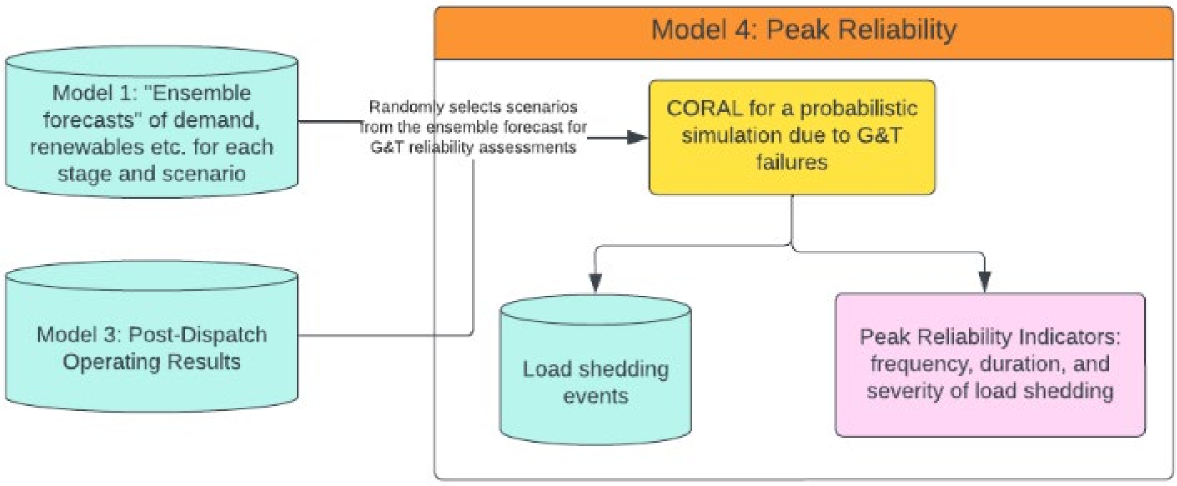
The reserve flexibility indicators aim to emulate real-time system operation, specifically assessing whether the reserves scheduled during weekly operational planning are sufficient to accommodate deviations between forecasted and actual system conditions, known as the "true up" process.

For each hour within the weekly horizon, the operating point derived from the weekly-ahead schedule is adjusted by replacing the forecasted demand and renewable generation values with the corresponding "true up" values from the real-time scenario. A new operating point is determined by redispatching only the available reserves, while respecting operational constraints. In cases where the problem is infeasible

— meaning reserves are insufficient — load shedding is calculated as a last resort, considering that certain generators may reduce output without ramping constraints but cannot increase generation.

Through this process, quantitative indices related to reserve flexibility are obtained. These include the risk that the "true up" cannot be accommodated within scheduled reserves, the expected shortfall of reserves under "true up" conditions, and the Conditional Value at Risk (CVaR) of reserve shortfall.

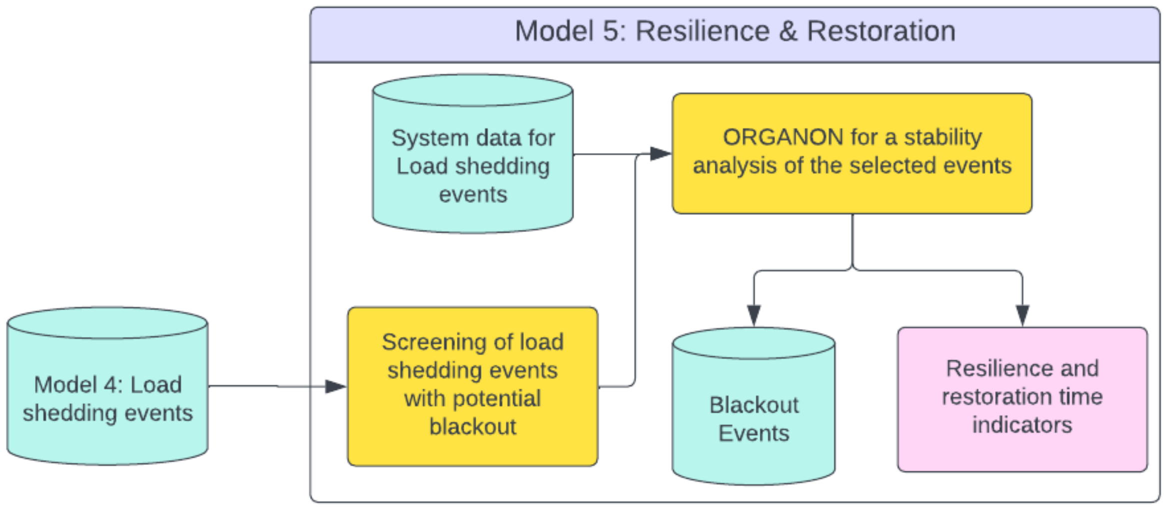
Model 4: Peak Reliability Indicators



The methodology for estimating peak reliability indicators builds upon the outcomes of the composite generation-transmission reliability model (CORAL). CORAL employs Monte Carlo simulations, randomly sampling failure and repair processes across all generation and transmission components to determine the availability of generation and transmission resources for each hour within a selected peak demand block.

The indicators derived from this methodology include interruption frequency, duration, and severity of supply interruptions, measured as a percentage of hourly demand during peak periods.

Model 5: Resilience and Restoration Indicators



Finally, model 5 will consider the peak reliability simulation results and identify scenarios where load interruptions occurred and select those with a high probability of causing blackouts and model the fault events in the time domain electrical studies. This allows analysis of the depth of load shedding and assessment of whether the event would lead to a blackout, as well as the system's restoration time following the disturbance.

Resilience indicators derived from this analysis include the occurrence of blackouts and the time required for system recovery after the initiating event.

Conclusions

This report presents a comprehensive framework of performance indicators designed to assess the health and operational effectiveness of electrical systems. By combining metrics derived from detailed probabilistic simulation models, the proposed indicators offer a multidimensional perspective encompassing reliability, flexibility and resilience of power systems.

The simulation-based indicators provide forward-looking insights into the system's ability to meet demand under uncertainty, its operational flexibility, and its capacity to recover from disruptions.

Together, these indicators form a robust toolset for monitoring system evolution, supporting decision-making, and guiding investments and operational improvements. The establishment of baselines and standardized methodologies further ensures consistency and comparability over time.

PSR AND ACADEMIC RESEARCH

Joaquim Dias Garcia

PSR is a leading contributor to the global academic and research landscape, engaging with top institutions and sharing our expertise through presentations, publications, and collaborative projects. Our commitment to innovation is reflected in our active participation in key industry and academic forums.

Recently, PSR contributions were recognized through the prestigious Leadership In Power Award from IEEE Power and Energy Society received by Luiz Barroso, PSR's CEO, for leadership in power and energy systems through research, policy, markets and regulatory contributions. (https://ieee-pes.org/about-pes/awards-scholarships/ieee-power-energy-society-leadership-in-power-award/).

Upcoming Academic Engagements

FERC Seminar

"Increasing Real-Time and Day-Ahead Market and Planning Efficiency Through Improved Software" (July 10th): Mario Pereira will deliver a presentation titled "Multiscale Stochastic Day- and Week-ahead Scheduling of a Large Renewable-dominated Power System – The Brazilian Case." More details are available here: https://www.ferc.gov/news-events/events/increasing-real-time-and-day-ahead-market-and-planning-efficiency-through-1.

International Conference on Stochastic Programming

PSR is sending a delegation to the premier event for **decision-making under uncertainty**, taking place in Paris from July 28th to August 1st. The PSR team is set to deliver the following presentations:

- **"Incorporation of risk metrics in electric system expansion planning and portfolio efficiency analysis"** by Lucas Guerreiro
- **"Multicut Benders Decomposition for Generation Expansion with Dynamic Probabilistic Reserves"** by Tiago Andrade
- **"Comparison between different parallelization schemes in SDDP policy training"** by Guilherme Bodin
- **"Multicyclic multistage stochastic programming using daisy chains"** by Gabriel Cunha
- **"ApplicationDrivenLearning.jl: A High-Performance Library for Training Predictive Models Based on the Application Cost"** by Joaquim Dias Garcia, a collaborative work with PUC-Rio.

More events

- **Brazilian Operations Research Society Conference (SBPO 2025 - October 5-9, Gramado, Brazil):** PSR will be actively involved. The list of accepted works will be published on August 2nd: https://sbpo2025.galoa.com.br/sbpo-2025/page/5407-home?lang=pt-br.

- **Brazilian Seminar on Electrical Energy Generation and Transmission (XXVIII SNPTEE - October 19-22, Recife, Brazil):** PSR's contributions will be featured. Accepted works will be announced on July 31st: https://snptee.com.br/.
- **IREP'2025 Symposium (Sorrento, Italy):** Our collaborative research, "Strategic Bidding in Energy Markets with Gradient-Based Iterative Methods," co-authored by PSR, **GeorgiaTech, Los Alamos National Lab, and Mines Paris PSL**, will be presented by Andrew Rosemberg (GeorgiaTech): https://www.irep2025.unisannio.it/home-page

Recent Academic Highlights

Hydro Scheduling 2025 Conference

A delegation from PSR, led by Mario Pereira, participated in the Hydro Scheduling 2025 conference (May 26-28) in Rio de Janeiro. Mario delivered a plenary talk on "Multiscale stochastic optimization of large hydro systems with AI-driven climate scenarios and HPC." (https://eventos.fgv.br/hydroscheduling-2025)

The PSR team also presented six additional works:

1. **"The IARA Model: A Market Design Simulator for Short-Term Electricity Price Formation**", by Gabriel Vidigal, showcasing the IARA software developed through a PSR-led project, coordinated by CCEE and funded by the World Bank. (Further information: https://iara.psr-inc.com/)
2. **"Virtual reservoir bids: A solution for the externalities in the operation of hydro cascades,"** by Gabriel Cunha, presenting a market mechanism developed as part of the PSR-CCEE-WorldBank project to facilitate bid-based markets in complex hydropower cascades.
3. **"Comparison between different parallelization schemes in SDDP policy training,"** by Guilherme Bodin, detailing early findings on novel strategies for accelerating SDDP.
4. **"Physical Guarantee for Interconnected Systems,"** by Rafael Benchimol Klausner, which addressed issues in Brazil's expansion planning and proposed innovative solutions, including a new Physical Guarantee computation strategy and a multi-attribute auction type.
5. **"LinearDecisionRules.jl,"** an open-source software package co-developed by Bernardo Freitas (FGV) and Joaquim Dias Garcia (PSR), designed to solve complex optimization problems under uncertainty. (Available at: https://github.com/bfpc/LinearDecisionRules.jl)
6. **"Effects of Systematic Bias in Inflow Forecasting on the Operational Planning of the Brazilian Energy System,"** a joint work with Alexandre Street (PUC-Rio) and Joaquim Dias Garcia (PSR), emphasizing the critical impact of inaccurate inflow forecasts on system operation.

INFORMS Computing Society Conference

PSR also played a significant role at the INFORMS Computing Society conference (March 14-16 in Toronto, Canada). Joaquim Dias Garcia served as cluster-chair of modeling systems, organizing four sessions. He presented **"ApplicationDrivenLearning.jl: A High-Performance Library for Training Predictive Models Based on the Application Cost"** (jointly developed with PUC-Rio researchers) and co-authored **"A Julia Package for Modeling Linear Decision Rules"** with Bernardo Freitas (FGV) and **"Extending DiffOpt.jl for Non-Convex Differentiable Optimization"** with Andrew Rosemberg (Georgia Tech).

CIGRE Symposium 2025

Renan Pinho from PSR presented "Methodology for valuing the flexibility attribute performed by BESS in the Brazilian Electric System" at the 2025 CIGRE Symposium in Trondheim, Norway (May 12-14). The findings from the structured methodology reinforce the potential of BESS as a cost-effective solution to support renewable generation integration while improving the economic and operational efficiency of the grid.

Recent Publications (2024 & 2025)

PSR's research frequently appears in leading academic journals. Here is a sample:

"Robustness: The Missing Ingredient in Generation Scheduling." Alexandre Street, Alexandre Moreira, José M Arroyo, Natalia Alguacil, Luiz Barroso. *IEEE Power and Energy Magazine*. 2025. This joint work from PSR, PUC-Rio, Lawrence Berkeley National Lab, and Universidad Castilla-La Mancha, explores the challenges and solutions for operating power systems with high uncertainty from renewable energy sources.

https://ieeexplore.ieee.org/document/10970215

"Long-term Hydrothermal Bid-based Market Simulator." J Dias Garcia, A Street, M Veiga Pereira. *IEEE Transactions on Energy Markets, Policy and Regulation*. 2025. This work, part of Joaquim Dias Garcia's PhD thesis (a collaboration between **PSR and PUC-Rio**), introduces a simulator for evaluating market power in large-scale bid-based markets with high hydroelectric penetration.

https://ieeexplore.ieee.org/document/10869374

"Learning Optimal Power Flow value functions with input-convex neural networks." A Rosemberg, M Tanneau, B Fanzeres, J Garcia, P Van Hentenryck. *Electric Power Systems Research*, 2024. This joint publication from **GeorgiaTech, PUC-Rio, and PSR** proposes a novel method for solving Optimal Power Flow parametric instances using neural networks.

https://www.sciencedirect.com/science/article/abs/pii/S0378779624005297

"Application-driven learning: A closed-loop prediction and optimization approach applied to dynamic reserves and demand forecasting." J Dias Garcia, A Street, T Homem-de-Mello, FD Muñoz. *Operations Research*. 2024. Developed as part of Joaquim Dias Garcia's PhD thesis (a collaborative effort between **PSR, PUC-Rio, Generadoras de Chile, and Universidad Adolfo Ibanez**), this methodology combines machine learning and optimization for enhanced reserves allocation.

https://pubsonline.informs.org/doi/10.1287/opre.2023.0565

"Regularization and optimization in model-based clustering." RA Sampaio, JD Garcia, M Poggi, T Vidal. *Pattern Recognition*. 2024. Part of Raphael Sampaio's MSc thesis (a joint project between **PSR, PUC-Rio, and Polytechnique Montreal**), this novel unsupervised machine learning methodology demonstrates superior performance.

https://www.sciencedirect.com/science/article/abs/pii/S003132032400061X

"Flexible differentiable optimization via model transformations." M Besançon, J Dias Garcia, B Legat, A Sharma. *INFORMS Journal on Computing*. 2024. This paper, a result of a collaboration between **PSR, Zuse Institute Berlin, KU Leuven, and Columbia University**, presents a new software package integrating optimization problems into machine learning pipelines.

https://pubsonline.informs.org/doi/10.1287/ijoc.2022.0283

"Disjunctive Programming meets QUBO." PM Xavier, P Ripper, J Pulsipher, JD Garcia, N Maculan, DEB Neira. *Computer Aided Chemical Engineering*. 2024. This paper was a joint development by **PSR, NASA, Purdue University, UFRJ, and Waterloo University.** Software is presented to bridge generic optimization models and quantum computers.

https://www.sciencedirect.com/science/article/abs/pii/B9780443288241505731

"Generation capacity expansion planning with spatially-resolved electricity demand and increasing variable renewable energy supply: Perspectives from power pooling in West Africa." Bissiri, M., Moura, P., Perez, R. C., Figueiredo, N. C., & da Silva, P. P. (2024). *Applied Energy, 364*, 123115. This work highlights a collaboration between **PSR and Universidade de Coimbra** (Portugal), utilizing PSR tools to address capacity expansion challenges in West Africa.

https://www.sciencedirect.com/science/article/pii/S0306261924004987