Ocean Energy Pathway

Developed by:

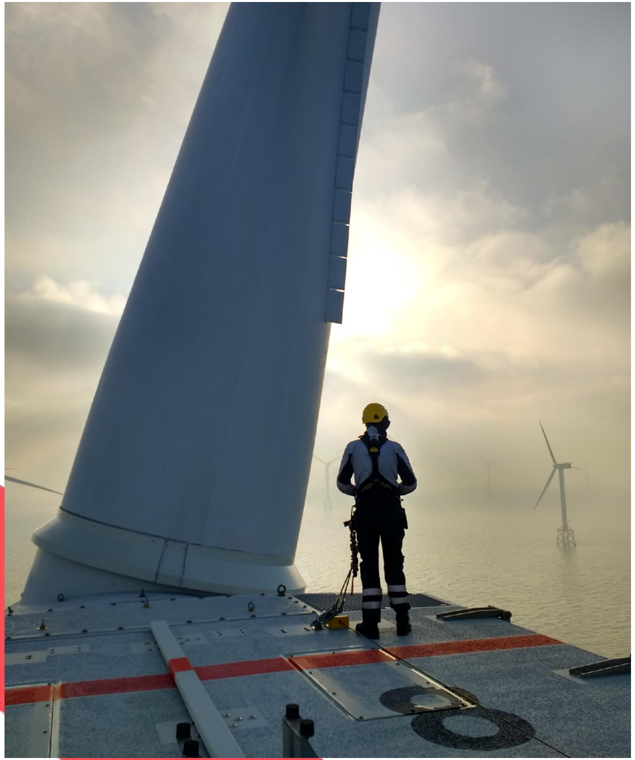
MRTS CONSULTORIA

Final Report

“Timeseries Analysis in Brazil”

The Strategic Role of Offshore Wind System Optimization, Grid Integration, and Market Design

Ocean Energy Pathway



Foreword

This report presents the final findings of the Timeseries Analysis in Brazil study, developed by MRTS Consultoria for Ocean Energy Pathway (OEP). The primary objective of this consulting project is to assess the strategic role of offshore wind power in the long-term evolution of the Brazilian Electricity System.

Over the course of four distinct Phases—ranging from comprehensive data acquisition and baseline system characterization to advanced scenario modeling, system optimization, and system interaction analysis —this study investigates how offshore wind interacts with existing generation sources and transmission infrastructure throughout the national territory.

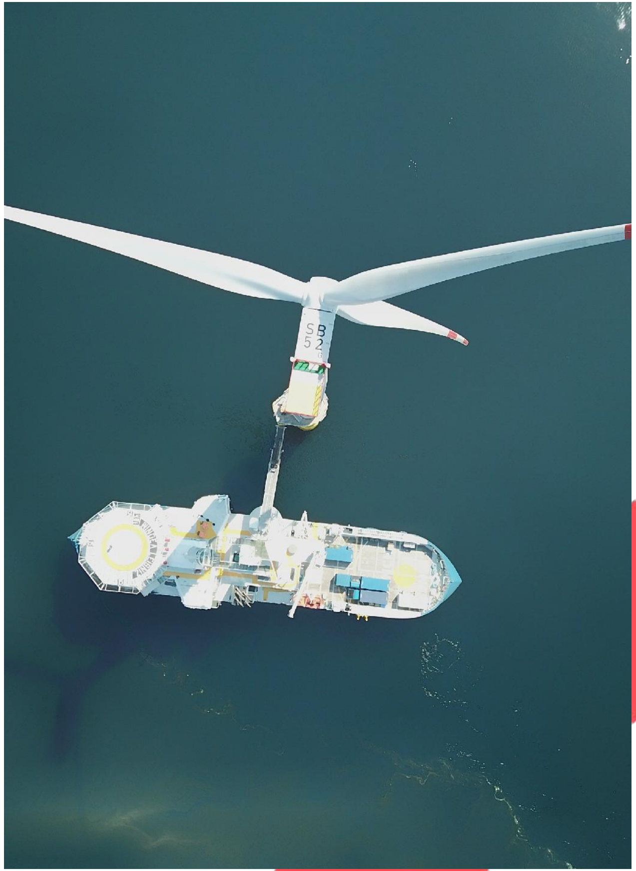
Foreword *(continued)*

The content presented in this material reflects the culmination of several technical meetings held throughout the project. The results were enriched by continuous interactions and revisions to the technical reports and explanatory notes from both the OEP team and the EPE (System Planner) staff, who actively accompanied the project's development. For more specific and technical details, the comprehensive activity reports issued for each phase can be consulted. Technical reports were made available to OEP over the course of the project's development, providing an in-depth view of the methodologies and findings summarized in this final presentation.

By evaluating crucial aspects such as energy complementarity, grid integration, and the operation and expansion of the National Interconnected System up to the 2050 horizon, the following results provide actionable insights, mapping limitations, and defining strategic business models.

We would like to express our gratitude to everyone who contributed to this endeavor. This comprehensive analysis was made possible through the dedicated efforts of the MRTS Consultoria project team: Dorel S. Ramos, Luiz A. S. Camargo, Luis F. Nogueira, Lais D. Leonel, Mateus H. Balan, Pedro S. Rosa, and Roberto Castro.

MRTS Consultoria



Objective and Main Phases

The main objective of this project is to assess the role of offshore wind power in the evolution of the Brazilian Electricity System, particularly considering issues such as: Complementarity with other generation sources, Grid Integration and Planning, and Operation and Expansion of the National Interconnected System, among others.

The timeseries collected for this study purposes cover the main regions with operating or planned power plants for wind (onshore and offshore), solar photovoltaic, and hydroelectric sources, organized according to the energy submarket to which they belong.

The scope is divided into 4 Phases: Data Acquisition and System Characterization; Scenario Modeling and System Optimization; System Interaction Analysis; and Results Dissemination.

Objective and Main Phases

Phase 1 **Data Acquisition and Baseline System and Characterization**	Phase 2 **Scenario Modeling and System Optimization**	Phase 3 **System Interaction Analysis**	Phase 4 **Report Delivered and Key results dissemination**
• Data Acquisition / Data Processing • Energy Demand Project • Strategic Planning and Grid Integration • Power Flow and Pricing • Power Flow and Pricing • Complementarity Analysis	• Energy Mix Forecast • Offshore Wind Energy in Climate Stress Scenarios	• Operational Impact Assessment • Ancillary Services and Revenue Schemes	• Overall Final Deliverables

Executive Summary

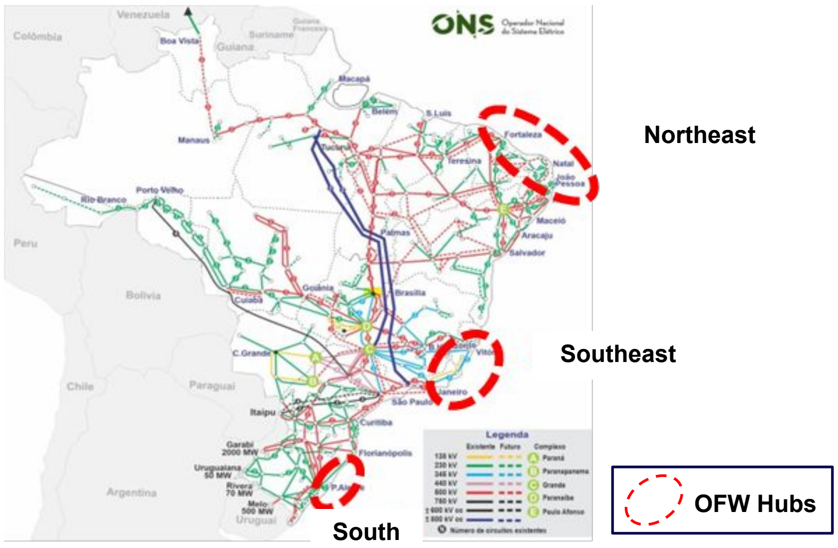
The Value Proposition of Offshore Wind

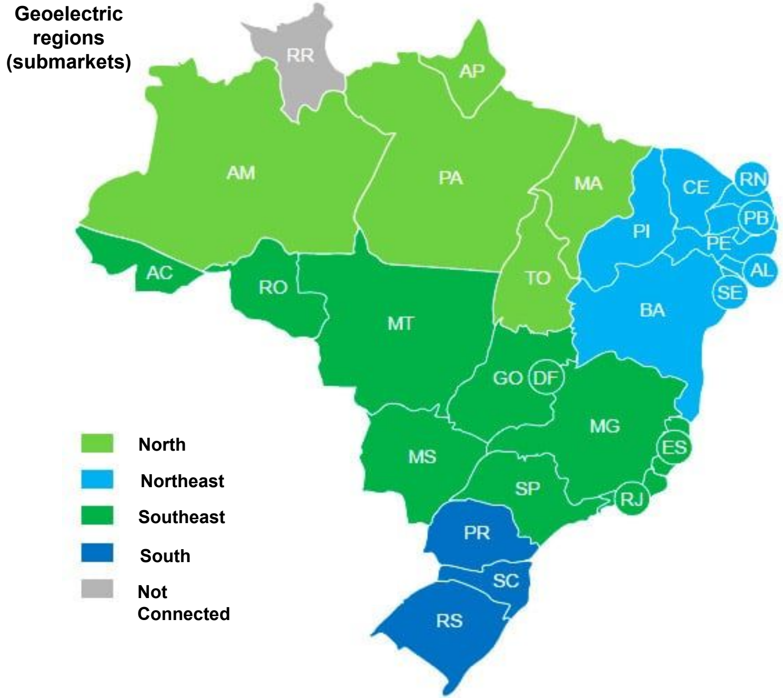
Executive Summary

The Strategic Role of Offshore Wind in Brazil

- This document synthesizes the findings of the "Timeseries Analysis in Brazil" study, developed by MRTS Consultoria for Ocean Energy Pathway (OEP). The primary objective is to assess the strategic role of offshore wind power in the long-term evolution of the Brazilian Electricity System up to the 2050 horizon.
- This study presents in-depth contributions on the role of Offshore Wind Power (OFW) in the context of planning the operation and expansion of the Brazilian system, considering the possibility of developing hubs in the Northeast, Southeast, and South regions.
- The timeseries collected for this study purposes cover the main regions with operating or planned power plants for wind (onshore and offshore), solar photovoltaic and hydroelectric sources, organized according to the energy submarket to which they belong.
- Based on an extensive collection of time series data from the main generation sources, the use of proprietary MRTS' models and EPE's official planning models, the study presents important aspects regarding the contributions, limitations, and alternatives for the integration of OFW energy source in the national territory and its geoelectric regions.

The Strategic Role of Offshore Wind in Brazil





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The Strategic Role of Offshore Wind in Brazil

The assessment concludes that offshore wind acts as strategic asset, with its contributions and challenges varying significantly across different geographic regions:

Regional Dynamics and Grid Integration:

Northeast Hub:

Despite possessing the most significant wind resource, the region faces severe transmission bottlenecks, with an estimated remaining grid capacity of only ~2.5 GW by 2039. To capitalize on this potential without relying on main grid expansions, projects should focus on Power-to-X models (such as green hydrogen production for export) and Power-to-Load models (attracting Data Centers).

Southeast Hub:

This region stands out for having the largest available connection margin up to 2039 (~9.5 GW). Proximity to major load centers minimizes technical losses and optimizes transmission costs. Furthermore, it offers significant opportunities for the decarbonization of the Oil & Gas industry's offshore platforms through direct Power-to-Load connections.

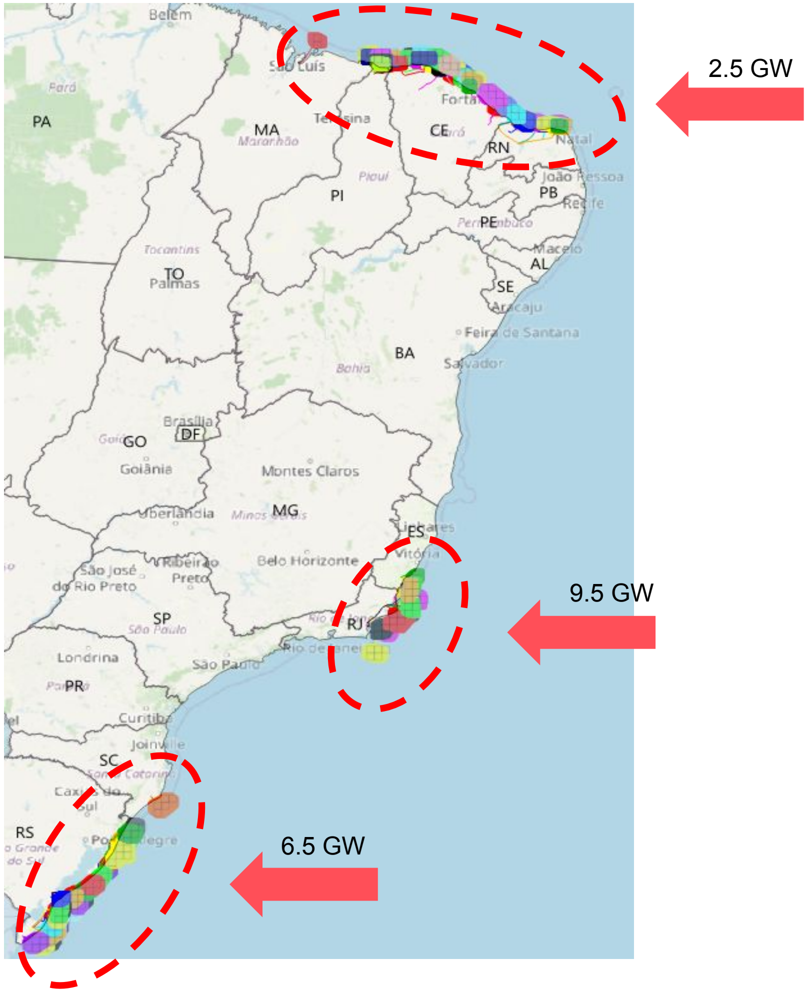
South Hub:

Features a robust transmission margin (~6.0 GW) and a constant generation profile over the 24-hour cycle. Peak wind speeds occur during the winter, which coincides with the region's highest energy demand, facilitating the balance between regional supply and demand.

Executive Summary

The Strategic Role of Offshore Wind in Brazil

The strategic location of offshore wind in the South and Southeast alters the perception of the regulatory "Location Signal". It helps equalize regional transmission prices (TUST) by significantly reducing the need for large interstate energy transfers.



Estimated Transmission Capacity in 2039 for the substations indicated in the planned offshore wind projects at each hub.
(Ref.: IBAMA/MME Map - environmental licensing)

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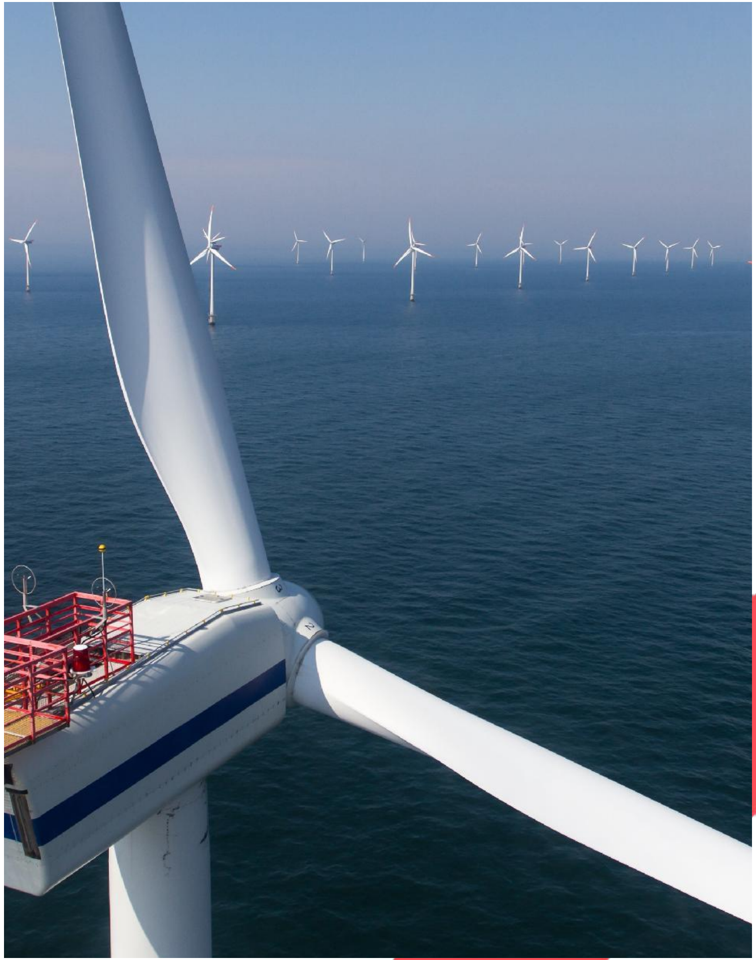
Executive Summary

The Strategic Role of Offshore Wind in Brazil

There is no single business model suitable for all regions of Brazil. OFW in Brazil should be developed through region-specific strategies, given the specific characteristics of each hub (northeast, southeast, and south).

In general, OFW is considered a vector that will enable the export of carbon-neutral fuels and facilitate the domestic production of higher value-added green products, in addition to meeting large load demands with clean energy. Once connected to the grid, OFW can become an ancillary services provider and contribute to the system's operation.



The Strategic Role of Offshore Wind in Brazil

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Business Model	Northeast Submarket	Southeast Submarket	South Submarket
Power-to-Grid (Grid Connection)	High Yield, Grid Constrained. Requires hybridization (Solar/BESS) to bypass saturated transmission and high TUST.	Generation-at-Load. Feeds primary demand directly, enabling corporate self-production with lower transmission costs.	Optimal Grid Access. Leverages abundant connection margins and lowest tariffs. Unlocks exports to SE and Mercosur.
Power-to-Load (Serving Loads)	The Grid Bypass. Focuses on coastal data centers (via submarine cables) to circumvent grid bottlenecks.	O&G & Tech Hub. Driven by pre-salt offshore platform decarbonization and dedicated data center supply.	Niche Coastal Demand. Targets planned data centers (RS), though excellent grid margins make off-grid less critical here.
Power-to-X (Green H2 & Fuels)	Global Export Hub. Leverages Pecém and Suape ports for massive-scale Green H2 and e-fuels for international markets.	Domestic Premium. Supplies regional heavy industry (e.g., Port of Açu) with high value-added green products.	Agri-Industrial Focus. Produces fertilizers and H2 products for domestic use and Mercosur cross-border export.
Strategic Summary	Massive raw potential; success relies on bypassing grid limits via H2 exports or dedicated off-grid loads.	The immediate market; lower yields are fully offset by direct load proximity and O&G synergies.	The balanced play; offers the most favorable grid conditions and unique cross-border integration opportunities.

Executive Summary

The Strategic Role of Offshore Wind in Brazil

Multi-Resource Complementarity and Regional Integration Benefits

Offshore wind generation demonstrates strong hourly complementarity with solar PV by leveraging a nighttime-heavy profile that improves the use of transmission infrastructure as solar output declines. This synergy is particularly effective during steep net-load ramp periods, where wind injections serve as counterbalance to the sharp drop in centralized and distributed solar generation, providing the system with necessary support during daily transition windows.

On a seasonal scale, wind speeds intensify during the dry months of the main river basins, revealing a robust monthly complementarity with hydropower inflows across the North, Northeast, and Southeast subsystems. This relationship supports greater hydrothermal regularization by allowing reservoirs to conserve water and operate more flexibly, which indirectly strengthens the energy balance and reliability of the National Interconnected System despite wind's intrinsic variability.

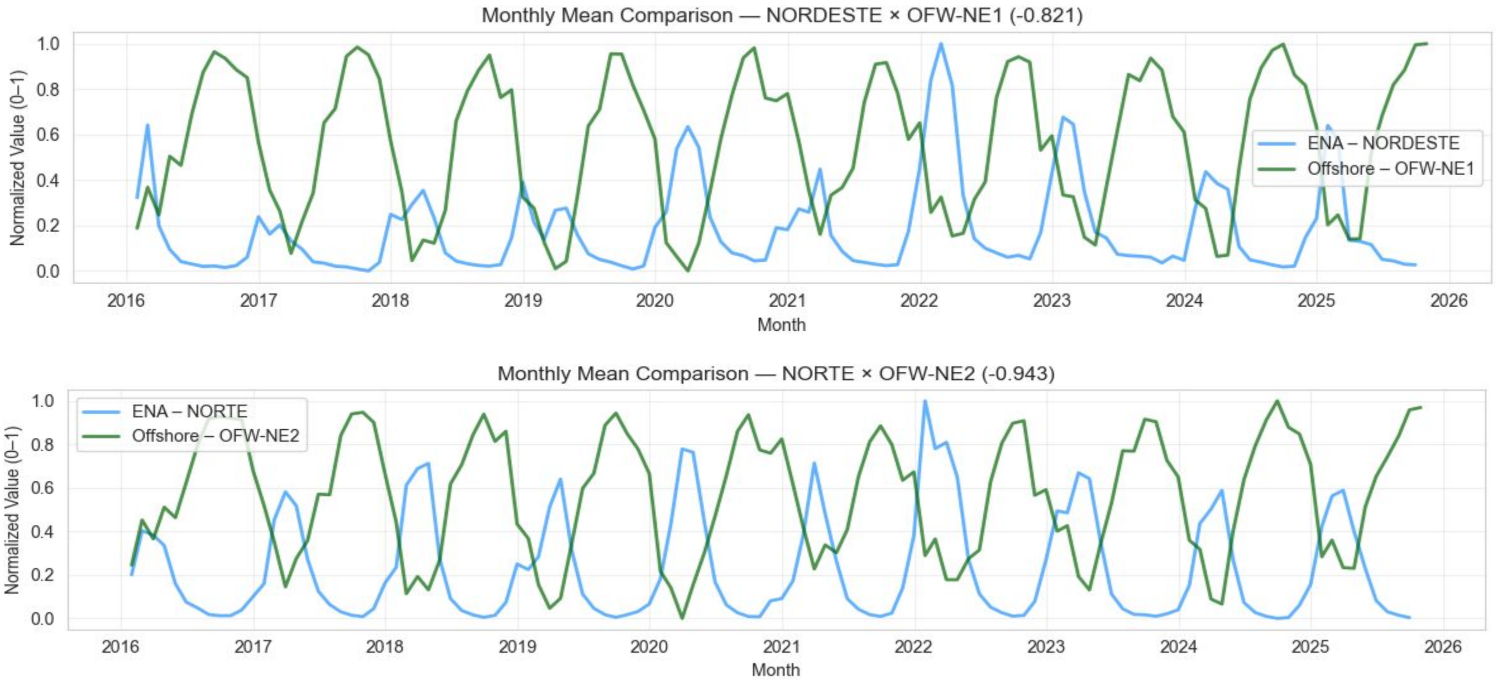
The Strategic Role of Offshore Wind in Brazil

Multi-Resource Complementarity and Regional Integration Benefits

The distinct profiles across the Northeast, Southeast, and South hubs offer a strategic geographic diversity that mitigates overall hydrological risk. While the Northeast provides higher capacity factors and seasonal variability, the Southeast and South benefit from lower daily amplitude variations and proximity to major load centers. These regional characteristics, combined with available transmission margins in the South and Southeast, enhance the system's ability to integrate large-scale intermittent sources while reducing losses and narrowing regional tariff asymmetries.

Monthly Correlation

Offshore Wind X Hydro (EER)



Example of Hydro-Wind Complementarity: Offshore wind hub in the Northeast and "Norte" and "Nordeste" EERs (Equivalent Energy Reservoir.
High degree of monthly negative correlation.

The Strategic Role of Offshore Wind in Brazil

Strategic Expansion Scenarios and Systemic Operability Analysis

The long-term expansion of the Brazilian matrix (2050) was evaluated using an iterative optimization methodology that bridges investment economics, grid costs and operation costs. By stress-testing capacity decisions by hydrothermal models, the analysis ensures that offshore wind integration is cost-effective and adapted to the operational dynamics of the National System.

A set of scenarios were designed to this analysis purpose. It begins with a reference case defining the optimal system configuration based on economic assumptions, demand growth, and technology costs. From this baseline, OFW is introduced through capacity constraints (e.g., 18 GW and 34 GW), forcing its inclusion and shifting the expansion of other generation sources and transmission investments. Cost sensitivity scenarios determine the breakeven point at which OFW becomes competitive and evaluate how small cost variations (±1%) affect its adoption and the generation mix. Finally, environmental scenarios incorporate emissions targets and climate change impacts.

In a neutral-economic environment, while the baseline least-cost expansion relies heavily on solar, onshore wind, and batteries, OFW emerges in some scenarios shifting the cost dynamics. For instance, OFW requires cost reductions ranging from 42% in the South to 62% in the Northeast to achieve spontaneous competitiveness.

The Strategic Role of Offshore Wind in Brazil

Strategic Expansion Scenarios and Systemic Operability Analysis

Implementing a mandated 18 GW of OFW increases total system costs by only 1.3%, while simultaneously reducing the need for long-distance transmission expansion by shifting generation closer to major demand centers. This balance is highly sensitive; a marginal 1% reduction beyond the breakeven point triggers a rapid increase in selected capacity to 16 GW. In addition, in the decarbonization-focused scenario, where emissions are reduced by 45% with a 32% increase in total cost, OFW is included in the energy mix despite its cost, as it remains competitive compared to other sources that become more expensive due to the need for Carbon Capture Systems.

Under severe climate stress and reduced hydrological inflows scenarios, the integration of 34 GW of OFW effectively offsets surging operational costs. By acting as a hedge against hydrological risk, OFW preserves hydro reservoirs and enhances overall energy storage levels, providing a safety margin for the grid under extreme conditions. It is noteworthy that in all scenarios where OFW is introduced, there is not only the expected shift from onshore wind in the Northeast to offshore wind in the Southeast and South, along with reduced transmission investments, but also a consistent increase in the adoption of BESS.

The Strategic Role of Offshore Wind in Brazil

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Business Models and Strategic Feasibility:

International experience indicates that in immature markets like Brazil, offshore wind power tends to depend strictly on incentive mechanisms, with Competitive Auctions & CfDs (Contracts for Differences) being the widely used model to guarantee the bankability and viability of offshore wind projects, whose revenues can be supplemented, predominantly, by the provision of ancillary services. Market-driven revenue models remain risky due to cost volatility and inflation, even in more mature regions.

Brazil has a long history of promoting onshore wind expansion through competitive auctions, in which, as the technology matured and the market consolidated, the risk allocation rules were adjusted until the market price and volume risks were assumed totally by the generator. The OFW challenge lies in designing contracts with less risk allocation to the end consumer.

Unlike the onshore wind sector, which matured by shifting all price and volume risks to generators via Regulated Auctions, the offshore challenge requires innovative contractual frameworks. To ensure project viability without overburdening end consumers, CfD model emerges as an alternative to balance investor security with systemic economic efficiency.

The Strategic Role of Offshore Wind in Brazil

Business Models and Strategic Feasibility:

Beyond energy sales, OFW farms are technically capable of providing critical grid support, such as voltage and frequency stability. Following international precedents like the United Kingdom, remunerating these ancillary services constitutes a vital mechanism to stack project revenues and enhance overall financial viability. In Brazil, current regulations do not provide for remuneration for the provision of these ancillary services by wind power plants. However, given the ongoing regulatory advances, the trend is for OFW to be remunerated for providing Reactive Power Support.

In addition, Brazil adopted the land concession auction scheme, following an international trend adopted in some countries with more mature markets. However, this model is being rethought because high interest rates and input costs have made upfront payments to the state challenging. Without price guarantees and with narrow margins, the risk of project abandonment has increased, forcing governments to consider the return of protection mechanisms (such as CFDs) to guarantee clean energy targets.

Consider incentive mechanisms for the development of the first projects and unlocking the market. If the government stacks these heavy upfront costs without providing a stabilizing revenue mechanism, there will be a risk of empty auction. In this scheme, promoting remuneration models beyond energy contracting, such as the provision of ancillary services and the trading of green energy certificates, would increase the attractiveness of projects.

Executive Summary

The Strategic Role of Offshore Wind in Brazil

Final Considerations

The "Timeseries Analysis in Brazil" study indicates that offshore wind (OFW) operates as a systemic asset, offering value across three pillars: operability, economic optimization, and market diversification.

Offshore wind provides a hydrological hedge due to its negative monthly correlation with hydroelectric inflows (reaching -0.94 in specific submarkets). Data shows that wind production increases during dry months in the main river basins, allowing the National Interconnected System (SIN) to manage reservoir levels, especially under climate change scenarios. Additionally, OFW serves as a tool for managing the "Duck Curve" because its generation increases during the late afternoon. This profile balances the reduction in solar PV output during peak demand intervals, reducing system reliance on fossil-fueled thermal dispatch.

The Strategic Role of Offshore Wind in Brazil

Final Considerations

While offshore wind involves increased initial capital expenditure (CAPEX) compared to onshore alternatives, it facilitates grid optimization. The study shows that locating generation near consumption centers in the South and Southeast reduces the requirement for long-distance transmission infrastructure. Consequently, the impact on total expansion costs is limited, representing a 1.5% increase in the Net Present Value (NPV) relative to the least-cost expansion scenario. This proximity also aids in addressing regional tariff asymmetries (TUST) by reducing the requirement for large-scale energy transfers between states. It is noteworthy that in all scenarios where OFW is introduced, there is not only the expected shift from onshore wind in the Northeast to offshore wind in the Southeast and South, along with reduced transmission investments, but also a consistent increase in the adoption of BESS.

The viability of OFW relies on regional strategies tailored to infrastructure constraints and the general characteristics of regional markets.. In the Northeast, where transmission margins are limited (estimated at 2.5 GW by 2039), the resource can be utilized via Power-to-X (Green Hydrogen) or Power-to-Load models to operate independently of the national grid. The Southeast and South hubs provide available connection margins (up to 9.5 GW) and proximity to industrial demand, such as the decarbonization of offshore Oil & Gas activities.

To support project bankability, the study identifies the transition to Contracts for Difference (CfDs) as a relevant step. This model addresses investor risk and market volatility while protecting the consumer. Furthermore, updating regulations to enable remuneration for ancillary services—such as voltage and frequency stability—provides the revenue stacking required to make offshore projects financially viable.

System Baseline & The Transmission Challenge

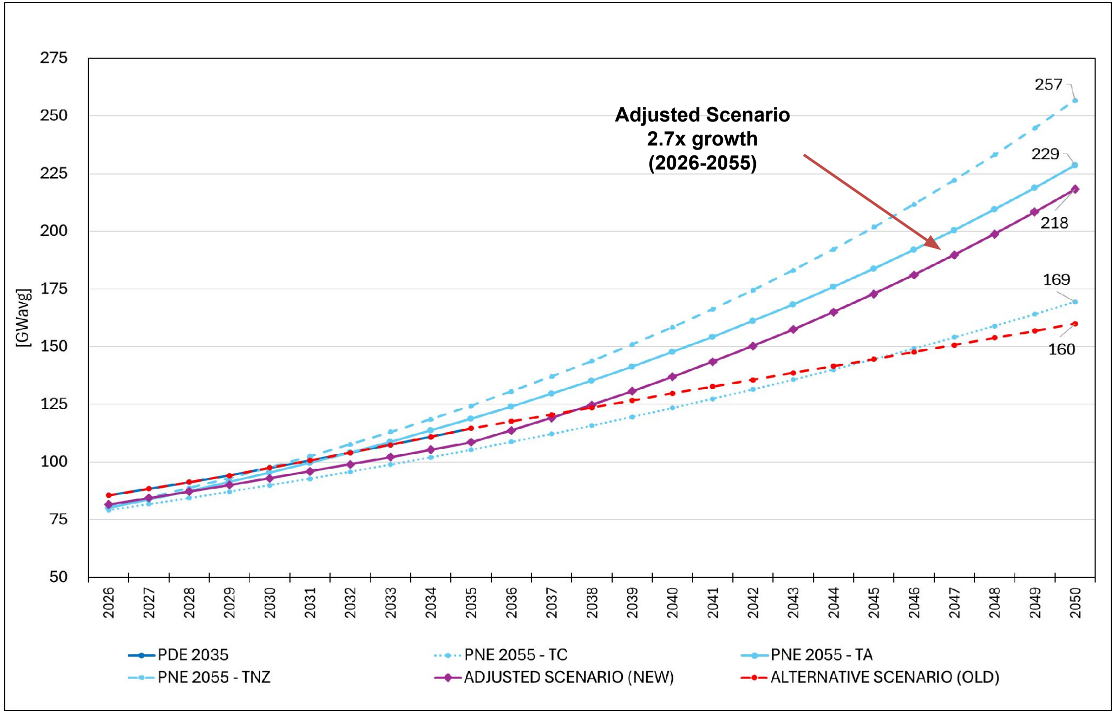
Baseline 2050

Demand Growth Exacerbates the Need for System Flexibility

- Demand forecasting is an important driver used for planning the expansion and operation of the system. For this reason, its projection was estimated in this study and considered in the simulations.
- Gross energy demand is projected to scale 2.7x by 2050, reaching 218 GWavg.
- Growth is driven by a 3.2% annual GDP increase, electrification, Data Centers, and H2 production.
- The aggressive penetration of distributed generation (solar PV) severely steepens the 'duck curve' by 2050. The net demand projection considers the growth expectation of distributed generation, which is projected based on an econometric-statistical model.
- Conclusion: The expected increase in demand will induce an expansion of the System's Supply. On the other hand, the SIN may face critical shortages of firm capacity and flexibility during evening load ramps.

Demand will reach 218 GWavg by 2050, reflecting the strong insertion of special loads (H2V and Data Centers) and an optimistic GDP (3.2% annually). The expected increase in demand will induce an expansion of the System's Supply, but the increasement of distributed solar energy means the operator will need massive fast-responding flexible capacity.

Demand Growth Exacerbates the Need for System Flexibility



Note: For the simulations, a load projection based on MRTS's model was carried out, updated with the most recent information published by EPE (PNE 2055) and adjusted by MRTS. The net demand projection considers the growth expectation of distributed generation, which is projected based on an econometric-statistical model. The adjusted scenario was built mainly based on the main assumptions of the PNE 2055 TA scenario. EPE's scenarios mainly differ in terms of GDP assumptions and expectations for the evolution of the energy sector.

- **PNE 2025 TNZ (Net Zero Transition) – 3.2x growth**
- **PNE 2055 TA (Elongated Transition) – 2.9x growth**
- **PNE 2055 TC (Continued Transition) – 2.1x growth**

Grid Constraints

Transmission Capacity Dictates Regional Expansion Vectors

- This study evaluated the maximum offshore wind capacity that the transmission system can receive.
- This study considers the transmission expansion assumptions presented by EPE for the 2039 timeframe (from Ten-Years Energy Plan), which is the most detailed information currently available on transmission expansion behavior over the long-term horizon.
- The study assesses the local and regional impacts of selected connection locations at each offshore wind hub: NE, SE and S regions.
- It was evaluated the maximum transmission capacity (connection) that the main substations—candidates to receive offshore wind projects— can support, given the expected system conditions.
- Simulations were processed using the Anarede Power Flow Model – Set of computer applications tools for analyzing electrical power systems for power flow studies, operation planning, and system expansion.

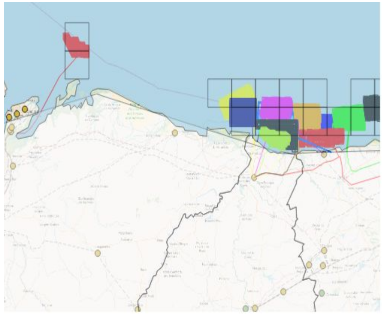
Grid Constraints

Transmission Capacity Dictates Regional Expansion Vectors

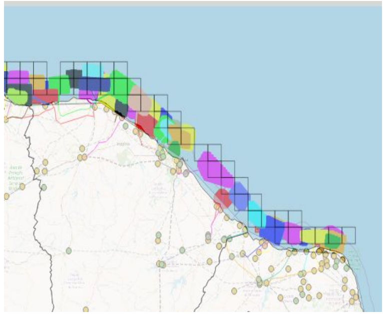
- The study considered 31 busbars associated with potential offshore wind connections in each of the three hubs:
  - 15x Northeast; 1x North (gathered); 7x Southeast; and 8x South
  - The busbars represent the main substations with indication to be connected by offshore wind power plants planned so far (ref. IBAMA/MMA map*).

Maps - Hubs of planned offshore wind projects and connecting substations.

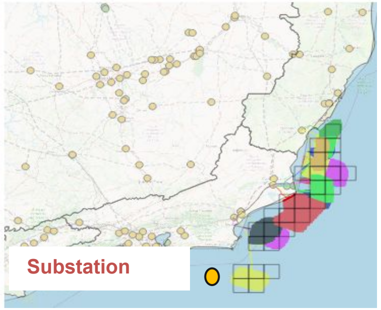
Northeast (NE)
Maranhão (MA); Piauí (PI); Ceará (CE)



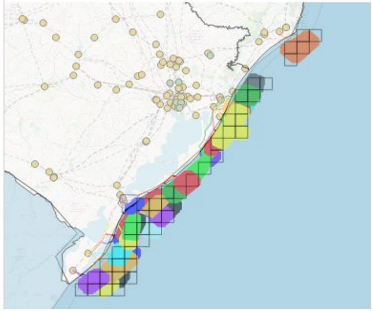
Northeast (NE)
Ceará (CE); Rio Grande do Norte (RN)



Southeast (SE)
Rio de Janeiro (RJ); Espírito Santo (ES)



South (S)
Rio Grande do Sul (RS); Santa Catarina (SC)



**IBAMA/MMA - “Complexos eólicos offshore: Projetos com processos de licenciamento ambiental abertos no IBAMA”, 2025.*

Grid Constraints

Transmission Capacity Dictates Regional Expansion Vectors

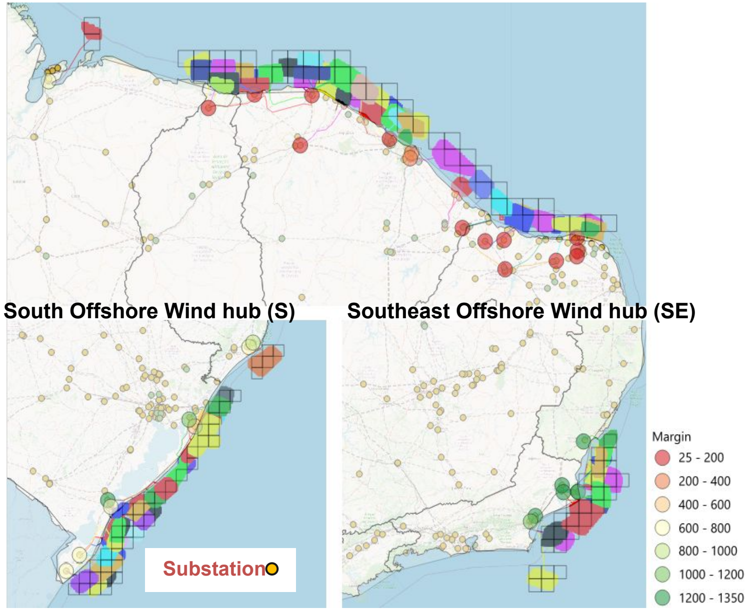
Long-term Power flow studies estimated an available connection capacity of 18 GW(2.5 GW in NE, 9.5 GW in SE, and 6.0 GW in S), considering the expansion investments foreseen in the latest ten-year transmission plan, with an analysis horizon adjusted to 2039.

- Northeast Hub (2.5 GW): Critical saturation across 16 substations; massive insertion requires synchronous compensators.
- Southeast (9.5 GW) & South (6.0 GW) Hubs: High available margins guide the natural expansion vector.

Although there is remaining capacity in the three hubs, many substations may not have sufficient capacity to accommodate the size of the projects planned* for the same connection locations, especially in the Northeast.

This fact should be considered in the planning studies (EPE), regarding the areas concession auctions.

Northeast Offshore Wind hub (NE)



**IBAMA/MMA map.*

These maps present the transmission margins obtained in the study. Green color indicates higher margins and Red color more restrictive transmission margins.

Grid Constraints

Transmission Capacity Dictates Regional Expansion Vectors

Conclusions:

- **Maximum Available Capacity:** Without unplanned grid reinforcements (in addition to those already foreseen by EPE in the ten-year transmission plan), the system can absorb up to 18 GW: 9.5 GW (Southeast), 6.0 GW (South), and 2.5 GW (Northeast).
- **Northeast Bottlenecks:** Critical saturation of transmission margins restricts capacity, making substantial system reinforcements mandatory for further expansion.
- **The Natural Expansion Vector:** High available margins in the Southeast and South guide near-term development, requiring significantly less effort in grid strengthening.
- **South vs. Southeast Trade-offs:** Although the South offers robust connection margins, its lower capacity factor and potential electrical losses must be carefully weighed against the Southeast, which remains the country's primary load center.

Transmission Capacity Dictates Regional Expansion Vectors

Subsystem	Total Margin Available (GW)	Number of Substations	Average Margin per Substation (MW/Substation)
Northeast (NE)	2.5	16	160
Southeast (SE)	9.5	8	1260
South (S)	6.0	7	850

Note: The available margins were calculated for each selected substation and indicate the maximum capacity that can be supported if no reinforcements or expansions are made to the grid/substations, in addition to what is currently planned for 2039. Since this is not specifically an electrical planning study, it has not just looked at the locality, but also the impact on its surroundings, taking the grid the way it is planned.

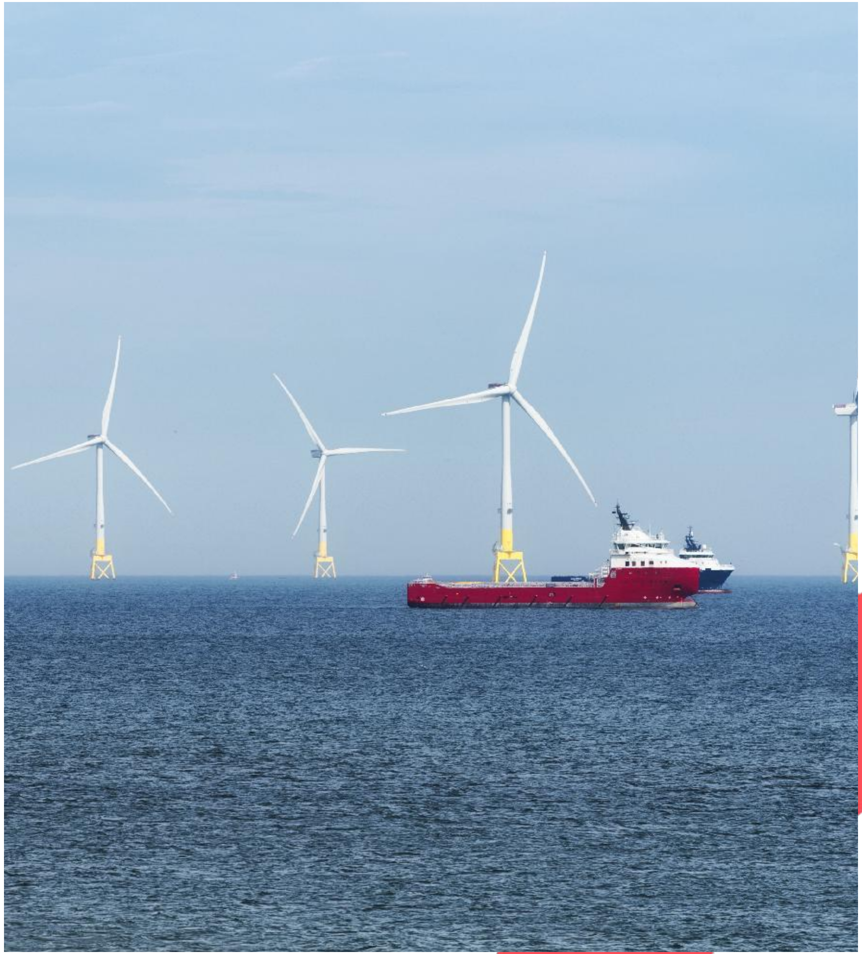
Regulatory Impacts

Offshore Wind Promotes TUST Redistribution

It was estimated the effects on the connection tariff (TUST - Transmission System Usage Fee) resulting from a prospective massive insertion of offshore wind projects in the three hubs of interest.

The simulations compare the distributive effect on tariff values considering scenarios with and without the participation of offshore wind power.

The analyses were performed based on the NODAL model, used by ANEEL (regulator) to estimate the value of connection tariffs, providing the locational economic signal.



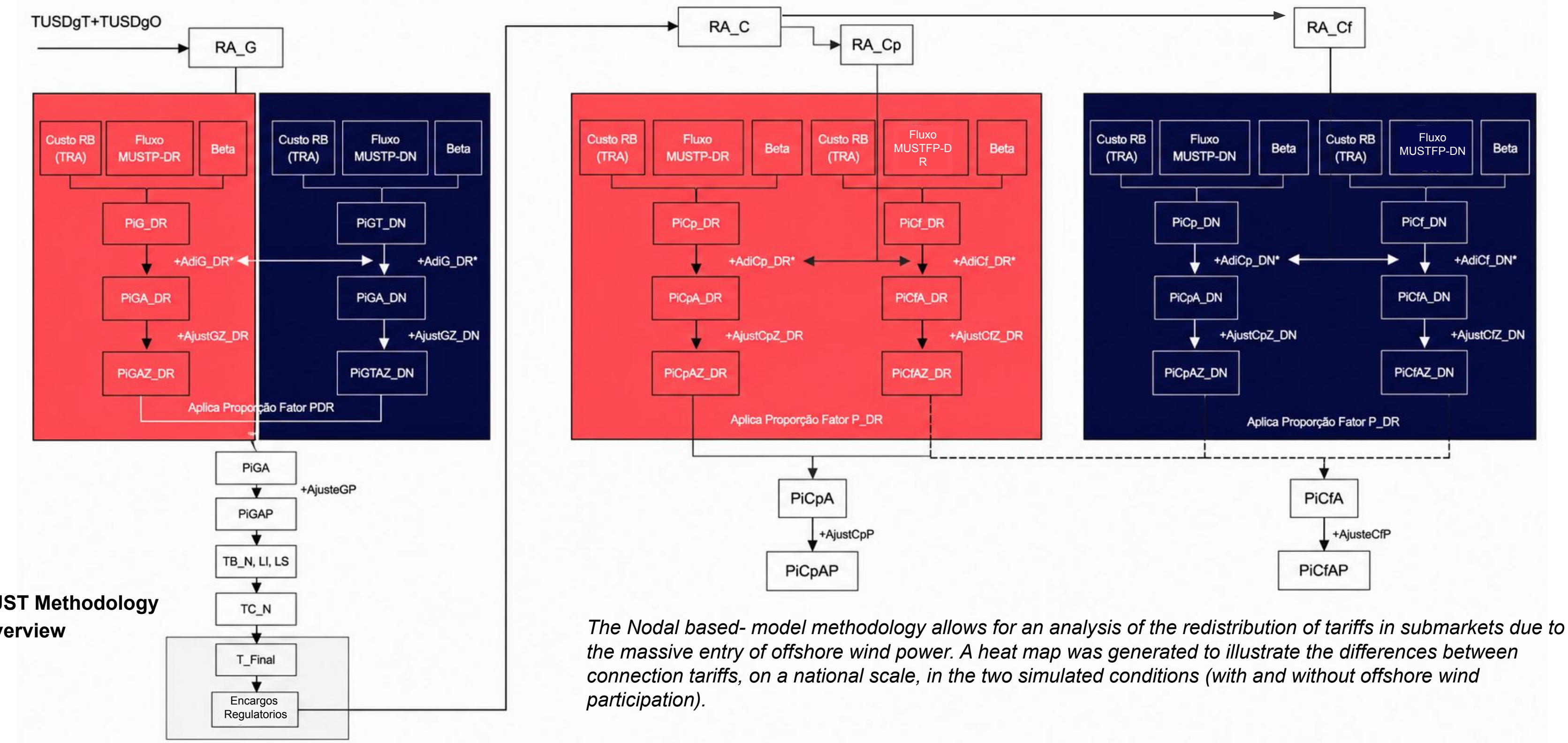
Regulatory Impacts

Offshore Wind Promotes TUST Redistribution

- As assumptions, offshore wind expansion is assumed to be equivalent to the previously estimated margin capacity (18 GW distributed across the 3 hubs) and the system configuration for the year 2034 (the furthest year with available information for coherent system modeling for the purposes of using the Nodal model).
- Thus, to evaluate the transmission tariff, it was considered that the available margin will be occupied by offshore wind farms in the 31 connections studied in the previous simulation (Northeast, Southeast and South hubs).
- In other words, the transmission margins obtained in the previous step were considered as power injections at each selected substation, in each of the considered hubs, at the same time: the entry of 2.5 GW in the Northeast hub, 9.5 GW in the Southeast, and 6.0 GW in the South.

Offshore Wind Promotes TUST Redistribution

TUST Methodology Overview



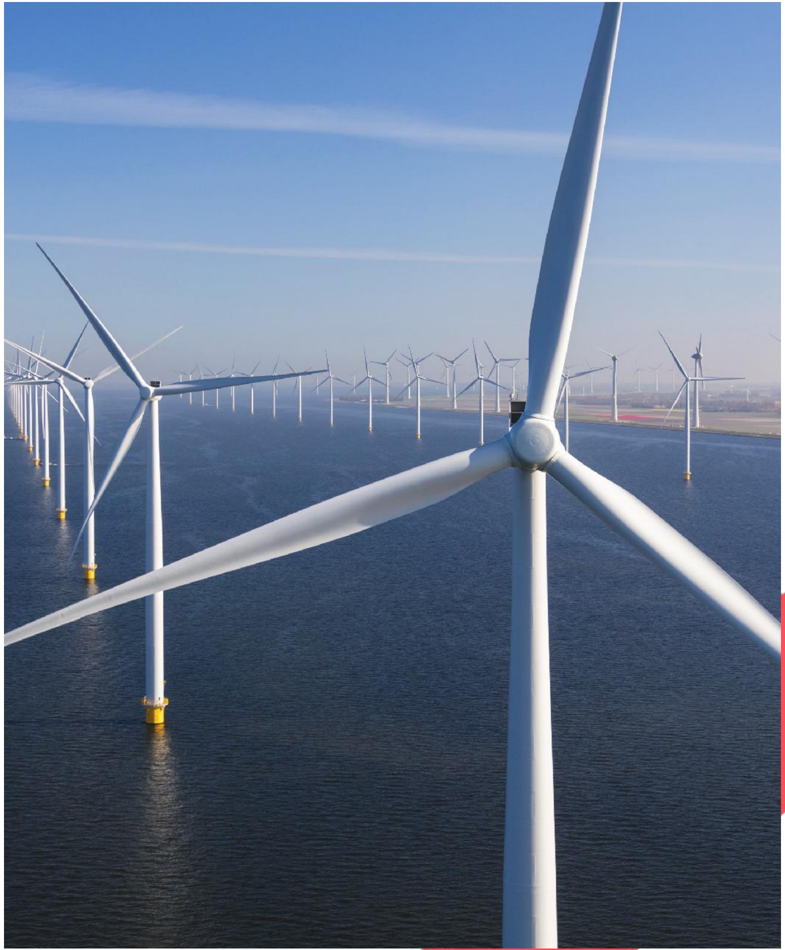
TUST Methodology Overview

The Nodal based- model methodology allows for an analysis of the redistribution of tariffs in submarkets due to the massive entry of offshore wind power. A heat map was generated to illustrate the differences between connection tariffs, on a national scale, in the two simulated conditions (with and without offshore wind participation).

Regulatory Impacts

Offshore Wind Promotes TUST Redistribution

- Simulations using ANEEL's NODAL model show offshore wind narrows the tariff asymmetry between N/NE and S/SE subsystems.
- By injecting power directly into load centers (S/SE), the model proportionally balances the Annual Permitted Revenue (RAP) distribution.
- Metrics: Without offshore wind, South tariffs are 42% of the Northeast's; with offshore wind, this ratio improves to 65%.



Offshore Wind Promotes TUST Redistribution

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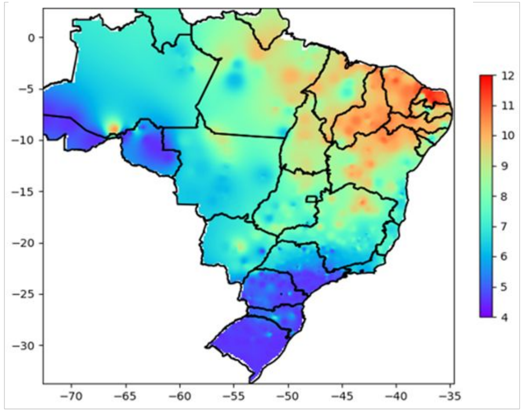
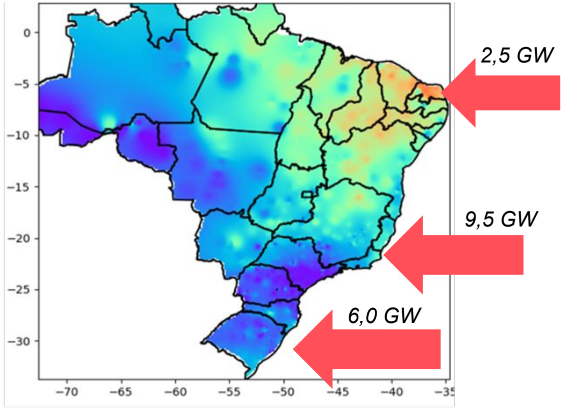
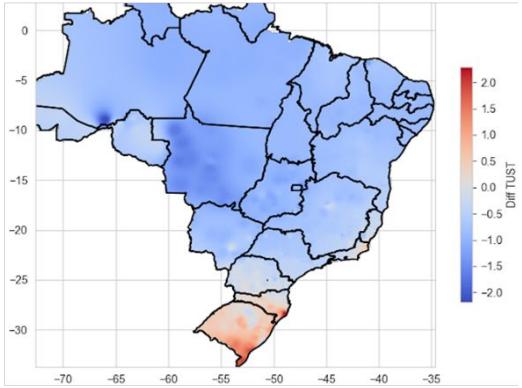
TRUST Projection Map
(Without OSW participation – base case)



TRUST Projection Map
(With OSW participation)



TRUST Projection Map
(With OSW participation)



Injecting offshore wind in the South and Southeast structurally improves the TUST. This promotes a redistributive effect on tariffs, reducing asymmetries between regions.

Regulatory Impacts

Offshore Wind Promotes TUST Redistribution

Conclusions - Connection Tariff (TUST): Redistributive Effects and Locational Signals

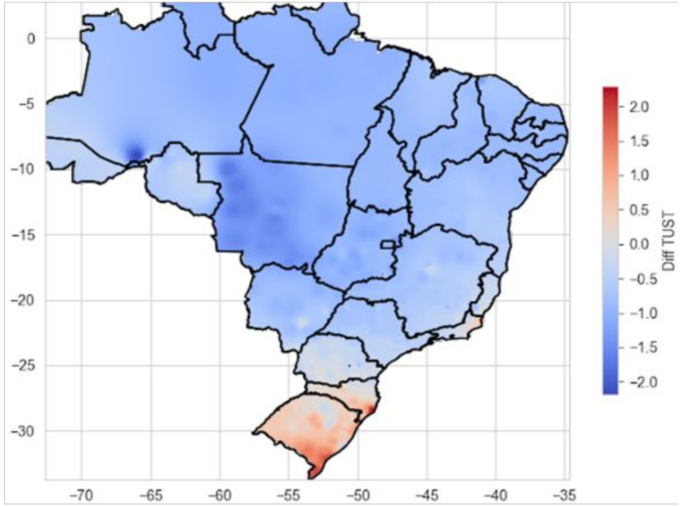
- **Regulatory Mechanics:** Transmission tariffs (TUST) apply nodal methodology and marginal cost theory to distribute the fixed Annual Permitted Transmission Revenue (RAP), making them highly sensitive to new power injections and grid topology.
- **Current Baseline Asymmetry:** The Northeast currently faces the highest tariffs due to saturated connection margins from a high concentration of existing renewables. Without offshore wind, South and Southeast tariffs are 42% and 66% of the Northeast's value, respectively.
- **The Redistributive Effect:** The strategic integration of offshore wind in the Southeast and South balances transmission line loads, driving a positive, system-wide tariff redistribution.
- **Regional Gap:** This effect narrows the regional asymmetry, bringing South and Southeast tariffs up to 65% and 74% of the Northeast's value, and reducing the gap between the South and Southeast themselves (from 64% to 87%).
- **Systemic Optimization:** Developing offshore wind near major consumption centers provides locational economic signals that optimize generation allocation, reduce electrical losses, and represent a gain for the entire system.

Offshore Wind Promotes TUST Redistribution

Connection Tariff (TUST)	Without OFW	With OFW
SE / NE	66%	74%
S / NE	42%	65%
S / SE	64%	87%

SE - Southeast; S - South; NE - Northeast

Delta TRUST Projection Map (With OSW participation)



Relative effect of TUST between subsystems (with and without offshore wind)

The Natural Advantage

Resource Complementarity

Complementarity Analysis

Data Set

Identifying the degree of complementarity between wind energy and other sources led to an understanding of the effect that its inclusion can have on the system's operation, which is a fundamental approach for this study.

- The analyses consist of determining correlation matrices of the typical profiles of these generation sources, distributed throughout the national territory.
- The typical profiles (Onshore Wind, Solar PV and Hydro) used in this analysis were determined based on several the data points collected in this study, transformed into generation series and organized by region and submarket in which the respective source has a prominent share.

Data Set

Source	Number of Profiles	Typical Profiles
Offshore Wind	4 regions: NE (2), SE (1) and S (1)	Northeast: OFW-NE1 and OFW-NE2; Southeast: OFW-SE; South: OFW-S
Onshore Wind	10 regions: NE (7) and S (3)	Northeast: ONW-NE-C and ONW-NE-I; South: ONW-S-C and ONW-S-I
Solar PV	5 regions: NE (2), SE (2) and S (1)	Northeast: PV-NE-C and PV-NE-I; Southeast: PV-SE-MG and PV-SE-SP; South: PV-S-RS.
Hydro	12 regions: N (3), NE (1), SE (6) and S (2)	ERR: Manaus-Amapá, Madeira, Teles Pires, Belo Monte, Norte, Nordeste, Paraná, Sudeste, Paranapanema, Itaipu, Iguaçu, Sul.

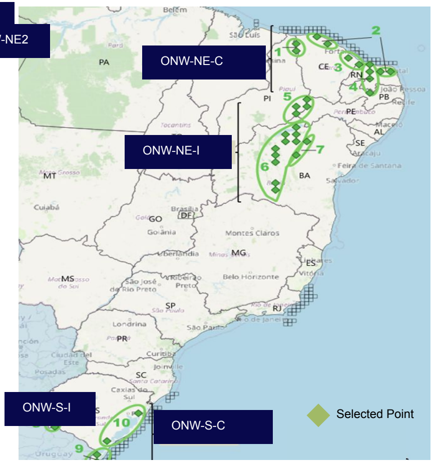
Note: For the hydro source, the selected points correspond to the Equivalent Energy Reservoirs (ERR), used by the operator - ONS for planning the system's operation. For each ERR, Natural Energy Inflow (ENA) historical data were collected. ENA represents the potential hydro generation that would result from the natural inflows to a reservoir, assuming all inflows are converted into energy.

Complementarity Analysis

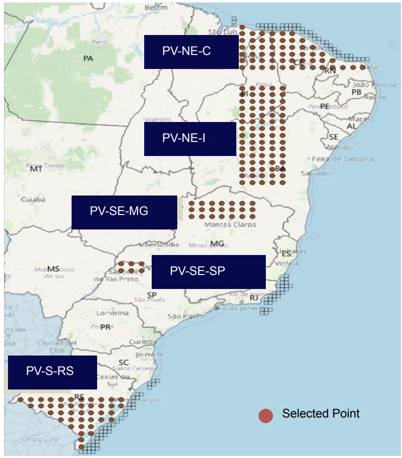
Data Set

Offshore Wind

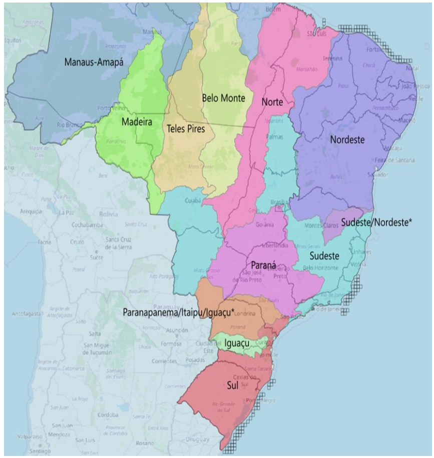
Onshore Wind



Solar PV



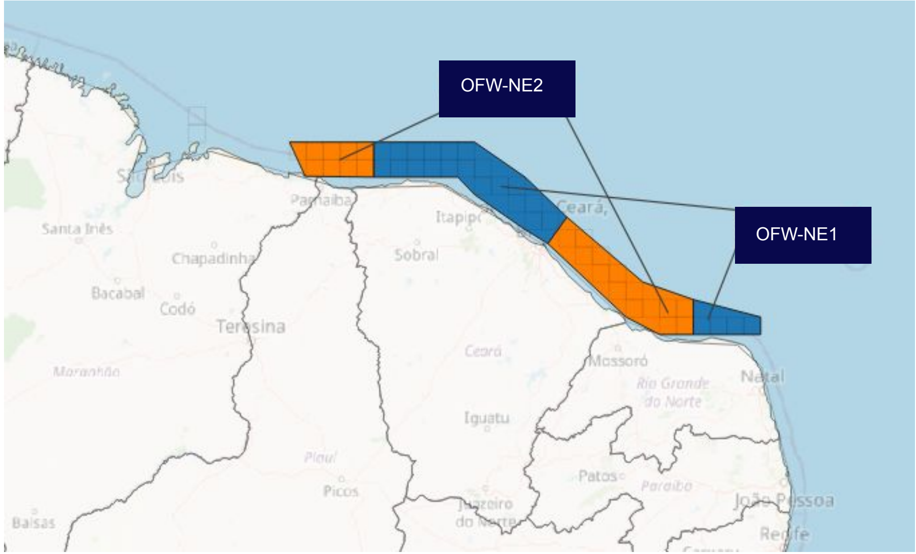
Energy Equivalent Reservoirs (ERR)



Complementarity Analysis

Offshore Wind Profiles (Hourly and Monthly)

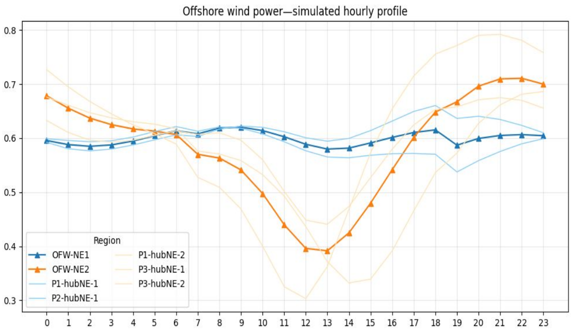
Offshore Wind Profiles – Northeast (NE)

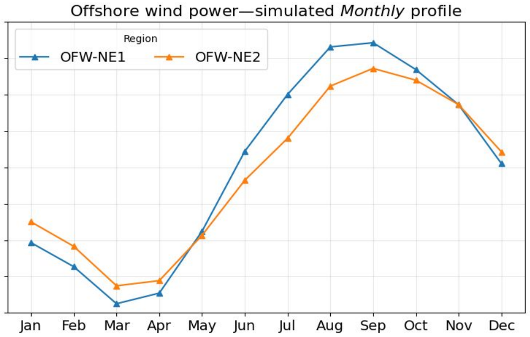


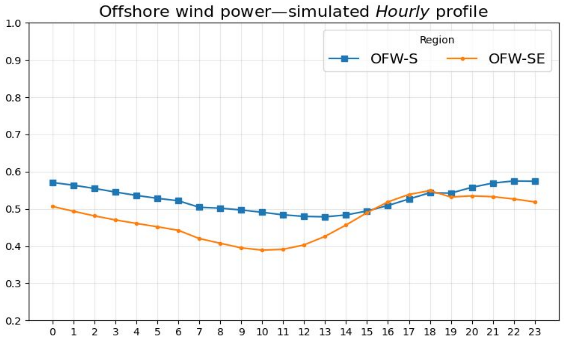
Offshore Wind Profiles – Southeast (SE) and South (S)

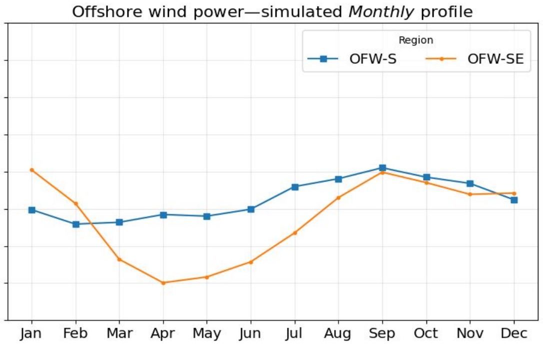
Complementarity Analysis

Offshore Wind Profiles (Hourly and Monthly)









Capacity Factor

OFW-NE1	OFW-NE2	OFW-S	OFW-SE
0,60	0,58	0,53	0,47

The collection, processing, and analysis of various ERA-5 data points in the regions of OFW development hubs revealed, among other things, that in the NE region there are two distinct hourly wind profiles in terms of modulation: one flatter and the other more seasonal. The generation profiles of the NE region exhibit greater seasonality and modulation (and capacity factors) than SE and S regions.

Complementarity Analysis

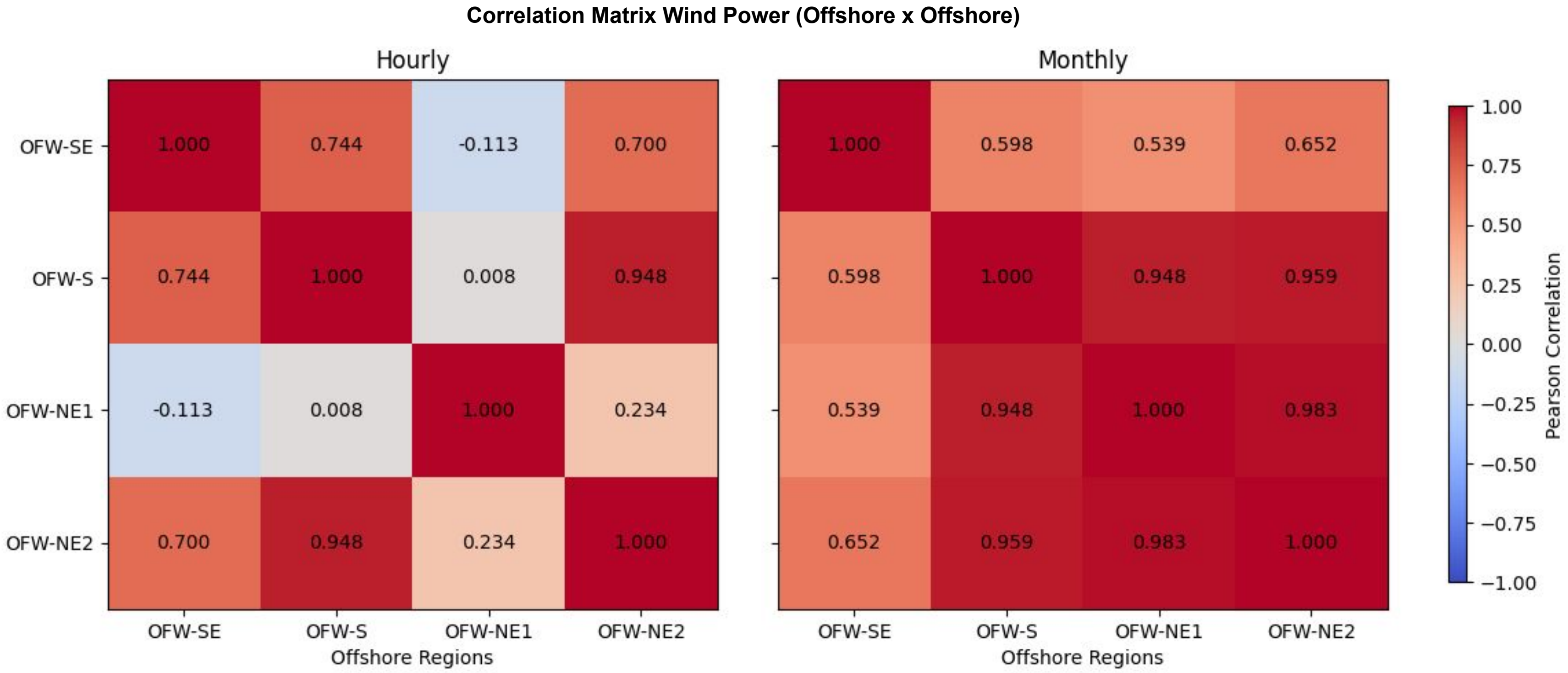
Offshore Wind Profiles Correlation

Analysis of the Correlation between Offshore Wind Hubs

Although typical offshore wind profiles differ in terms of seasonality (monthly) and modulation (hourly), they exhibit positive complementarity (correlation), indicating that periods of higher wind intensity occur simultaneously in these regions (although at different levels).

The only exception is the relationship between the NE-1 and SE profiles, which shows a slight hourly negative correlation (almost neutral).

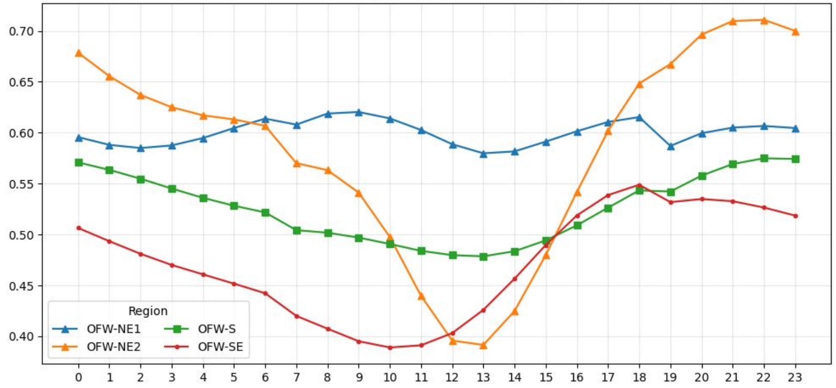
Offshore Wind Profiles Correlation



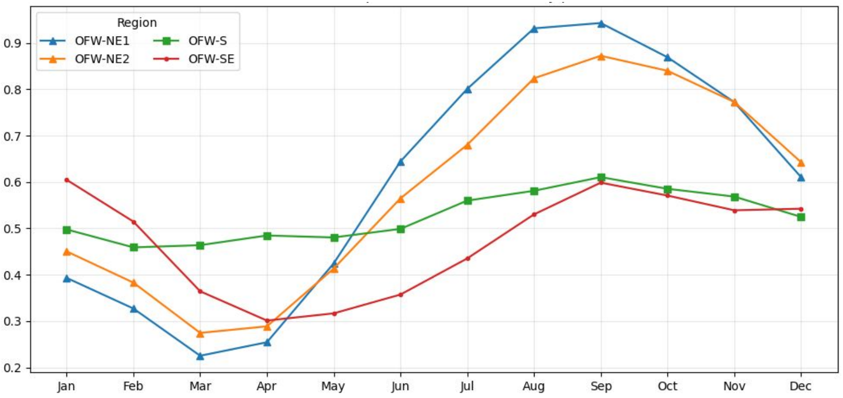
Complementarity Analysis

Offshore Wind Profiles Correlation

Offshore Wind Power– Simulated Hourly Profile



Offshore Wind Power– Simulated Monthly Profile



Hourly Complementarity

Offshore Wind Mitigates the Solar 'Duck Curve'

- Offshore wind demonstrates strong hourly negative correlation with solar PV across all assessed hubs.
- Generation intensity reliably peaks during the late afternoon and early evening net-load ramps.
- System Value: Pairing nighttime offshore wind with daytime solar optimizes the utilization factor of existing transmission lines.

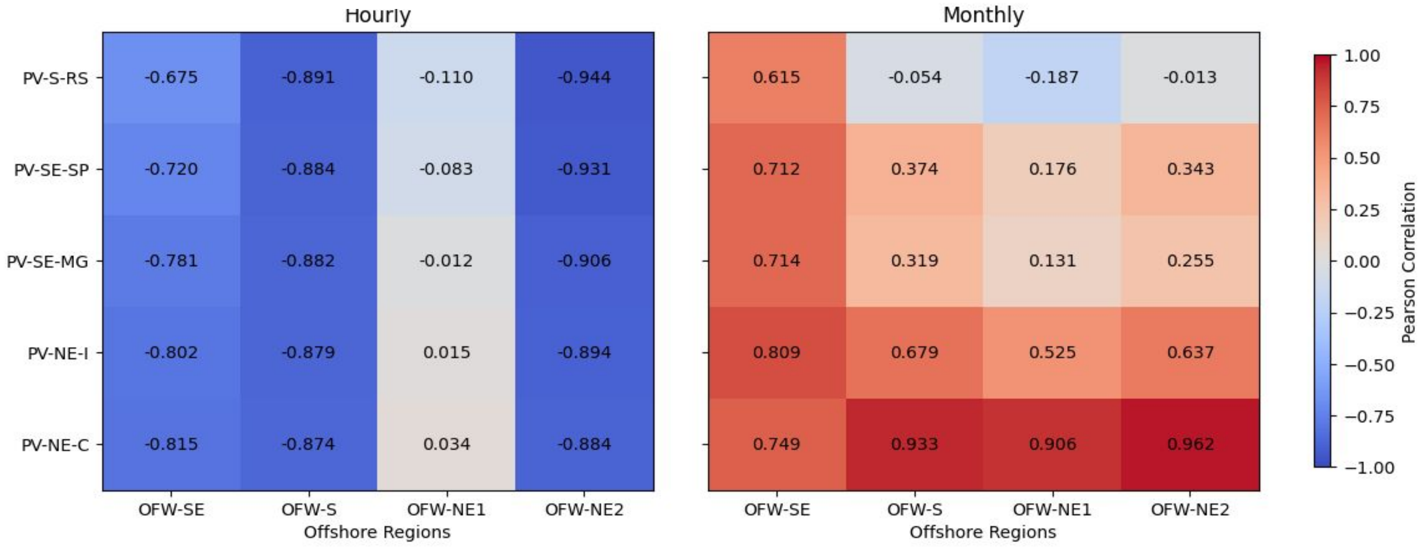
Offshore wind is naturally counter-cyclical to solar on an hourly basis. As solar drops, offshore winds pick up, providing firm capacity during the peak ramp.

Hourly Complementarity

Offshore Wind Mitigates the Solar 'Duck Curve'

Hourly and Monthly Correlation Matrices: Offshore Wind x Solar PV

Solar PV profiles



Offshore Wind Profiles (OFW)

Monthly Complementarity

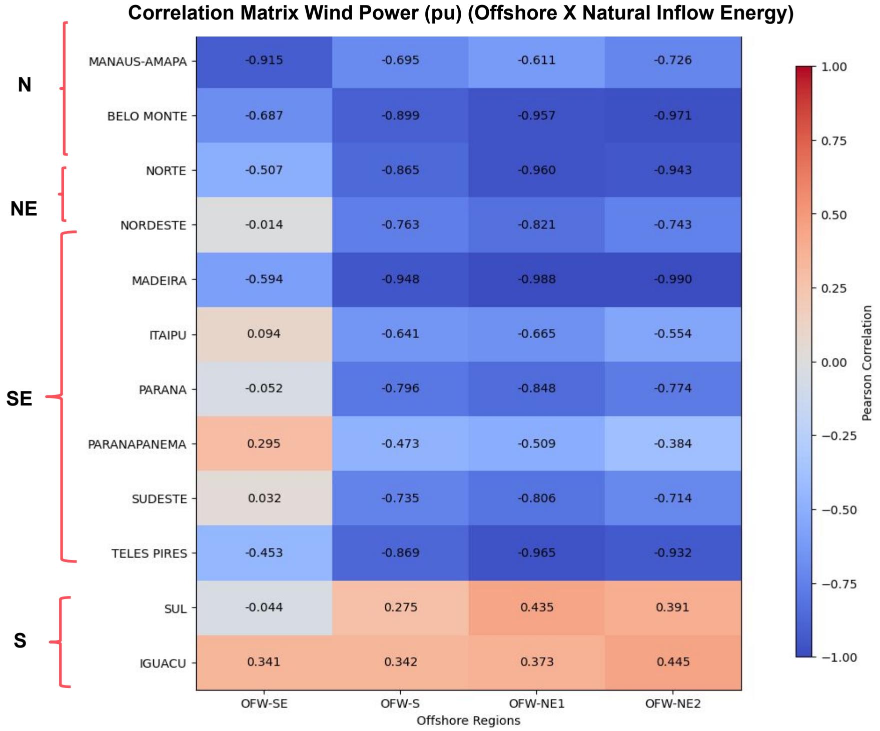
Offshore Wind as a Hydrological Hedge

- **Robust Complementarity (NE & South):** Offshore wind farms in the Northeast and South hubs demonstrate strong monthly complementarity with most major reservoirs across the North, Northeast, and Southeast.
- **Southeast Dynamics:** While the Southeast hub also complements several reservoirs in these regions, it exhibits a lower degree of synergy compared to the other hubs, including slight positive correlations in specific cases.
- **Systemic Optimization:** Overall, the monthly correlation results confirm that offshore wind has significant potential to complement the national hydroelectric generation fleet.
- **Operational & Financial Benefits:** This natural synergy allows for the optimization of energy stored in the system, directly improving grid flexibility, minimizing curtailment risks, and optimizing overall operating costs.

Monthly Complementarity

Offshore Wind as a Hydrological Hedge

OFW and EERs reveals high negative correlations, indicating a significant level of hydro-wind complementarity in a monthly basis. This suggests that periods of low hydro intensity can be complemented by periods of high OFW intensity, resulting in operational' system benefits.



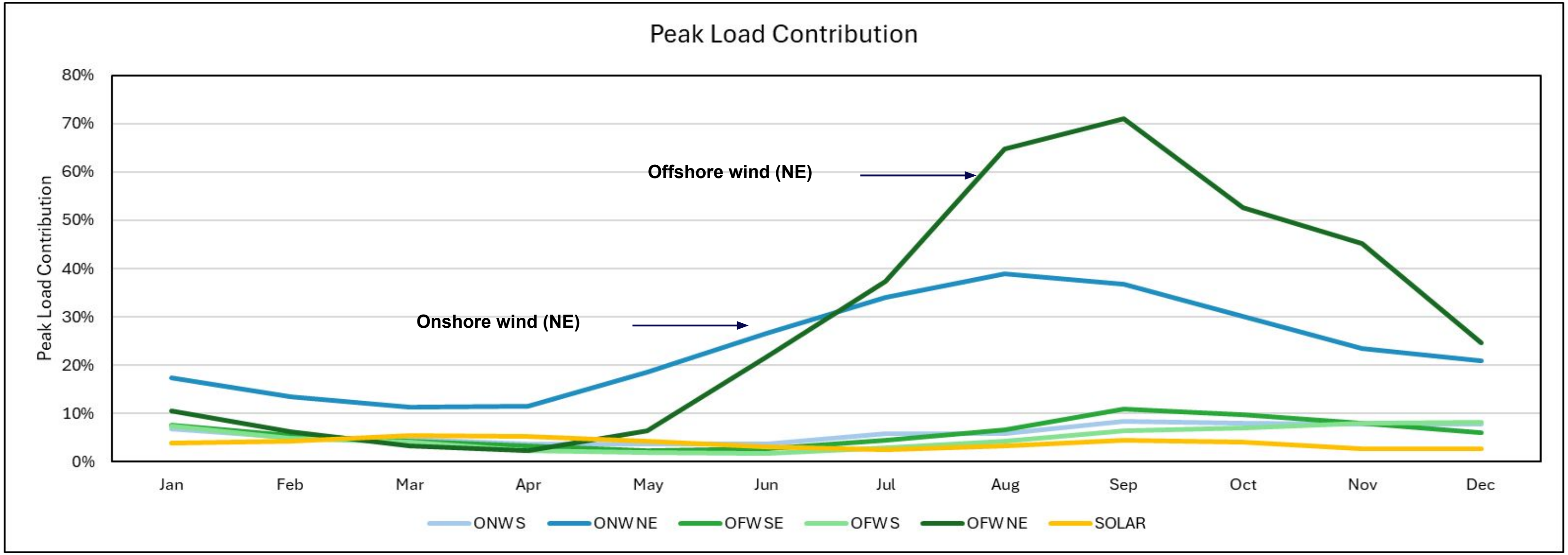
Reliability Metrics

Offshore Outperforms Onshore Wind in Peak Contribution

- While offshore and onshore wind share similar seasonal patterns, offshore capacity factors are significantly and consistently higher.
- Peak Load Contribution: During the most critical dry months (August to October), offshore wind delivers nearly double the reliable firm capacity of onshore wind.
- Solar power contribution is notably low, primarily due to the requirement for firm capacity during peak load hours. Offshore wind in the South and Southeast regions holds a slight advantage over solar power regarding peak demand contribution.
- System Value: In the Northeast, OFW peak contribution reaches up to 71%.

Reliability Metrics

Offshore Outperforms Onshore Wind in Peak Contribution



During the critical late dry season, offshore wind delivers nearly double the reliable peak load capacity compared to onshore wind.

Complementarity Analysis

Conclusions

- **Regional Profiles**: Offshore wind in the Northeast have higher capacity factors and seasonal variability (with a nighttime peak), while the Southeast and South show lower daily generation fluctuations.
- **Solar Synergy**: There is strong hourly complementarity between offshore wind (especially in the South and Southeast) and solar PV; combining nighttime wind with daytime solar optimizes transmission line utilization.
- **Load Ramp Support**: Offshore production intensifies precisely as solar generation declines and system demand rises rapidly, providing the necessary capacity to follow the ramp.
- **Transition Stability**: Despite intrinsic source variability, offshore energy injections serve as a beneficial counterbalance during system load transition periods.
- **Proximity to Demand**: Offshore development in the Southeast, near Brazil's largest load centers, helps reduce technical losses and transmission tariffs.

Complementarity Analysis

Conclusions

- **Hydrological Complementarity:** Offshore wind complements hydroelectric inflows (ENA), as winds are typically stronger during the dry season in major river basins.
- **Regularization and Flexibility:** Offshore integration supports hydrothermal regularization and reservoir storage in the North, Northeast, and Southeast, increasing system flexibility as intermittent sources grow.
- **Strategic Resilience:** In summary, offshore wind could be a key resource for the security of the National Interconnected System (SIN), as it mitigates hydrological risks, improves reservoir management, and reduces the need for thermal backup.
- **Continued Studies:** Subsequent investigations (Phases 2 and 3) continued the analysis of the aforementioned energy complementarities.

Capacity Expansion

System Optimization Scenarios

Linear Optimization Model Coupled with NEWAVE

Methodology

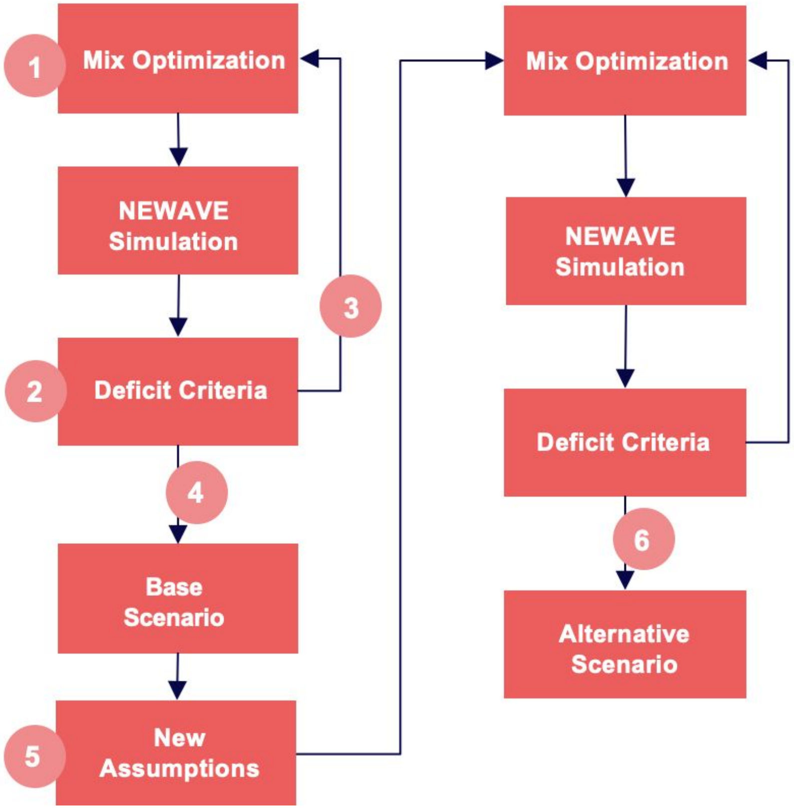
Overview of the methodology applied for scenario modeling and system optimization.

- **Initial Optimization (Step 1):** An initial optimization is performed in a Python model to define the addition of new generation sources and the expansion of transmission interconnections. The objective is to minimize total system costs (investment and operation) while incorporating peak capacity and energy balance constraints.
- **Detailed Simulation (Step 2):** The resulting generation mix is then simulated in NEWAVE to provide a detailed representation of seasonal effects, load-block modulation, and hydroelectric reservoir operation. This step is essential to properly internalize indirect costs and the Marginal Operating Cost (CMO).
- **Risk Adjustment & Base Scenario (Steps 3 & 4):** Based on the NEWAVE results, additional constraints are identified and fed back into the initial Python model. This iterative process continues (averaging 2 to 3 iterations) until the target deficit criterion (90% power adequacy requirement) is met. Once this acceptable risk level is aligned, the optimal Base Scenario is established.
- **Alternative Scenarios (Steps 5 & 6):** To test different hypotheses, new assumptions are introduced. The same iterative procedure is followed, adding constraints to the matrix until the alternative scenarios reach the exact same risk level (deficit criterion) as the Base Scenario, ensuring a standardized baseline for comparison.

Linear Optimization Model Coupled with NEWAVE

Methodology

The core strength of this methodology lies in bridging long-term expansion economics with dispatch realities. By iteratively stress-testing our investment decisions through NEWAVE, we sought to ensure that each proposed scenario was economically viable, systemically coherent, and adapted to the complex hydrothermal dynamics of the Brazilian electricity grid.



CAPEX Assumptions

Ocean Energy Pathway

Offshore wind power (OFW) has high costs compared to other sources, being lower only than coal-fired thermal power, nuclear power, and other CCS options.

Cost projections for 2050 (ref. NREL) indicate that offshore wind power has a 30% reduction margin as it matures, narrowing the gap with other sources.

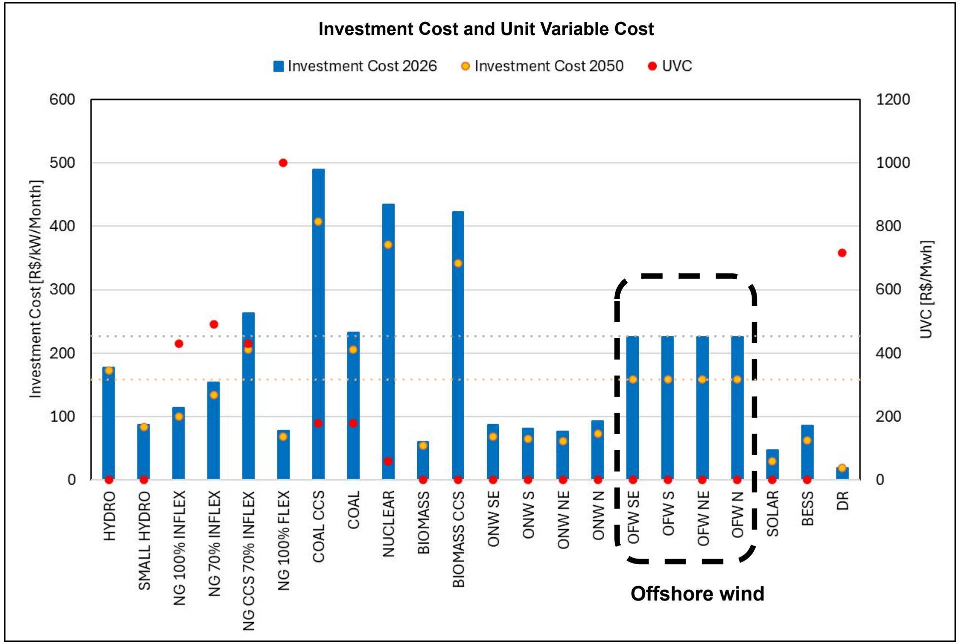
- OFW shows high investment costs in 2026 (R$225/kW/month), with 30% reduction by 2050.
- Onshore wind (ONW) and Solar remain among the lowest-cost options, combining low CAPEX and zero variable cost.
- Thermal plants (NG, coal, nuclear) present high variable cost, especially coal and gas with CCS, increasing total system cost despite dispatch flexibility.
- Biomass and hydro offer a balanced profile, with moderate investment costs and low variable costs.
- Cost reductions toward 2050 are more pronounced for capital-intensive technologies (e.g., offshore wind and CCS), with greater margin for maturation.

The 2050 Learning Curve

CAPEX Assumptions

Investment Cost Expectations of Candidate Sources (2026 vs 2050)

Projected monthly costs for the sources considered as options for expanding the energy mix



Note: For thermal sources, the unit variable cost (UVC) is also considered.
Applying global learning curves, it is projected a 30% cost reduction by 2050, forming the basis of simulations/optimizations.

Grid Expansion Cost

In the model's decision-making process regarding system expansion, the costs of expanding the transmission system between submarkets are considered. The greater the distance between submarkets, the higher the cost of expanding the grid between them.

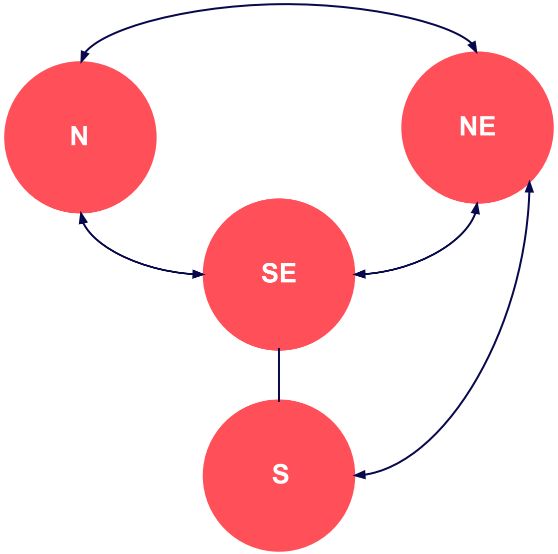
That is, if the model indicates an expansion of supply in the Northeast (NE) to supply the Southeast (SE), the model implicitly considers the cost of expanding the source plus the cost of expanding the NE-SE transmission.

Grid Expansion Cost

The greater the distance between submarkets, the higher the cost of expanding the grid between them. The model optimization takes these costs into account when selecting the generation sources for the mix.

Note on Grid representation:

- **Grid Optimization Baseline:** The initial network configuration and parameters are established based on the PMO (Monthly Operation Program) data.
- **Expansion Decision-Making:** Using these reference costs, the model evaluates the energy balance to determine if additional grid capacity is required to minimize overall system costs.
- **Interconnection Cost Matrix:** Transmission costs between submarkets (N, NE, SE, S) are factored into the optimization, with the S-NE link currently presenting the highest expansion or usage cost at 71.50 R$/kW/month.
- Despite its simplified nature, this modeling approach effectively captures the distinct seasonal profiles of the energy sources within each submarket.



Overview of the 8 Strategic Scenarios (2050)

Reference

Scenario	Name	Detailed Description
Scen. 1	Base Scenario	Baseline case considering economic assumptions, supply limits for each generation source, energy and peak demand constraints, as well as source-specific CAPEX with differentiated learning rates. These assumptions lead to the definition of the optimal installed capacity* for the Brazilian Interconnected System (SIN) in 2050.

Additional Capacity

Scenario	Name	Detailed Description
Scen. 2	18 GW OFW	Designed to assess the impact on total system cost considering the addition of 18 GW of offshore wind (OFW) capacity.
Scen. 6	34 GW OFW	Considers the gradual integration of 34 GW of OFW capacity into the generation mix among 2040 and 2050.

Overview of the 8 Strategic Scenarios (2050)

Ocean Energy Pathway

Cost Sensitivity

Scenario	Name	Detailed Description
Scen. 3	Breakeven	Aims to determine the cost reduction level (Breakeven) at which OFW (considering CAPEX, O&M, and associated charges) becomes economically viable by 2050 in the SIN. Cost reductions by submarket.
Scen. 4	1% Cost Reduction	Assesses the impact of a 1% reduction in OFW costs to determine the resulting installed capacity, the updated cost level, and which generation sources are displaced.**
Scen. 5	1% Cost Increase	Evaluates a 1% increase in OFW costs while constraining the system to maintain the same capacity addition as in Scenario 4, to assess the resulting Total System Cost.**

Note: CAPEX and OPEX variations applied uniformly over the baseline.

Environmental Factors

Scenario	Name	Detailed Description
Scen. 7	Emissions Reduction	Scenario in which the objective function is modified to minimize greenhouse gas (GHG) emissions.
Scen. 8	Climate Change	Base scenario incorporating climate change impacts, compared against a compensatory scenario with the addition of OFW capacity.***

** **Optimal Capacity:** Defined as the result of a linear optimization model that minimizes total system costs, including generation expansion (CAPEX), transmission expansion between submarkets (SE, S, NE, and N), and operational costs. The model is implemented in Python using linear optimization and refined through NEWAVE simulations.*

*** **Sensitivity Scenarios:** In these scenarios, operational costs were not refined using NEWAVE.*

**** Considers restricted hydrological projections and long-term stress scenarios established in the literature.*

Scenario 1

Reference

Scenario	Name	Detailed Description
Scen. 1	Base Scenario	Baseline case considering economic assumptions, supply limits for each generation source, energy and peak demand constraints, as well as source-specific CAPEX with differentiated learning rates. These assumptions lead to the definition of the optimal installed capacity* for the Brazilian Interconnected System (SIN) in 2050.

*** Optimal Capacity:** *Defined as the result of a linear optimization model that minimizes total system costs, including generation expansion (CAPEX), transmission expansion between submarkets (SE, S, NE, and N), and operational costs. The model is implemented in Python using linear optimization and refined through NEWAVE simulations.*

Ocean Energy Pathway

Base Scenario

Scenario 1

Takeaways

- Capital-Intensive Baseline (BRL 1.4 Trillion): Expansion is heavily driven by new capacity (73% CAPEX). To keep OPEX stable, the model prioritizes local submarket adequacy, avoiding major interregional transmission investments.
- The Intermittency Challenge: The low peak contribution of renewables demands a much higher capacity-to-demand ratio, forcing a massive reliance on Battery Storage (BESS) and Demand Response.
- Supply & Growth Bottlenecks: Competitive solar and onshore wind face annual growth caps, a challenge compounded by the severe lack of new, viable hydroelectric and biomass projects.

Scenario 1

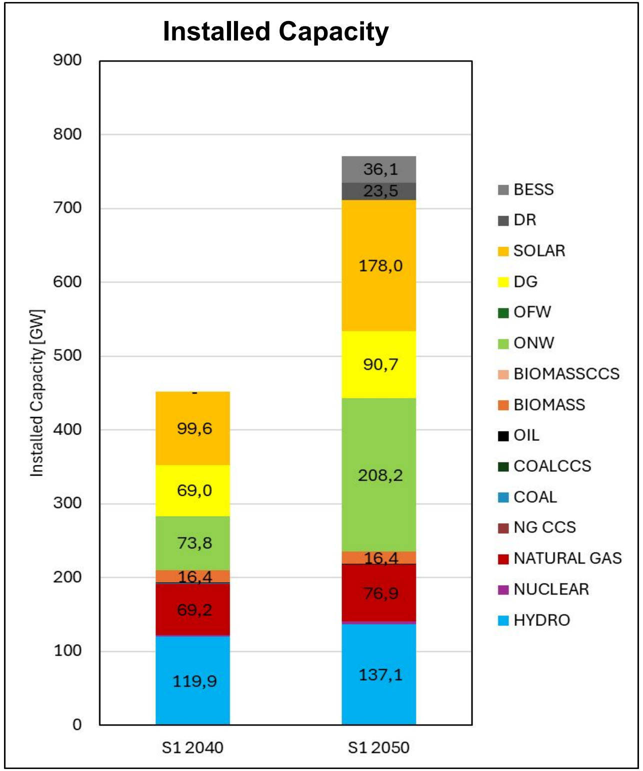
Base Scenario Reveals Heavy Reliance on Intermittency and BESS

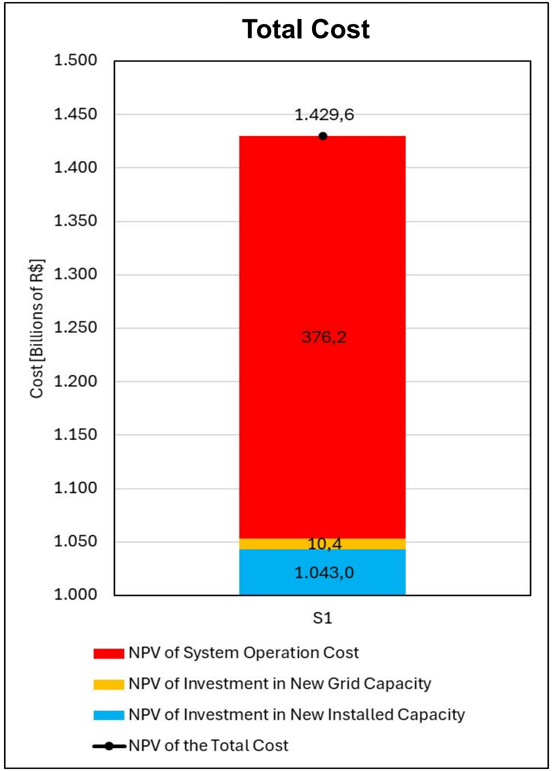
The 2050 baseline simulation projects a BRL 1.4 trillion system cost focusing on local submarket power adequacy with minimal interregional links. To manage renewable intermittency, the system dictates a higher capacity-to-demand ratio, fueling substantial growth in solar, onshore wind, Battery Energy Storage System (BESS), and demand response. At current cost projections, offshore wind does not enter the 2050 mix organically without policy constraints.

- **Capacity-to-Demand Ratio**: Significant increase in the installed capacity-to-demand ratio, primarily due to the limited peak-contribution of intermittent sources.
- **Renewable Expansion**: Solar and onshore wind are highly competitive; however, their total capacity is capped by predefined maximum annual growth rates.
- **Supply Constraints:** Biomass and hydroelectric sources remain cost-effective but are limited by the low availability of new viable projects.
- **Energy Storage & Demand Side**: Substantial growth in BESS (Battery Energy Storage Systems) and Demand Response is projected by 2050.
- **System Cost Breakdown:** Total system cost for Scenario 1 reaches BRL 1.4 trillion, with 73% allocated to new capacity investments (CAPEX).
- **Operational Stability**: Operating costs (OPEX) remain stable as minimal additional thermal capacity is dispatched.
- **Regional Power Constraints**: Low investment in interregional links, as the model prioritizes addressing power adequacy requirements within each individual submarket.

Scenario 1

Base Scenario Reveals Heavy Reliance on Intermittency and BESS





18 GW Offshore Wind

Additional Capacity

Scenario	Name	Detailed Description
Scen. 2	18 GW OFW	Designed to assess the impact on total system cost considering the addition of 18 GW of offshore wind (OFW) capacity. Addition of 18 GW of Offshore Wind (constraint), total available capacity defined according to the Phase 1 transmission margin study, allocated as follows: **9.5 GW in the Southeast, 2.5 GW in the Northeast, 6.0 GW in the South**

Scenario 2

18 GW Offshore Wind

Takeaways

- Integrating 18 GW of offshore wind increases total system costs by a marginal 1.3% (BRL 18.8 billion), proving highly viable as grid savings offset the technology's integration costs.
- Allocating capacity primarily in the South and Southeast displaces remote Northeast onshore wind, bringing power directly to major load centers and drastically reducing transmission requirements.
- The optimized grid architecture keeps operational costs entirely stable, requiring only a minimal 1 GW of Battery Energy Storage (BESS) for local balancing.

Scenario 2

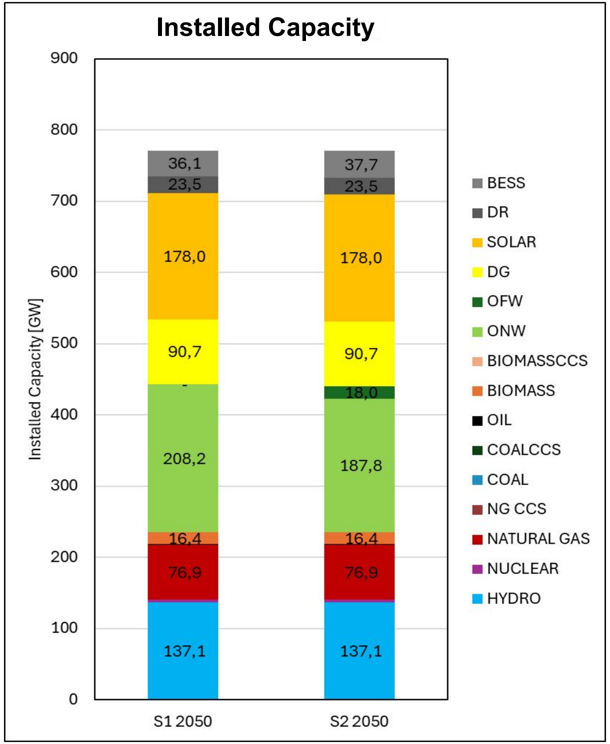
18 GW Offshore Wind Integration Achieves Grid OPEX Neutrality

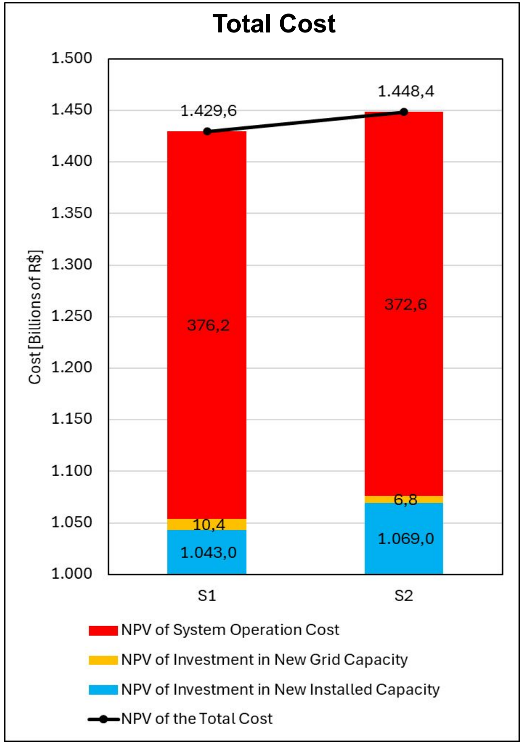
The integration of 18 GW of OFW capacity emerges as a viable alternative, proving economically feasible because grid-related savings largely offset the technology's integration costs. By strategically allocating the new capacity—mainly in the South and Southeast—to displace onshore wind in the Northeast, generation is brought closer to major load centers, which drastically reduces transmission requirements. As a result of these transmission savings, combined with stable operational costs and a 1 GW need for battery storage (BESS) for local balancing, the total system cost increases by BRL 18.8 billion. This represents a minimal variance of 1.3% (ref. scenario), confirming the economic viability of the grid optimization.

- **Grid Optimization via Strategic Relocation:** Displacing Northeast (NE) onshore wind with South and Southeast (S/SE) offshore projects drastically reduces transmission requirements by bringing generation closer to major load centers.
- **System Balancing & Reliability Adjustments:** This shift necessitated a marginal 1 GW increase in BESS capacity, acting primarily as a local adjustment to support the new power configuration.
- **Operational Cost Neutrality:** SIN operating costs remain stable, as the offshore wind integration does not significantly impact the existing thermal dispatch or baseline OPEX.
- **Economic Feasibility:** The total system cost increased by only BRL 18.8 billion (a 1.3% variance), indicating that grid-related savings can offset the integration costs of the offshore capacity.

Scenario 2

18 GW Offshore Wind Integration Achieves Grid OPEX Neutrality





Breakeven, 1% Cost Reduction and 1% Cost Increase

Ocean Energy Pathway

Cost Sensitivity

Scenario	Name	Detailed Description
Scen. 3	Breakeven	Aims to determine the cost reduction level (Breakeven) at which OFW (considering CAPEX, O&M, and associated charges) becomes economically viable by 2050 in the SIN. Cost reductions by submarket.
Scen. 4	1% Cost Reduction	Assesses the impact of a 1% reduction in OFW costs to determine the resulting installed capacity, the updated cost level, and which generation sources are displaced.**
Scen. 5	1% Cost Increase	Evaluates a 1% increase in OFW costs while constraining the system to maintain the same capacity addition as in Scenario 4, to assess the resulting Total System Cost.**

Note: CAPEX and OPEX variations applied uniformly over the baseline.
*** Sensitivity Scenarios: In these scenarios, operational costs were not refined using NEWAVE.*

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

Takeaways

- Breakeven (S3): To enter the mix organically, variable costs must drop by 62% to 81 R$/kW/m (NE), 48% to 98 R$/kW/m (SE), and 42% to 106 R$/kW/m (S). At this threshold, 10.1 GW is adopted naturally.
- High Elasticity (S4): A mere 1% further CAPEX reduction drives optimal capacity to 16.8 GW.
- Capital Substitution: Offshore wind displaces grid expansions, dropping transmission CAPEX from 10.4B to 7.3B.

Ocean Energy Pathway

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

- **Sensitivity Analysis of Offshore Wind Costs:** The monthly cost (R$/kW/month) of offshore wind was reduced in 1% increments until the optimization model selected its inclusion in the 2050 generation mix.
- **Submarket-specific Execution:** This procedure was performed individually for each submarket (NE, SE, and S).
- **Integrated Scenario (Scenario 3 - Breakeven):** Subsequently, a combined scenario was developed where the cost reductions were applied simultaneously across all three submarkets.
- **Lower Bound Sensitivity (Scenario 4 – 1% Cost Reduction):** For this scenario, the cost was further reduced by an additional 1% from the threshold identified in Scenario 3, followed by the respective simulations.
- **Upper Bound Sensitivity (Scenario 5 – 1% Cost Increase):** For this scenario, a constraint was applied forcing the same OFW capacity found in Scenario 4, but with a 1% higher cost premium.

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

Sensitivity Analysis of Offshore Wind Costs and **Submarket-specific execution (NE, SE, and S)**

To determine when offshore wind can enter the 2050 generation mix, the study used the Baseline (Scenario 1) as a total cost reference. Considering the 2026-2050 learning curve, offshore wind costs were gradually reduced in individual submarket simulations until they became economically competitive against the baseline.

The model identified that reaching these regional tipping points requires significant, variable cost reductions from 2026 values: 62% for the Northeast, 48% for the Southeast, and 42% for the South. Ultimately, these established competitiveness thresholds serve as the foundation for Scenarios 3 and 4, allowing the model to prioritize offshore wind for regional power adequacy.

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

- **Regional Competitiveness Thresholds:** To enter the generation mix by 2050, offshore wind required significant cost reductions compared to the 2026 baseline.
- **The Northeast (NE)** submarket showed the highest required discount at 62%.
- **Variable Reduction Rates**: The optimization model identified different "tipping points" for each submarket. While the NE required a drastic 62% cut, the Southeast (SE) and South (S) submarkets became competitive with lower reductions of 48% and 42%, respectively.
- **Sensitivity Basis:** These discounted values served as the foundation for Scenario 3 (combined reduction) and Scenario 4 (lower bound), allowing the model to prioritize offshore wind as a strategic resource for regional power adequacy.

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

The monthly cost values obtained:

	Type	Submarket	Learning Rate CAPEX	Learning Rate O&M	Reduction	Monthly Investment Cost R$/kW/month 2026	Monthly Investment Cost R$/kW/month 2050
	EOL-OFF	SE	2,455%	0,664%	0%	226	158
	EOL-OFF	SE	2,455%	0,664%	-48%	117	98
	EOL-OFF	S	2,455%	0,664%	0%	226	158
	EOL-OFF	S	2,455%	0,664%	-42%	131	106
Reference -	EOL-OFF	NE	2,455%	0,664%	0%	226	158
Reduction -	EOL-OFF	NE	2,455%	0,664%	-62%	86	81

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

South Submarket: In the South, where offshore wind became viable at BRL 131/kW/month, several combinations of potential cost reductions are available, particularly regarding sectoral charges.

Southeast Submarket: The Southeast requires a more significant reduction (BRL 117/kW/month; 48%); however, there are still viable combinations of cost-drivers that can be explored.

Northeast Submarket: The Northeast faces the greatest challenge (reduce to BRL 86/kW/month; 62%) due to direct competition with onshore wind, which exerts extreme pressure on all cost components.

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

Type	Submarket	Reduction	Monthly Invest. Cost R$/kW/month 2026	Monthly Invest. Cost R$/kW/month 2050
EOL-OFF	SE	-48%	117	98
EOL-OFF	S	-42%	131	106
EOL-OFF	NE	-62%	86	81

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

Offshore Wind Monthly Cost as a function of variations in CAPEX, Charges and O&M

CAPEPX [R$/kW]	O&M=338 [R$/kW.year]				O&M=288 [R$/kW.year]				O&M=238 [R$/kW.year]			
Sectoral Charges [R$/kW.year]	630	530	430	330	630	530	430	330	630	530	430	330
15.600	225,8	217,1	208,4	199,7	221,4	212,8	204,1	195,4	217,1	208,4	199,7	191,0
14.600	216,7	208,0	199,3	190,6	212,4	203,7	195,0	186,3	208,0	199,3	190,6	182,0
13.600	207,6	198,9	190,2	181,6	203,3	194,6	185,9	177,2	198,9	190,2	181,6	172,9
12.600	198,5	189,8	181,2	172,5	194,2	185,5	176,8	168,1	189,8	181,2	172,5	163,8
11.600	189,4	180,8	172,1	163,4	185,1	176,4	167,7	159,0	180,8	172,1	163,4	154,7
10.600	180,4	171,7	163,0	154,3	176,0	167,3	158,6	150,0	171,7	163,0	154,3	145,6
9.600	171,3	162,6	153,9	145,2	166,9	158,3	149,6	140,9	162,6	153,9	145,2	136,5
8.600	162,2	153,5	144,8	136,1	157,9	149,2	140,5	131,8	153,5	144,8	136,1	127,5
7.600	153,1	144,4	135,7	127,1	148,8	140,1	131,4	122,7	144,4	135,7	127,1	118,4
6.600	144,0	135,3	126,7	118,0	139,7	131,0	122,3	113,6	135,3	126,7	118,0	109,3

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase

At a breakeven threshold (S.3), 10 GW of Offshore Wind successfully enters the 2050 generation mix, while a mere 1% further cost reduction (S.4) drives this capacity to 16 GW. Integrating OFW proves highly efficient, as it maintains stable system operation costs at BRL 375 billion by displacing other capital-intensive investments—like onshore wind and transmission—rather than increasing day-to-day grid expenses.

By strategically concentrating OFW in the South and Southeast, the model avoids high regional interconnection costs, significantly reducing the required investment in new grid capacity from BRL 10.4 billion to BRL 7.3 billion. Ultimately, alongside the structural necessity of Demand Response (23.5 GW) and BESS (~37 GW) across all scenarios, OFW works synergistically with storage to reduce overall expenditures on interconnection capacity expansion.

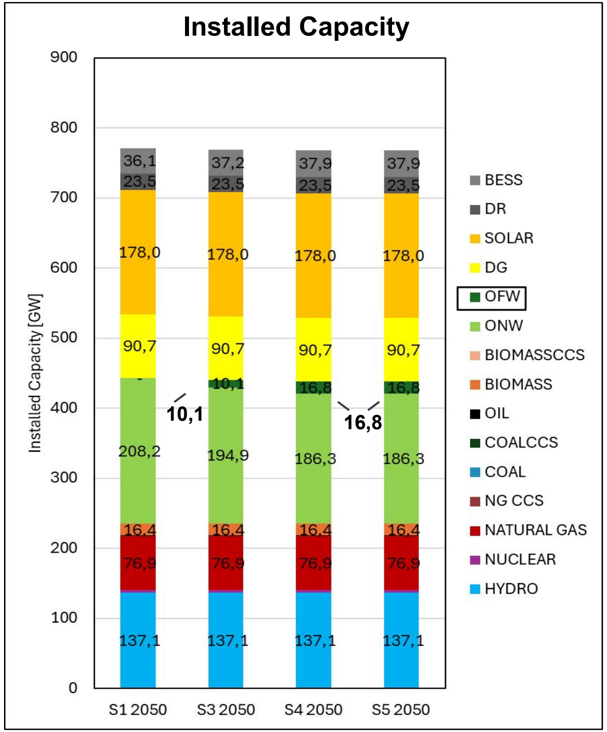
Scenarios 3, 4 and 5

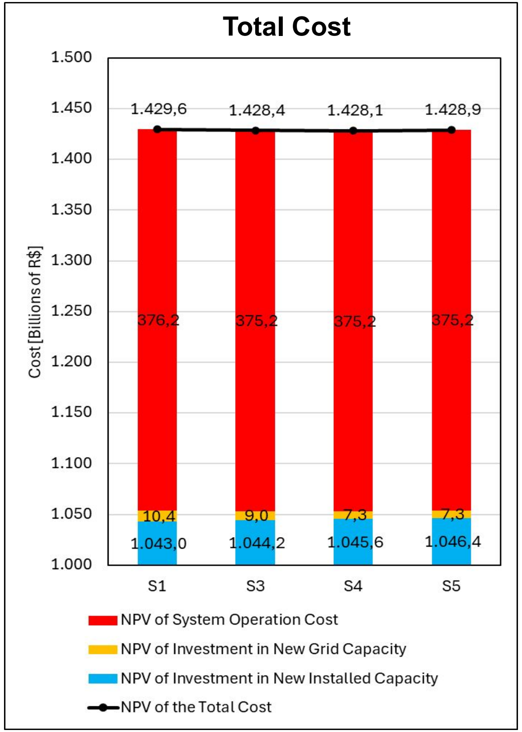
Breakeven, 1% Cost Reduction and 1% Cost Increase

- **Scenario 3 (Breakeven):** This represents the equivalent cost scenario, sitting at the threshold of OFW entry, with a total cost very close to Scen. 1. In this case, the optimization model added 10 GW of OFW to the generation mix.
- **Scenario 4:** By reducing the OFW cost found in Scenario 3 by an additional 1%, the installed capacity reached 16 GW by 2050.
- **Transmission Avoidance:** The interconnection cost matrix shows high expansion costs (up to 71.50 R$/kW/month for S-NE). By increasing OFW in the South and Southeast, the model reduces the "NPV of Investment in New Grid Capacity" from BRL 10.4 billion (S1) to BRL 7.3 billion (S4/S5).
- **CAPEX vs. OPEX Balance:** Across scenarios 1 and 3, the System Operation Cost remains stable (BRL 375B). This indicates that the entry of OFW primarily displaces other capital-intensive investments (like ONW or Transmission) rather than increasing the cost of running the grid.
- **Flexibility and Storage Integration.** The consistent presence of Demand Response (23.5 GW) and growing BESS (~37 GW) across all scenarios indicates that storage is a structural requirement for high-renewable systems, regardless of whether the wind is onshore or offshore. OFW, combined with BESS, contributes to reducing expenditures on interconnection capacity expansion.

Scenarios 3, 4 and 5

Breakeven, 1% Cost Reduction and 1% Cost Increase





Note: Operational Cost Assumptions: Scenarios 4 and 5 did not undergo NEWAVE refinement; instead, the system operation costs from Scenario 3 were utilized as a baseline.

Scenario 6

34 GW Offshore Wind

Additional Capacity

Scenario	Name	Detailed Description
Scen. 6	34 GW OFW	Considers the gradual integration of 34 GW of OFW capacity into the generation mix among 2040 and 2050.

Scenario 6

34 GW Offshore Wind

Main results:

- Injecting 33.7 GW (32.3 GW in S, 1.4 GW in SE) increases total system NPV by only 1.8% (BRL 25 billion).
- Decentralization Asset: Generating power directly at major load centers drives new interconnection capacity costs down from BRL 10.4 billion to just BRL 4.0 billion.
- The Brazilian grid architecture is highly robust and capable of absorbing massive coastal generation with marginal financial variance.

Scenario 6

34 GW Offshore Wind High Penetration Proves System Robustness

By initially scaling down costs to integrate approx. 34 GW of offshore wind and subsequently setting this as a constraint at full cost parameters, the study evaluated a high-penetration scenario that added 33.7 GW of OFW to the system (32.3 GW in the South and 1.4 GW in the Southeast).

Although this extensive expansion led to a nominal system cost increase of BRL 25 billion, the financial impact remains marginal, representing a variance of only 1.8% relative to the total system NPV.

Importantly, the strategic placement of this offshore wind capacity in the South and Southeast significantly minimized interregional power flow requirements, optimizing grid infrastructure by driving interconnection capacity expansion costs down from BRL 10.4 billion to just BRL 4 billion.

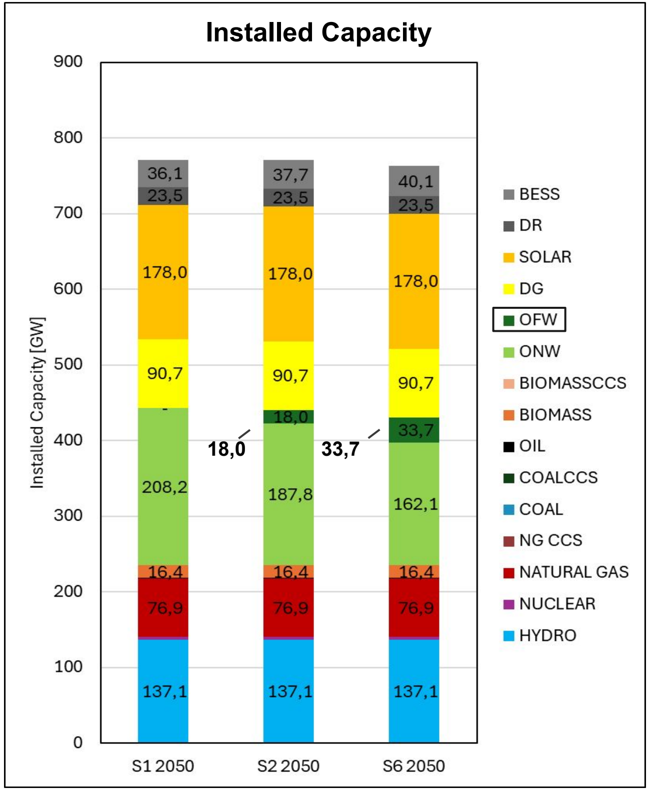
Scenario 6

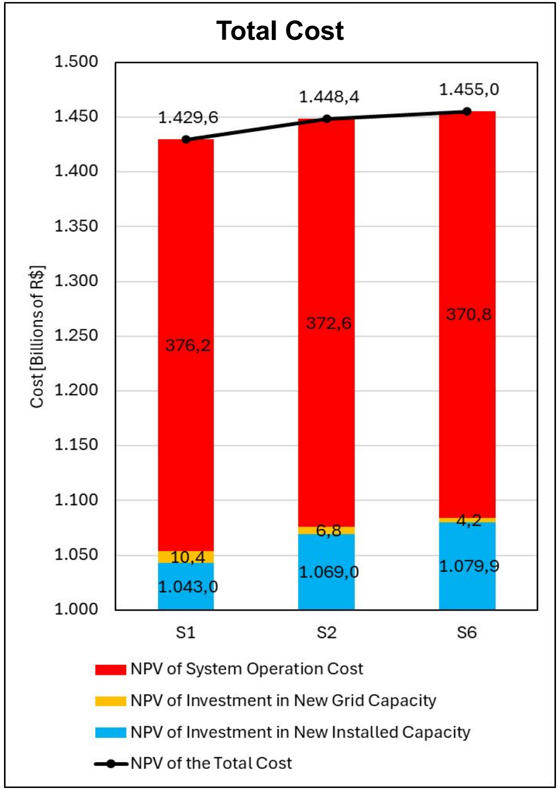
34 GW Offshore Wind High Penetration Proves System Robustness

- **Offshore Capacity Expansion:** A total of 33.7 GW of offshore wind was added to the system, comprising 32.3 GW in the South and 1.4 GW in the Southeast. This expansion led to a BRL 25 billion increase in total system cost.
- **Marginal Financial Impact:** Despite the BRL 25 billion nominal increase, this represents a variance of only 1.8% relative to the total system NPV.
- **Grid Infrastructure Optimization:** The strategic placement of offshore wind in the South and Southeast reduced interconnection capacity expansion costs from BRL 10.4 billion to BRL 4 billion, significantly minimizing interregional power flow requirements.

Scenario 6

34 GW Offshore Wind High Penetration Proves System Robustness





Ocean Energy Pathway

Scenarios 1, 2 and 6

Hydrothermal Impact Analysis

Comparative analysis of 18 GW and 34 GW OFW configurations to evaluate their impact on system-wide reservoir storage levels.

- Integrating 18 GW and 34 GW configurations structurally reinforces hydro reservoir levels.
- Average Storage Gains: Reservoir levels increase by 1.5% (S.2) and 2.6% (S.6) in the final simulation year.
- Stress Resilience: Under 1st percentile drought conditions, storage levels increase by up to 4.9% (S.2) and 7.3% (S.6). It means, in severe droughts, reservoirs hold up to 7.3% more water simply because offshore wind is carrying the load.
- Financial Impact: Higher storage lowers the opportunity cost of water, significantly reducing Marginal Operating Costs (CMO).

Scenarios 1, 2 and 6

Hydrothermal Impact Analysis

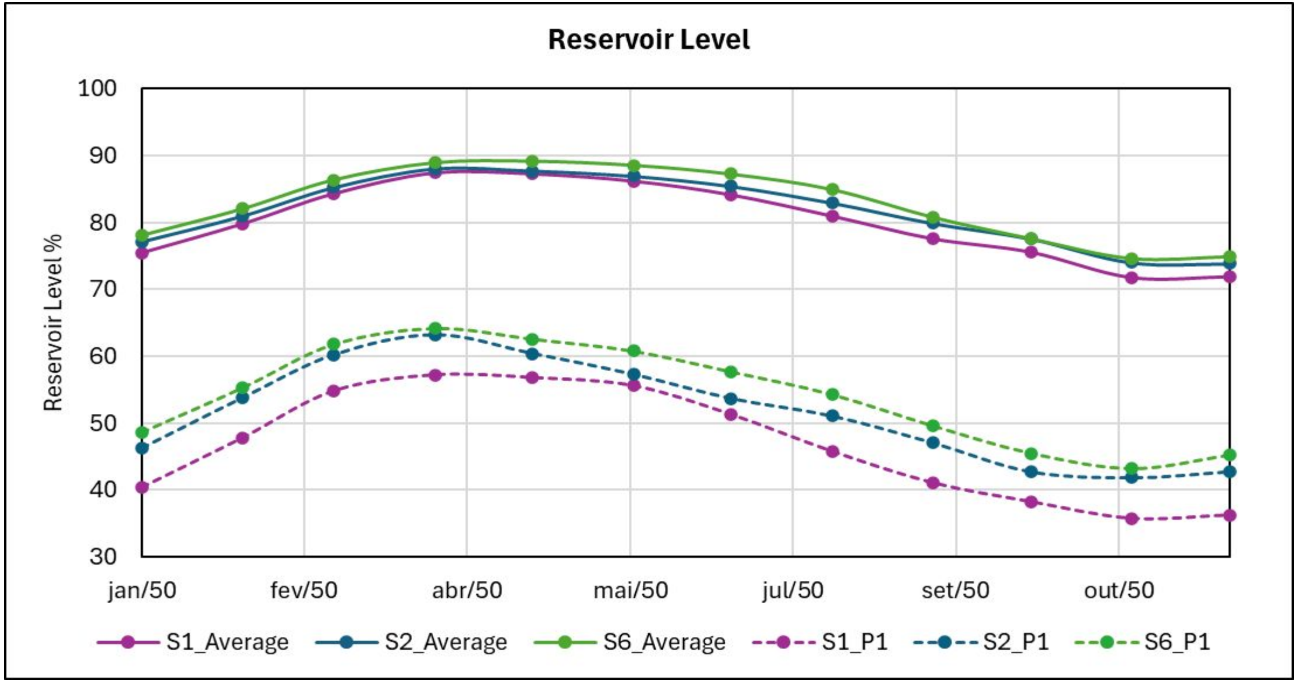
- **Economic Variance:** Total system costs for the OFW scenarios are only 1.3% and 1.8% higher than the baseline, representing a marginal relative variation.
- **Storage Preservation Synergy:** The integrated offshore configuration significantly reinforces reservoir levels. This effect is driven by the strategic shift from onshore to offshore capacity, increased BESS integration, and reduced grid expansion requirements.
- **Average Storage Gains:** In the final simulation year, the average reservoir levels increased by 1.5% (Scenario 2) and 2.6% (Scenario 4) compared to the baseline.
- **Resilience in Critical Scenarios:** Under stress conditions (1st percentile of 2,000 synthetic series), the benefits are even more pronounced, with storage levels increasing by 4.9% and 7.3% in Scenarios 2 and 4, respectively.
- **Economic Benefit Monetization:** The value of enhanced reservoir storage is captured within the system's operating costs (OPEX). Higher storage levels lead to a lower opportunity cost of water, which in turn reduces the Marginal Operating Cost (CMO) and the overall system operation expenditure.

Scenarios 1, 2 and 6

Hydrothermal Impact Analysis

	S1_Avg	S1_P1	S2_Avg	S2_P1	S6_Avg	S6_P1
2050 Average	80,2%	46,8%	81,7%	51,7%	82,8%	54,1%
Variation to S1	0,0%	0,0%	1,5%	4,9%	2,6%	7,3%

Avg (Average) ; P1 (Percentile 1%); S1 (reference scenario); S2 (18 GW scenario); S6 (34 GW scenario)



Scenario 7

Emissions Reduction

Environmental Factors

Scenario	Name	Detailed Description
Scen. 7	Emissions Reduction	Scenario in which the objective function is modified to minimize greenhouse gas (GHG) emissions. To emulate an Environmental Externality Pricing, a penalty was integrated into the objective function, assigning a carbon value high enough to prioritize GHG reduction over total system expenditure.

Scenario 7

Emissions Reduction

Takeaways:

- Applying a severe carbon penalty forces the phase-out of thermal dispatch and minimizes GHG emissions.
- Organic Integration: Offshore wind enters the optimal mix organically, reaching 9.5 GW by 2050 due to its firm, low-carbon profile.
- The Cost of Decarbonization: Achieving a 45% emission reduction requires a BRL 470 billion system investment (a 32% CAPEX increase), largely driven by a 2.4x surge in BESS capacity.

Scenario 7

Carbon-Constrained Optimization Reconfigures the Matrix

The main result is the structural Matrix Reconfiguration. While the total installed capacity remains nearly identical to Scenario 1, the generation mix is significantly rebalanced toward low-carbon sources. OFW enters the optimal mix in 2048, reaching 9.5 GW by 2050 solely based on its competitive profile within a carbon-constrained framework.

If Brazil mandates net-zero, OFW enters organically with 9.5 GW. However, completely phasing out thermal plants requires a massive 32% increase in total system investment over the Scenario 1 baseline.

Emission reduction targets drive a 2.4x increase in BESS capacity, primarily necessitated by the phase-out of thermal dispatch.

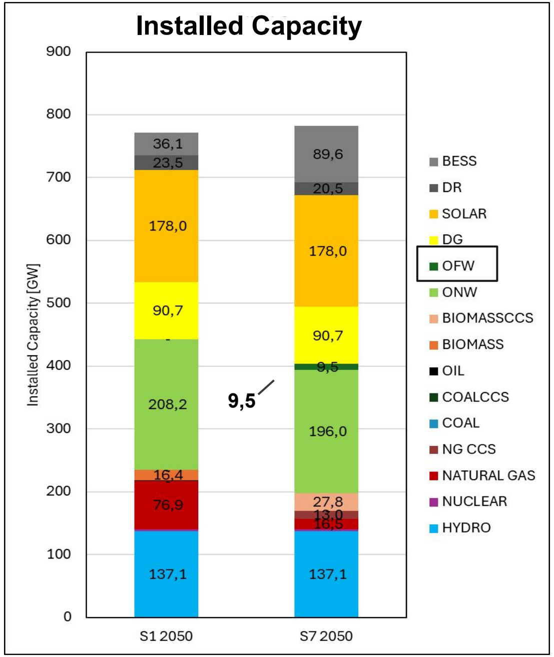
Scenario 7

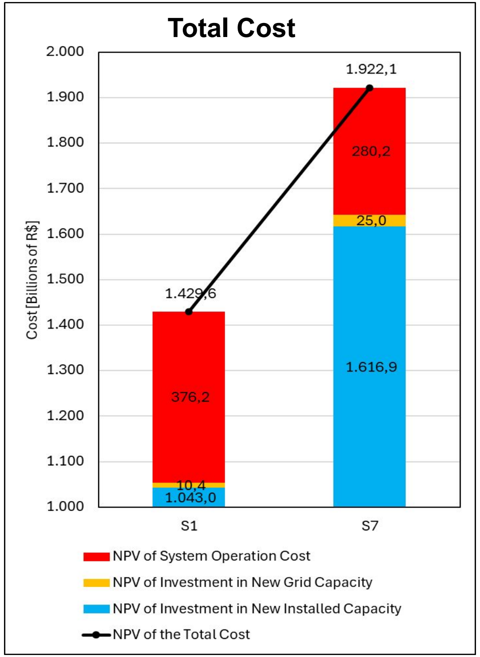
Carbon-Constrained Optimization Reconfigures the Matrix

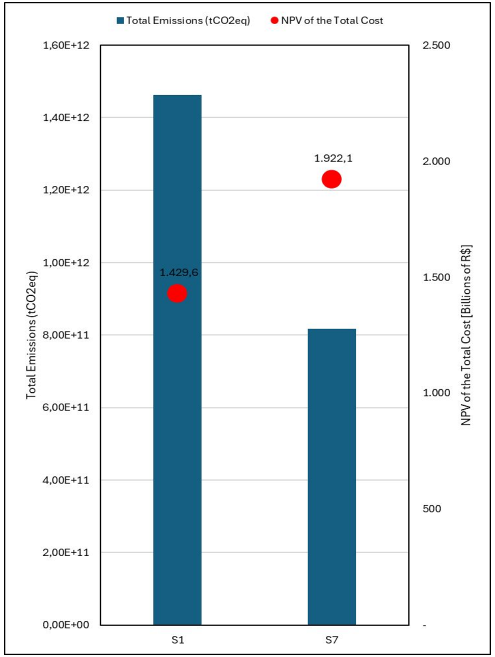
- **Cost & Infrastructure Trade-offs:** Despite a 25% decrease in operating costs (OPEX), there is a 2.5x surge in interconnection investment and a 60% overall increase in new capacity CAPEX.
- **Offshore Wind Viability:** Offshore wind enters the optimal mix in 2048, reaching 9.5 GW by 2050 solely based on its competitive profile within a carbon-constrained framework.
- **Decarbonization Investment:** Achieving a 45% reduction in total emissions (2026–2050) requires an additional system investment of BRL 470 billion, a 32% increase over the Scenario 1 baseline.

Scenario 7

Carbon-Constrained Optimization Reconfigures the Matrix







Scenario 8

Climate Change

Environmental Factors

Scenario	Name	Detailed Description
Scen. 8	Climate Change	Base scenario incorporating climate change impacts, compared against a compensatory scenario with the addition of OFW capacity.***

Note: Considers restricted hydrological projections and long-term stress scenarios established in the literature.
Note 2: The results presented in this section represent updates from the studies conducted in Phase 2.2 of this project.

Scenario 8

Climate Change

This activity aimed to assess the role of OFW in providing resilience to face climate stress scenarios that affect hydropower production. Specifically, it was investigated the contribution of OFW to displacing and conserving hydroelectric generation in drought and climate change scenarios.

Takeaways:

- Stress Model: Projects a 20% reduction in hydro inflows alongside a 4% increase in demand by 2050.
- The Cost of Inaction: Without mitigation, heavy reliance on emergency thermal dispatch causes *system operating costs* to spike by 7.8 times.
- The Hedge: Integrating 34 GW of offshore wind fully neutralizes this *system operating costs* shock, saving BRL 70 billion in thermal dispatch and maintaining system cost parity.
- Under climate change, operational costs explode by 7.8 times. Injecting 34 GW of offshore wind neutralizes that shock. The BRL 70 billion increase in overall investment is fully offset by an equivalent BRL 70 billion reduction in system operating costs (OPEX), highlighting the economic resilience.

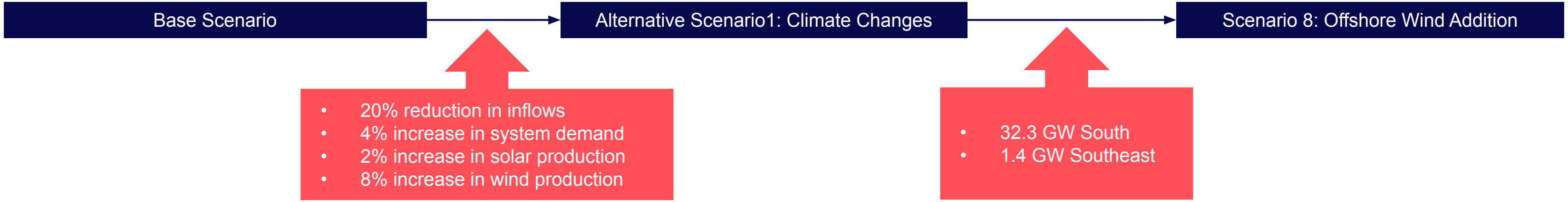
Scenario 8

Climate Change

Methodology overview

- Simulations were carried out with the same methodology as previews scenarios**.**
- The **climate change input data was** represented by the EPE study **“Impacts of Climate Change on Power Generation Planning”*, whose data were made available by EPE for this project.**
- A **stress scenario** is estimated based on NEWAVE simulations and using climate change data.
    - The stress scenario implies that a much greater installed capacity will be required to meet the same demand, due to the expected reduction in hydropower output. As a result, **it will be proposed an alternative energy mix, emphasizing the potential of OFW and other sources to offset lower hydropower generation.**

Base scenario incorporating climate change impacts, compared against a compensatory scenario with the addition of offshore wind capacity.



**EPE/PSR/Tempo OK: Projeto: “Impactos das Mudanças Climáticas no Planejamento do Setor Elétrico Brasileiro”. Produto 4, 5 e 6 –”Definição de Portfólio de Geração e Resultados Operativos” . Published: October 2025.*

Scenario 8

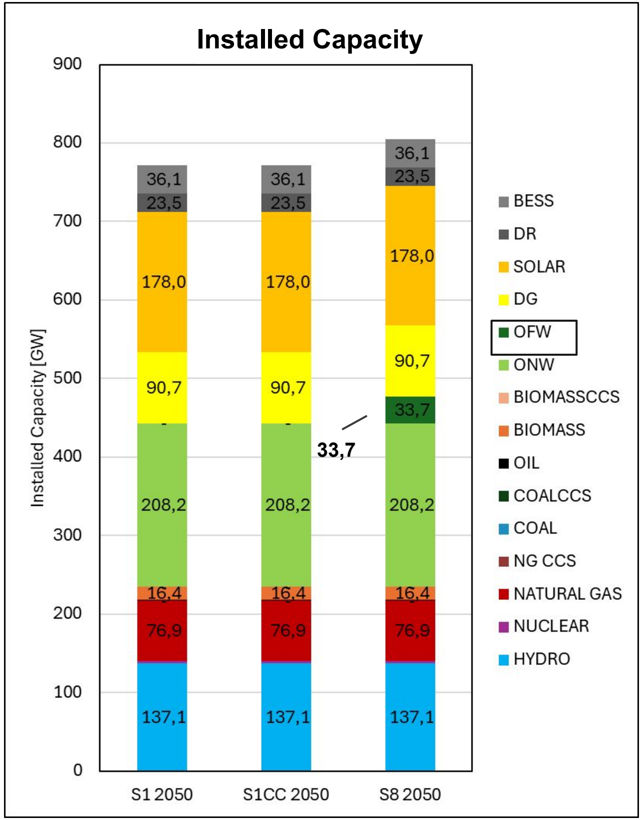
Climate Change

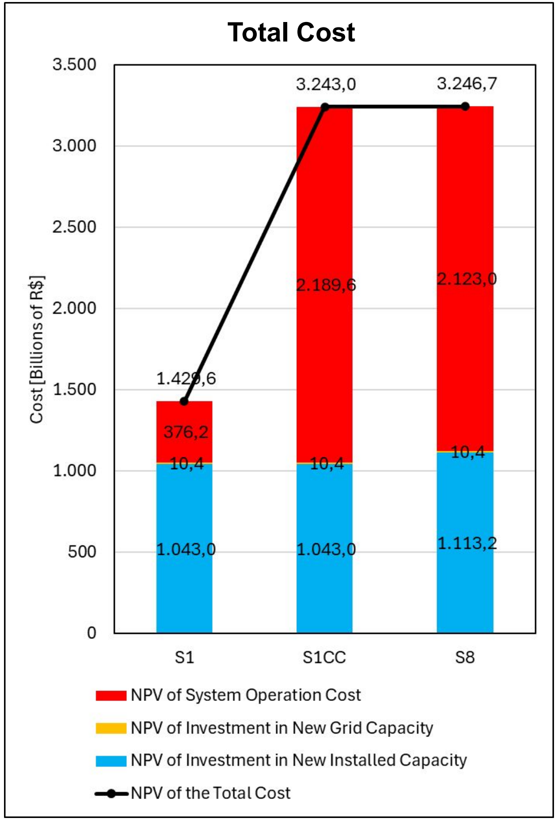
Failing to adapt to climate change would drive system operating costs up by 7.8 times due to a heavy reliance on emergency thermal dispatch to offset reduced hydro inflows. However, integrating 34 GW of offshore wind serves as a mitigation strategy that maintains total system cost parity. The BRL 70 billion investment in offshore wind is entirely neutralized by an equivalent BRL 70 billion reduction in system operating costs, demonstrating that offshore wind enhances supply reliability and provides crucial economic resilience in a severely climate-constrained environment.

- **Cost of Climate Inaction:** Comparing Scenario 1 (Baseline) against the climate-impacted projection reveals that failing to adapt would increase system operating costs (OPEX) by 7.8 times.
- **Operational Costs and Dispatch Pressure:** The surge in system operating costs is driven by the high frequency of energy deficits and the heavy reliance on thermal dispatch to compensate for reduced river inflows.
- **Offshore Wind as a Mitigation Strategy:** Integrating 34 GW of OFW (Scenario 8) at reference costs maintains total system cost parity. The BRL 70 billion increase in CAPEX is fully offset by an equivalent BRL 70 billion reduction in OPEX, highlighting the economic resilience provided by offshore wind in a climate-constrained environment.
- **Resilience and Economic Parity:** While the initial simulation showed limited progress in solving the core issues, the addition of **offshore wind**—even at reference prices—indicates the feasibility of maintaining **system cost parity** while enhancing supply reliability.

Scenario 8

Climate Change





Conclusions of the Strategic Scenarios Analysis

- **Decentralization as a Grid Asset:** Substituting onshore wind expansion in the Northeast with Offshore Wind (OFW) in the South and Southeast functions as a "generation-at-load" solution. This significantly reduces dependence on major interregional transmission lines and optimizes power flow across the National Interconnected System (SIN).
- **Structural Reduction in Transmission CAPEX**: Integrating 18 GW of OFW enables direct savings in grid expansion (dropping from BRL 10.4 billion to 7.3 billion). In high-penetration scenarios (33 GW), these savings can reach 60%, freeing up capital allocation for other areas of the energy sector.
- **Displacement of "Energy Distance":** By bringing generation closer to the main consumption centers (SE/S submarkets), the system reduces technical transmission losses and mitigates the curtailment risks currently affecting the Northeast submarket due to export constraints.
- **The "Net Zero" Impact on Operating Costs**: Despite the initial investment, total system operating costs remain stable. OFW does not significantly alter the inflexible thermal fleet but effectively replaces the need for costly new transmission infrastructure.

Conclusions of the Strategic Scenarios Analysis

- **Hydrological Insurance Policy:** Under severe climate stress (20% reduction in hydro inflows), OFW shifts from a cost to a strategic financial hedge. The BRL 70 billion investment is fully offset by savings in expensive thermal dispatch and the prevention of energy deficits. This benefit can be even greater with larger quantities.
- **Seasonal Synergy with Reservoirs:** OFW delivers superior performance during the late dry season (August to October). This complementarity allows for a more conservative management of hydro reservoirs, preserving stored energy (EARM%) for months of higher hydrological uncertainty.
- **Cost Gap vs. System Value**: While OFW still requires CAPEX reductions (42% to 62%) for pure market competitiveness, its contribution to supply security (Peak Load Contribution) is double that of onshore wind, justifying incentives based on reliability rather than just energy volume.
- **Path to 2050:** With an NPV variance of only 1.8% in the 33.7 GW scenario, the Brazilian system possesses the robustness to absorb a massive offshore matrix, provided that transmission planning is coordinated with coastal connection points.
- **Strategic Decoupling:** OFW allows the decoupling of load growth from the need for continental-scale transmission projects (NE -> SE), promoting a more balanced grid that is resilient to extreme weather events in the North and Northeast regions.

Market Design

Ancillary Services & Regional Business Models

Ancillary Services

Monetizing Grid Stability Attributes

- **Capabilities**: Offshore wind can provide critical grid support, primarily Reactive Power Support and Primary Frequency Control.
- **Regulatory Gap**: Brazil currently relies on fixed-tariffs for Hydro/Thermal (R$10.41/MVAr-h) and does not remunerate wind source (and solar) for these services.
- **Evolution:** ANEEL's ongoing 'regulatory sandboxes' signal a transition toward competitive, remunerated markets for Reactive Power, unlocking secondary revenue streams.

Monetizing Grid Stability Attributes

Ocean Energy Pathway

Ancillary Services and Remuneration (Brazil)

Service	Description	Remuneration	Applicable Resources
Reactive Power Support	Voltage control service through absorption or injection of reactive power.	By availability; Paid by AST	Hydro and Thermal
Primary Frequency Control	Fast automatic response to stabilize the frequency of an electrical system.	Mandatory service; unremunerated	All generators connected to the SIN
Secondary Frequency Control	Automatic control that restores system frequency and tie-line flows after the primary response.	By availability; Paid by AST	Hydro and Thermal
Operating Power Reserve	Scheduled spare generation kept ready to meet contingencies and balance supply-demand in real time.	By availability; Paid by AST	Thermal
Black Start	Capability to energize and re-start portions of the grid without external power supply, enabling system restoration.	By availability; Paid by AST	Hydro and Thermal

International Benchmark

On the international stage, particularly in UK, there are practical examples of contracts for ancillary services involving offshore wind farms. In Brazil, reactive power control presents a highly viable short-term implementation pathway. Dogger Bank in the UK secured a 10-year fixed contract to provide reactive power.

Project Name	Ancillary Service	Market / Framework	Remuneration Type	Duration	Contract Model	Key Technology
Dogger Bank C	Voltage Control / Reactive Power	Pennines & Voltage 2026 Pathfinder (NESO)	Availability Payment (Fixed Fee)	10 years (2024–34)	£22.5 Million (Total)	VSC-HVDC Onshore Converters
Beatrice	Inertia & Short-Circuit Level	Stability Pathfinder Phase 2 (NESO)	Fixed Availability + Utilization Fee	10 years (2024–34)	Part of £323M Portfolio	Synchronous Condenser
Hornsea 3	Frequency Response (FFR / DC)	Balancing Services Market (Enduring Auction)	Pay-as-clear (Daily Auctions)	Operational Life	Market Price + Capacity Market	300MW/600MWh BESS (Iceni)
Hornsea 4	Grid Stability & Virtual Inertia	Bilateral Connection Agreement	Avoided Penalties / Grid Support	Life of Asset	System Benefit / Indirect Revenue	Grid-Forming STATCOMs
Hywind Scotland	Frequency Response (FCR)	Ancillary Services Market (Merchant)	Performance-based Payment	Variable	Spot Market Revenue	Floating Turbine Control
Hollandse Kust Zuid	Frequency Reserves (FCR & aFRR)	Dutch Balancing Market (TenneT)	Real-time Clearing (Non-subsidized)	Continuous	Market Bidding (No Floor)	Advanced Power Plant Controller

Securing Bankable Secondary Revenues

International Benchmark

Notes:

- **Fixed-Price "Pathfinder" (UK Strategy):** The Pathfinder model (by the operator NESO) is a tender specifically for Capex-heavy services. It guarantees a fixed revenue stream for 10 years, allowing developers (such as SSE at Dogger Bank C) to finance expensive technologies like HVDC converters or synchronous condensers that would not be economically viable through energy sales alone.
- **Merchant Balancing (European Strategy):** In countries like the Netherlands (e.g., Hollandse Kust Zuid), the wind farm operates without government subsidies (*zero-subsidy*). Revenue is generated through "Price Arbitrage" and by offering real-time flexibility in the FCR and aFRR markets. This is a higher-risk model, but it yields high returns during periods of significant grid volatility.
- **The BESS Integration (2026 Trend):** Projects like **Hornsea 3** (through the Iceni storage unit) demonstrate that offshore wind is now "Revenue Stacking": selling wholesale energy while simultaneously using batteries to capture high-frequency payments in the Balancing Services market.
- **Grid-Forming as "Standard":** In the UK, as of 2025/26, Grid-Forming capability (synthetic inertia) is transitioning from being an "optional service" to becoming a mandatory connection requirement in specific critical grid areas, ultimately reducing long-term system costs for the developer.
- **Market-Based Services**: In the EU (e.g., Hollandse Kust Zuid), there are fewer long-term "fixed" contracts. Instead, wind farms bid into daily markets (FCR/aFRR), where they are paid based on their availability to help the grid in real-time.

From CfDs and PPAs to the Brazilian Auction Model

Remuneration Mechanisms

- Different types of contracts have been explored internationally as a vehicle for remunerating OFW.
- CfDs have been widely applied in government initiatives, as they reduce market price risk, and are considered an evolution from subsidized contracts (e.g., Feed-in Tariffs). Corporate PPAs have gained strength in the private sector, with the sharing of price and volume risks between the parties. Additionally, Ancillary Services Contracts and f RECs have also been considered as instruments for generating additional revenue.

Remuneration Mechanisms

Mechanism	Core Concept & Advantage	Key Risk / Limitation
Contract for Difference (CfD)	Two-way stabilization. Mitigates price risk and enables large-scale, bankable projects.	Limited market upside; heavily requires public support mechanisms.
Feed-in Tariffs (FiT)	Long-term fixed price. De-risks early-stage markets with a simple, predictable structure.	High subsidy dependence; typically phased out as markets mature.
Power Purchase Agreements (PPAs)	Private bilateral contracts. Provides long-term revenue visibility, reducing reliance on public support.	Complex risk allocation; financing depends entirely on offtaker credit quality.
Renewable Energy Certificates (RECs)	Green monetization. Creates an additional revenue stream supporting corporate decarbonization.	Lacks bankability on its own; requires a dedicated regulated market framework.
Ancillary Services	Grid support. Increases the system value of offshore wind and enables revenue stacking.	Often mandatory without payment; revenue depends heavily on market design.
Regulated Auctions (Brazil)	National standard model. Offers long-term quantity or availability contracts with fixed prices.	As the market matures, short-term exposure risks are shifted to the generator.

Brazil has a long history of promoting onshore wind expansion through competitive auctions, in which, as the technology matured and the market consolidated, the risk allocation rules were adjusted until the market price and volume risks were assumed totally by the generator. The OFW challenge lies in designing contracts with less risk allocation to the end consumer, with the rationale applied to CfD contracts being an alternative to be considered.

Brazilian Legal Framework (Law 15.097/2025)

International experience teaches that, for the first auctions in Brazil, among other aspects, the following should be sought:

- **Concession Model**: Establishes competitive auctions for maritime 'energy prisms' via Planned (Government) or Permanent (Investor) offers.
- **Mandatory Financial Burdens**: Winners face upfront Signature Bonuses, Area Occupation Fees, and monthly Proportional Participation (Royalties).
- **The Bankability Challenge**: Imposing high state fees without coupling them to revenue stabilization mechanisms (like CfDs) severely risks auction failures, as observed recently in the US and UK.
- **International Experience:** Germany and the Netherlands (negative bidding) and the USA (lease sales) are examples of countries that practice land concession auctions. However, this model is being rethought because high interest rates and input costs have made upfront payments to the state challenging. Without price guarantees and with narrow margins, the risk of project abandonment has increased, forcing governments to consider the return of protection mechanisms (such as CFDs) to guarantee clean energy targets.

Risks and Opportunities

Brazilian Legal Framework (Law 15.097/2025)

International experience teaches that, for the first auctions in Brazil, among other aspects, the following should be sought:

- **Calibration of the concession's reference price:** It must be estimated considering its composition within the other project implementation costs and the immaturity of the national market (excessive costs for the concession may lead to the infeasibility of the projects).
- **Business Models**: Foster business models based on the regional vocations of each development hub and the systemic benefits (and avoided costs) of each solution.
- **Contracting scheme:** Consider incentive mechanisms for the development of the first projects and unlocking the market. If the government stacks these heavy upfront costs without providing a stabilizing revenue mechanism, there will be a risk of empty auction.
- **Auction timing and project maturity:** Revenue support auctions should be launched only after key site development risks have been reduced through pre-development activities. This enables competitive and bankable bids based on mature project designs and procurement strategies, ensuring competition is based on well-developed projects rather than early-stage site allocation.
- **Additional revenues:** Foster remuneration models in addition to energy contracting, such as the provision of ancillary services and the trading of green energy certificates.

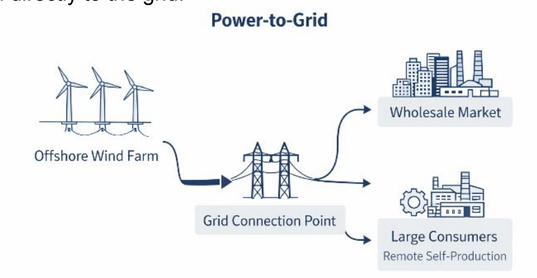
Business Models for the Brazilian Market

Brazil possesses unique characteristics for the implementation of various types of business models involving offshore wind energy, given the energy and economic diversity observed in each of its development hubs (Northeast, Southeast, and South). Public development policies should consider these diversities and be geared towards valuing these regional strengths.

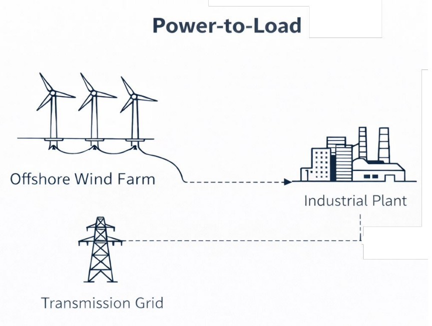
- **Power-to-Grid:** Direct integration into the SIN for wholesale trading or remote self-production.
- **Power-to-Load:** Off-grid, dedicated supply to localized mega-loads (Data Centers, O&G platforms).
- **Power-to-X:** Exclusive connection to industrial plants for Green Hydrogen, Ammonia, or e-fuels production.
- **Hybrid Models:** Co-locating with BESS or Solar PV to optimize connection usage and smooth intermittency.

Business Models for the Brazilian Market

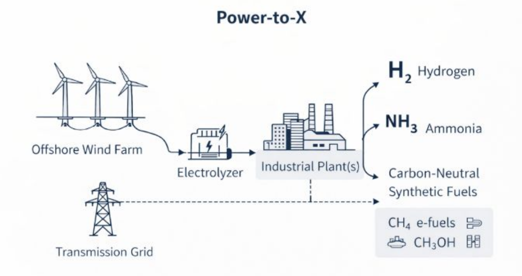
Power-to Grid:
OFW connected directly to the grid.



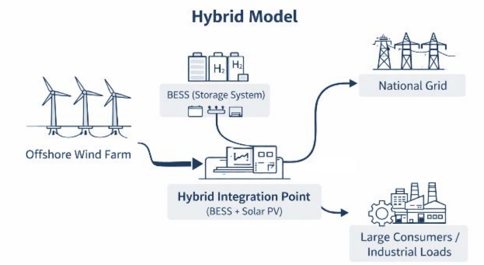
Power-to-Load:
OFW connected exclusively to meet specific demand (off-grid).



Power-to-X:
OFW connected exclusively to industrial plants for converting electricity into other forms of energy or storable chemical products.



Hybrid Models:
OFW sharing connection with Solar and/or Storage Systems.



The Power-to-X and Export Powerhouse

Northeast Hub

- Constraint: Saturated transmission margins (max 2.5 GW) and high TUST make massive grid-connected projects economically and technically challenging.
- Advantage: Unmatched capacity factors (59.2%) and excellent geographic positioning for global logistics.
- Strategic Vocation: Strongly dictates off-grid models—specifically Power-to-X (exporting Green H2 via Pecém/Suape ports) and Power-to-Load (serving global data hubs).

Business Model	Strategic Value & Opportunities	Key Constraints & Enablers
Power-to-Grid	Highest yield & synergy. Delivers strong hydro/solar complementarity and unlocks ancillary service revenues.	Grid saturated. Severely limited by high TUST and transmission bottlenecks. Requires hybridization (Solar/BESS) to optimize grid access.
Power-to-Load	The Grid Bypass. Directly supplies large coastal off-grid loads, completely avoiding transmission constraints.	Data Center focus. Highly suited for global data hubs, leveraging the region's extensive international submarine cable infrastructure.
Power-to-X	Export Powerhouse. Unmatched capacity factors and strategic ports (Pecém, Suape) drive competitive Green H2 and e-fuels.	Certification risks. Grid-connected P2X is hampered by local grid costs and strict international green certification protocols.

The Northeast has the best winds in the world, but the grid is full. The vocation here is producing Green Hydrogen at ports for export or bringing Data Centers directly to the coast.

Southeast Hub

- Advantage: Highest available transmission margin (9.5 GW) and direct proximity to Brazil's largest industrial load centers, avoiding long-distance transmission losses.
- Constraint: Slightly lower capacity factor (47.3%) compared to the Northeast.
- Strategic Vocation: Ideal for Power-to-Grid (corporate PPAs for heavy industry self-production) and Power-to-Load (electrifying and decarbonizing pre-salt offshore O&G platforms).

Business Model	Strategic Value & Opportunities	Key Constraints & Enablers
Power-to-Grid	Generation-at-Load. Directly feeds Brazil's primary load center, unlocking corporate self-production models with lower transmission losses and lower TUST.	Lower Yield Trade-off. Excellent grid connectivity and ancillary revenue potential must compensate for a lower capacity factor compared to the NE and South.
Power-to-Load	O&G Decarbonization. Prime opportunity to electrify and decarbonize pre-salt offshore platforms, leveraging strong synergies with the Oil & Gas industry.	Data Center Proximity. The strong regional market and robust cabling infrastructure highly justify dedicated off-grid data center supply.
Power-to-X	Domestic Premium. Shifts focus from pure export to supplying regional heavy industries with high value-added green products for the domestic market.	Industrial Port Synergy. Development is heavily supported by established O&G infrastructure (RJ/ES) and strategic logistical hubs like the Port of Açu.

The Southeast has 9.5 GW of headroom right next to São Paulo, Rio de Janeiro and Espírito Santo. The vocation is connecting directly to the grid to power heavy industry or running cables to decarbonize offshore O&G platforms.

South Hub

- Advantage: A highly balanced scenario offering medium-high capacity factors (52.6%), robust connection margins (6.0GW), and the lowest TUST in the country.
- System Impact: Stabilizes the grid by generating close to the second-largest national load center.
- **Strategic Vocation: Highly favorable for Power-to-Grid (domestic supply and Mercosur export to Argentina/Uruguay) and Power-to-X (supporting local fertilizer industries)**

Business Model	Strategic Value & Opportunities	Key Constraints & Enablers
Power-to-Grid	Regional & Mercosur Integration. Directly supplies Brazil's second-largest load center while unlocking cross-border transmission exports to Uruguay and Argentina.	Optimal Grid Conditions. Highly driven by the country's lowest transmission tariffs (TUST) and abundant connection margins, balancing a moderate but competitive capacity factor.
Power-to-Load	Targeted Coastal Demand. Dedicated supply for localized industrial clusters and planned mega-loads (e.g., Data Centers in Rio Grande do Sul).	Overshadowed by Grid Access. While off-grid reduces deployment costs, the region's excellent transmission availability makes standard grid-connection comparatively more attractive.
Power-to-X	Agri-Industrial Focus. Strong economic alignment for producing green hydrogen and fertilizers, serving the domestic market and exporting to Mercosur.	Port Infrastructure Reliance. Implementation and scale are highly dependent on utilizing and upgrading the Port of Rio Grande as the primary logistical support base.

The South is suitable for standard grid connection, supplying the local industrial base, producing fertilizers, and exporting power directly to Uruguay and Argentina. The 'export' of excess energy from the southern submarket to the southeastern submarket also appears to be a coherent strategy.

Regional Qualitative Assessment

There is no single business model suitable for all regions of Brazil. OFW in Brazil should be developed through region-specific strategies, given the specific characteristics of each hub (northeast, southeast, and south).

In general, OFW is considered a vector that will enable the export of carbon-neutral fuels and facilitate the domestic production of higher value-added green products, in addition to meeting large load demands with clean energy. Once connected to the grid, OFW can become an ancillary services provider and contribute to the system's operation.

Business Model	Northeast Submarket	Southeast Submarket	South Submarket
Power-to-Grid (Grid Connection)	High Yield, Grid Constrained. Requires hybridization (Solar/BESS) to bypass saturated transmission and high TUST.	Generation-at-Load. Feeds primary demand directly, enabling corporate self-production with lower transmission costs.	Optimal Grid Access. Leverages abundant connection margins and lowest tariffs. Unlocks exports to SE and Mercosur.
Power-to-Load (Serving Loads)	The Grid Bypass. Focuses on coastal data centers (via submarine cables) to circumvent grid bottlenecks.	O&G & Tech Hub. Driven by pre-salt offshore platform decarbonization and dedicated data center supply.	Niche Coastal Demand. Targets planned data centers (RS), though excellent grid margins make off-grid less critical here.
Power-to-X (Green H2 & Fuels)	Global Export Hub. Leverages Pecém and Suape ports for massive-scale Green H2 and e-fuels for international markets.	Domestic Premium. Supplies regional heavy industry (e.g., Port of Açu) with high value-added green products.	Agri-Industrial Focus. Produces fertilizers and H2 products for domestic use and Mercosur cross-border export.
Strategic Summary	Massive raw potential; success relies on bypassing grid limits via H2 exports or dedicated off-grid loads.	The immediate market; lower yields are fully offset by direct load proximity and O&G synergies.	The balanced play; offers the most favorable grid conditions and unique cross-border integration opportunities.

Policy Roadmap

- **Implement CfDs:** The government must adopt bidirectional CfD in initial auctions to eliminate market price risk and lower the WACC.
- **Monetize Ancillary Services:** ANEEL must regulate long-term contracts for voltage and frequency control, creating bankable secondary revenues.
- **Recognize 'Avoided Costs':** Establish regulatory frameworks that exempt off-grid (Power-to-Load) projects from specific TUST and system charges.
- **Incentivize O&G Synergy:** Monetize fuel displacement by aggressively supporting offshore platform electrification.

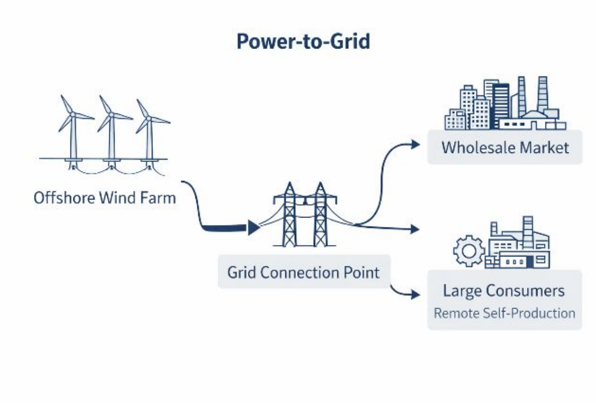
Power-to-Grid (Grid Connection)

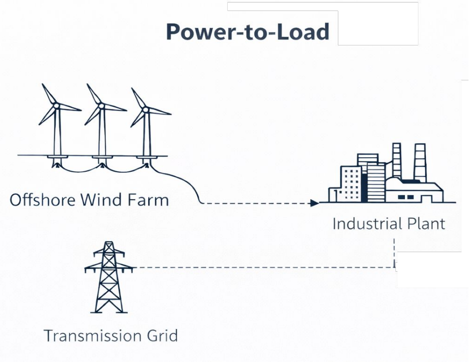
- **Implement Contracts for Difference (CfDs):** Adopt bidirectional financial stabilization mechanisms to eliminate market price risk and significantly lower the Weighted Average Cost of Capital (WACC).
- **Adaptive Auction Parameters**: Ensure auction price ceilings and budgets are responsive to inflation and interest rate volatility to prevent project cancellations.
- **Ancillary Services Remuneration:** Establish long-term contracts for grid support services (voltage/frequency control) to transform systemic benefits into a secondary revenue stream.

Power-to-Load (Dedicated Loads)

- **Regulatory Recognition of "Avoided Costs":** Create a framework that recognizes the value of grid independence, exempting off-grid models from certain transmission tariffs and system charges.
- **O&G Decarbonization Incentives:** Promote the electrification of offshore platforms to replace gas turbines, monetizing fuel displacement and carbon emission reductions.
- **Industrial Anchor Contracts:** Encourage long-term self-production PPAs with electro-intensive sectors, such as steel and data centers, to ensure bankability through captive demand.

Recommendations for Power-to-Grid & Power-to-Load





Policy Roadmap

- **Blended Public Support for P2X**: Combine CAPEX grants for electrolyzers with operational energy subsidies to de-risk early Green H2 projects.
- **Port Integration**: Align maritime area auctions directly with national hydrogen strategies and existing industrial port zones (Pecém, Suape, Açu).
- **Green Premium Certification:** Develop robust, internationally recognized certification frameworks to capture EU CBAM price premiums.

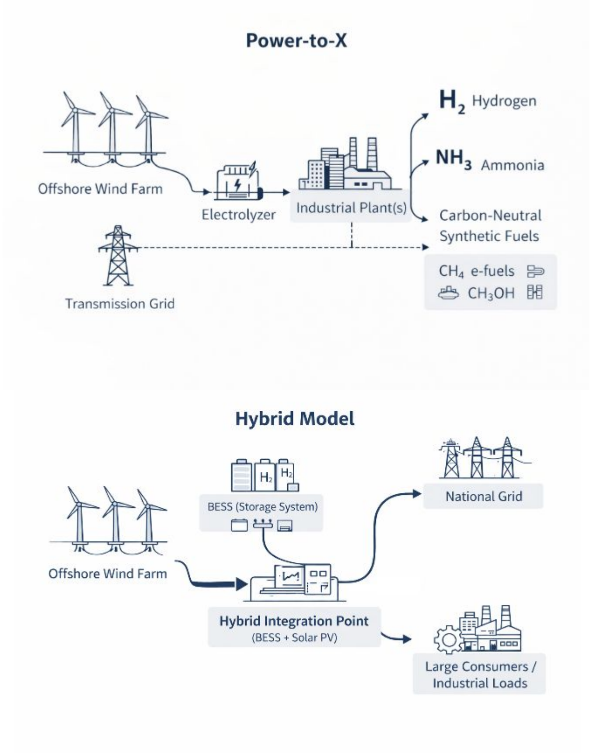
Power-to-X (Green H2 & Synthetic Fuels)

- **Blended Public Support:** Combine CAPEX grants for electroliers with energy production subsidies to reduce the initial equity burden.
- **Certification for "Green Premium":** Develop a robust hydrogen certification framework to capture international price premiums and ensure compliance with regulations like the EU's CBAM (*Carbon Border Adjustment Mechanism*).
- Integration with Port Hubs: Align offshore area auctions with national hydrogen strategies and existing industrial port infrastructure (e.g., Pecém, Suape, Açu).

Hybrid Models (Revenue Stacking)

- **Maximize Infrastructure via Complementarity:** Prioritize projects that combine wind with solar to increase the capacity factor and optimize the use of expensive subsea transmission assets.
- **Regulate Storage for Arbitrage:** Establish rules for Battery Energy Storage Systems (BESS) to capture intraday price variations and reduce energy wastage from curtailment.
- **Enable Revenue Stacking:** Allow projects to accumulate multiple revenue streams—such as energy sales, RECs, and fast-response services—to increase overall project resilience.

Recommendations for Power-to-X & Hybrid Models



Conclusions

Conclusions

Regional Hub Analysis (Northeast, Southeast, and South)

- **Grid connection conditions and integration of the Northeast Hub.** The Northeast possesses significant wind resources; however, the current transmission grid faces capacity constraints. To enable large-scale projects in this region, the study indicates the need for new investments in connection infrastructure or the adoption of local consumption models.

- **Strategic alternatives for the development of the Northeast Hub.** Given the transmission constraints to the national grid, the study recommends strategic options such as the production of green hydrogen and its derivatives, as well as the Power-to-Load model focused on attracting Data Centers. In these scenarios, energy is consumed locally, transforming electricity transport limitations into an opportunity for technological development and the export of low-carbon products.

- **Competitive infrastructure advantages of the Southeast Hub.** The Southeast region has the largest available margin for connecting new projects to the power grid through 2039. Proximity to major load centers reduces the need for long-distance energy transmission, thereby decreasing technical losses and optimizing transmission costs.

- **Decarbonization of the Oil & Gas industry in the Southeast.** There is a significant opportunity to connect wind farms directly to offshore platforms. This allows for the replacement of fossil fuel-based generation with renewable sources, reducing carbon emissions in oil production (Power-to-Load).

Regional Hub Analysis (Northeast, Southeast, and South)

- **Wind profile and generation stability in the Southern Hub.** The Southern Hub exhibits a constant generation profile throughout the 24-hour cycle. This stability facilitates power system operation planning and provides a predictable energy source for industrial units within the region.
- **Wind seasonality in the South and meeting winter demand.** In the South, peak wind speeds occur during low-temperature periods when energy demand increases. Offshore production in this region coincides with seasonal needs, supporting the balance between regional supply and demand.
- **Integration challenges of the Northeast Hub compared to the South and Southeast.** The Northeast Hub possesses the largest wind resource but faces severe transmission bottlenecks (this study estimated a remaining capacity of ~2.5 GW), while the Southeast and South have more robust transmission margins (~9.5 GW and ~6.0 GW, respectively). Thus, Northeast requires the development of Power-to-X and Power-to-Load models to avoid saturating the basic export network to the Southeast and, at the same time, exploit its high potential for offshore wind energy resources.

Conclusions

Business Models and Strategic Viability

- **Viability of the Power-to-Grid (PTG) model.** In this model, energy is injected into the National Interconnected System (SIN) for sale in the free or regulated markets. It proves most viable in regions with existing transmission infrastructure, such as the Southeast and the South.
- **Operation of the Power-to-Load (PTL) model for specific loads.** Generation is connected directly to an industrial consumer. This model is attractive for companies seeking to ensure long-term supply security and reduce costs associated with public grid usage charges. The model where generation is directly connected (Power-to-Load) to an industrial or mining load brings important benefits, such as reduced risk of "curtailment" and elimination of transmission charges, making it highly attractive to large industrial consumers.
- **Efficiency in combining onshore and offshore wind farms.** Shared use of connection infrastructure, such as substations and transmission lines between onshore and offshore power plants, reduces initial investment costs compared to developing isolated infrastructures.
- **Revenue generation through ancillary grid services.** Beyond energy sales, offshore wind farms can provide voltage and frequency stability to the power system. Internationally, as observed in the United Kingdom, these services are remunerated and assist in the financial viability of the projects.

Business Models and Strategic Viability

- **Evolution of risk allocation and contract design for offshore wind.** Unlike onshore wind, which matured by shifting price and volume risks entirely to the generator by Regulated Auctions, the offshore wind challenge requires new contractual frameworks. The study suggests that to make the source viable without overburdening the end consumer, the Contracts for Difference (CfD) model emerges as a key alternative to balance investor security with the system's economic efficiency.

- **Area concession models and economic risk mitigation.** While markets such as Germany, the Netherlands, and the USA have utilized lease auctions (upfront payments), the global scenario of high interest rates and input costs has prompted a reassessment of this model. The study suggests that Brazil must balance state revenue collection with protection mechanisms, such as Contracts for Difference (CfDs), to prevent project abandonment and ensure that clean energy targets remain financially viable despite the sector's narrow margins.

Conclusions

System Operation and Reservoir Management

- **Offshore wind contribution to hydroelectric reservoir management.** Offshore generation acts as a strategic reserve. By generating energy during dry periods, it allows hydroelectric plants to reduce production and store water for use during times of higher necessity. The study projects that the addition of 34 GW of offshore power could maintain reservoirs in the Southeast/Central-West region up to 7.3% above the reference level in unfavorable hydrology scenarios.
- **Improvement of reservoir levels during water scarcity scenarios.** The study projects that the presence of offshore wind can maintain reservoir levels in the Southeast and Midwest regions above safety limits, even in years with rainfall volumes below the historical average.
- **Impact of the source on reducing thermal power plant dispatch.** With stable generation located near load centers, offshore wind reduces the need to dispatch expensive fossil-fueled thermal plants, resulting in lower overall system operation costs.
- **Supply security of offshore wind compared to onshore wind.** Offshore wind features a higher capacity factor and greater consistency. At sea, winds encounter less topographic interference, resulting in firm energy production to meet load requirements during peak hours.

System Operation and Reservoir Management

- **Reduction of technical losses in the National Interconnected System (SIN).** Since projects can be installed near major consumption areas (Southeast and South submarkets), the energy travels shorter distances. This reduces the electricity dissipation that naturally occurs over very long transmission lines.
- **Offshore wind power alter the perception of the regulatory "Location Signal”:** The entry of this source in the South and Southeast tends to equalize transmission prices (TUST) between regions, as it reduces the need for large interstate energy transfers, promoting a more geographically balanced system.
- **Supporting the solar generation ramp-down at sunset.** Solar energy production drops rapidly at sunset, precisely when household consumption rises. The offshore wind profile in Brazil shows a production increase during this specific interval, smoothing the transition and enhancing operational security.

Conclusions

Costs, Methodology, and Strategic Vision

- **Impact on the total expansion cost of the national power system.** While the initial investment per plant is higher than other sources, offshore wind reduces the need for thousands of kilometers of new transmission lines if connected in south and southeast regions or by power-to-load arrangements in northeast. The total system cost remains balanced when considering the avoided grid investments. Although the CAPEX of offshore wind is higher, it reduces the need for new investments in large North-Southeast transmission lines, resulting in a net impact on the NPV of the expansion of only ~1.5% more than the baseline scenario.

- **International cost reduction trends and economies of scale.** Following international examples, equipment standardization and the development of a local supply chain are the primary drivers for cost reduction over time, as accounted for in the learning curve for Brazil.

- **Importance of hourly data analysis for project viability.** Hourly data analysis proves that offshore wind maintains production when other renewable sources are absent, which increases the value of the energy generated for both the system and the investor.

- **Strategic role of offshore wind for the future of the Brazilian power sector.** Offshore wind positions itself as a source of firm capacity and load proximity. Its essential role is to provide system resilience, ensuring the country can continue to grow with clean energy without compromising supply security or price stability.

Ocean Energy Pathway

Developed by:

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"Timeseries Analysis in Brazil"

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Technical Reports Issued

- **OEP - MRTS -EPE Meeting _ 2025_10_06.pptx**: Work plan and schedule discussed with EPE regarding offshore wind's (OFW) role in the national system.
- **PPT-01-MRTS-OEP-Kick_off_250917-rev.pptx**: Revised kick-off presentation with updated work plan and grid connection points.
- **PPT-02-MRTS-OEP-1stMonthlyProgessMeeting_20251022-SV3**: Progress report detailing critical substations for transmission reinforcement in OFW hubs.
- **PPT-02-MRTS-OEP-Phase1Report_shortversion.pptx**: Ph 1 short report version with preliminary summaries of demand, grid integration, and complementarity.
- **PPT-03-MRTS-OEP-1stMonthlyProgessMeeting_20251022-FV1.pptx**: Progress report detailing critical substations for transmission reinforcement in OFW hubs.
- **PPT-04-MRTS-OEP-Phase1-ExecutiveSummary_BWP_rev2_20251027_Portuguese.pptx**: PT-BR Ph 1 executive summary highlighting offshore wind complementarity with hydro and solar sources.
- **PPT-05-MRTS-OEP-Phase1-Report_rev1_clarifications.pptx**: Final Ph 1 version with clarifications on regional asymmetries and TUST redistribution.
- **PPT-05-MRTS-OEP-Phase1-Final Review.pptx**: Ph 1 final review consolidating findings on system resilience and transmission bottlenecks.
- **PPT-05-MRTS-OEP-Produto_2_V11.pptx**: Final Ph 2 scenario study proposing a realistic 2.7% annual load growth rate.
- **PPT-06-MRTS-OEP-2ndMonthlyMeeting_Phase2_v11.pptx**: Ph 2 report comparing CAPEX between national and international sources.
- **PPT-07-MRTS-OEP-Phase2-Report_20251212_PT.pptx**: PT-BR Ph 2 report presenting scenario modeling and optimization of the energy mix through 2050.
- **PPT-08-MRTS-OEP-3rdMonthlyMeeting_Phase3_rev20260113_V7.pptx**: Ph 3 systemic interaction analysis covering ancillary services and SIN operational impact.
- **PPT-09-MRTS-OEP_Phase_03_RevenueScheme_Review_V1.pptx**: Analysis of remuneration mechanisms (CfDs/auctions) and business models.
- **PPT-10-MRTS-OEP_Phase_03_NewScenarios_RF.pptx**: Ph 3 results comparing operational and expansion costs between scenarios with and without OFW wind.
- **PPT-11-MRTS-OEP_Phase4_FinalReport:** currently document. Mains results, findings and conclusions.

Annex

Wind Energy Expansion Cost

In the methodology applied (similar to that used by EPE), for the simulation's purposes, CAPEX, OPEX and related costs are transformed into total monthly costs for each type of energy source considered as a candidate for expansion. The cost breakdown is structured to capture the main economic and technical drivers for each source generation technology across submarkets. Current costs are from the PDE 2035 report (EPE). A cost variation (maturity/learning) curve is applied to simulate expected cost reductions over the planning horizon (using the NREL reference).

Projects

Onshore (EOL) and Offshore Wind (EOL-OFF)

Wind Monthly Cost Expectations

Type	Submarket	Service Life	Capex R$/kW	Sectoral Charges R$/kW.year	Monthly Capex Cost R$/kW/month	O&M R$/kW.year	O&M + monthly Charges R$/kW/month	Interest During Construction (IDC)	Averaga Capacity Factor	LCOE 2026	Learning Rate CAPEX	Learning Rate O&M	Monthly Investment Cost R$/kW/month 2026	Monthly Investment Cost R$/kW/month 2050	Total Reduction
EOL	S	20	6.850	150	59,32	110	22,58	6,4%	39,6%	283,38	1,284%	0,801%	81,90	64,50	21,2%
EOL	NE	20	6.200	160	53,69	110	23,45	6,4%	45,8%	230,75	1,284%	0,801%	77,14	61,23	20,6%
EOL	N	20	8.100	160	70,15	110	23,45	6,4%	45,8%	279,96	1,284%	0,801%	93,60	73,33	21,7%
EOL-OFF	SE	20	15.600	630	141,70	338	84,08	11,6%	47,3%	654,10	2,455%	0,664%	225,78	158,36	29,9%
EOL-OFF	S	20	15.600	630	141,70	338	84,08	11,6%	52,6%	587,82	2,455%	0,664%	225,78	158,36	29,9%
EOL-OFF	NE	20	15.600	630	141,70	338	84,08	11,6%	59,2%	522,70	2,455%	0,664%	225,78	158,36	29,9%

Note: LCOE is used here for reference purposes only, since the performance of each generation source is assessed based on its technical characteristics within the overall installed capacity mix of the SIN, in relation to system costs. For the cost assumptions made for the other candidate sources, see the Annex.

Annex

Wind Energy Expansion Cost

Clarification regarding the breakdown of the monthly cost of the sources:

- Each entry is defined by its type and submarket, considering a specific service life and associated investment and operational parameters. The CAPEX (R$/kW) represents the upfront investment cost, which is converted into a monthly CAPEX cost (R$/kW/month) to enable comparability with recurring costs. In addition, sectoral charges (R$/kW.year) are incorporated and combined with CAPEX to reflect their monthly impact. Operational costs are represented by O&M (R$/kW.year) and aggregated into O&M plus monthly charges (R$/kW/month), providing a complete view of recurring expenses. The Interest During Construction (IDC) accounts for financial costs incurred during the project implementation phase.

- Future cost dynamics are incorporated through learning rates for CAPEX and O&M, allowing the estimation of cost reductions over time. These assumptions are reflected in the monthly investment cost for 2026 and 2050, enabling a comparison of cost evolution.