Ocean Energy Pathway

The Strategic Role of Offshore Wind in Brazil

Analysis and Simulations with Time Series, System Optimisation, Grid Integration, and Market Design

July 2026

Disclaimer: The results of this study reflect the analytical and modelling processes developed by MRTS Consultoria for Ocean Energy Pathway (OEP). The findings and conclusions presented do not necessarily express the individual views of the institutions that collaborated with or were consulted during the project, nor do they incorporate other works currently being developed by those institutions.

The scenarios assessed represent analytical pathways, not predictions. They are designed to illuminate trade-offs and strategic choices and should be read in the context of the full technical reports produced across the four phases of this study.

Foreword

This report presents the final findings of **The Strategic Role of Offshore Wind 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 characterisation to advanced scenario modelling, system optimisation, and system interaction analysis —this study investigates how offshore wind interacts with existing generation sources and transmission infrastructure throughout the national territory.

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.

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 endeavour. 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

Foreword

Brazil's electricity system has long been a global benchmark for clean energy leadership. Built upon hydropower and strengthened by renewables, it enabled the country to combine economic growth with one of the world's lowest-carbon power matrices. Yet the next phase of the energy transition will require greater resilience, flexibility, and geographic balance.

It is from this perspective that Ocean Energy Pathway (OEP) proudly commissioned this study delivered by MRTS. Our objective was not only to assess the technical potential of offshore wind, but to deepen the understanding of why Brazil needs offshore wind and why this technology is so strategic for the country's future energy system.

The findings presented throughout this report demonstrate that offshore wind is far more than an additional renewable source. Offshore wind can strengthen the Brazilian matrix through three critical pillars: diversifying the energy mix, hedging against increasing hydro-climate risks, and ensuring the long-term expansion of a clean and reliable electricity system.

While the scenarios presented are not forecasts, they offer a structured exploration of how offshore wind may contribute under different assumptions relating to demand growth, transmission constraints, hydro-climatic stress, and cost evolution.

This study also highlights the opportunity offshore wind offers to rebalance renewable generation toward the South and Southeast through Power-to-Grid models, reducing transmission congestion while bringing generation closer to major load centres. At the same time, the Northeast emerges as a global powerhouse capable of enabling bold Power-to-X, powershoring, and Power-to-Load strategies linked to new low-carbon industries.

Offshore wind is also a long-term industrial transformation opportunity. Global experience demonstrates strong cost-reduction pathways driven by economies of scale, learning curves, and coordinated infrastructure development, reinforcing the importance of long-term State vision and regulatory coordination.

OEP would also like to express a special thank you to Chris Lloyd, whose active engagement, methodological contributions, and extensive offshore wind experience significantly strengthened the strategic vision and robustness of this study.

As climate change reshapes hydrological conditions and electricity demand continues to grow, offshore wind can become a cornerstone of Brazil's ability to remain a global energy leader while preserving the clean profile of its expanding power system.

Julia Paletta
Country Head Brazil - Ocean Energy Pathway

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1. Project overview

The overarching goal of this study is to deepen the understanding of the strategic role offshore wind can play in the future evolution of the Brazilian electricity system and why the development of this technology makes structural sense for Brazil. Beyond evaluating generation potential, the study seeks to explore how offshore wind can contribute to a more resilient, flexible, and geographically balanced power matrix, while supporting the long-term expansion of a clean electricity system under increasing climate and transmission challenges.

This project assesses the role of offshore wind power in the evolution of the Brazilian Electricity System up to the 2050 horizon. It considers issues such as complementarity with other generation sources, grid integration and planning, and the operation and expansion of the National Interconnected System, among others.

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

The scope of the study is divided into four phases: Data Acquisition and System Characterisation; Scenario Modelling and System Optimisation; System Interaction Analysis; and Results Dissemination.

Phase 1: Data Acquisition and Baseline System 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 Mix Forecast	Operational Impact Assessment	Overall Final Deliverables
Energy Demand Projection	Offshore Wind Energy in Climate Stress Scenarios	Ancillary Services and Revenue Schemes	
Strategic Planning and Grid Integration			
Power Flow and Pricing			
Complementarity Analysis			

It presents in-depth contributions on the role of Offshore Wind Power (OSW) 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.

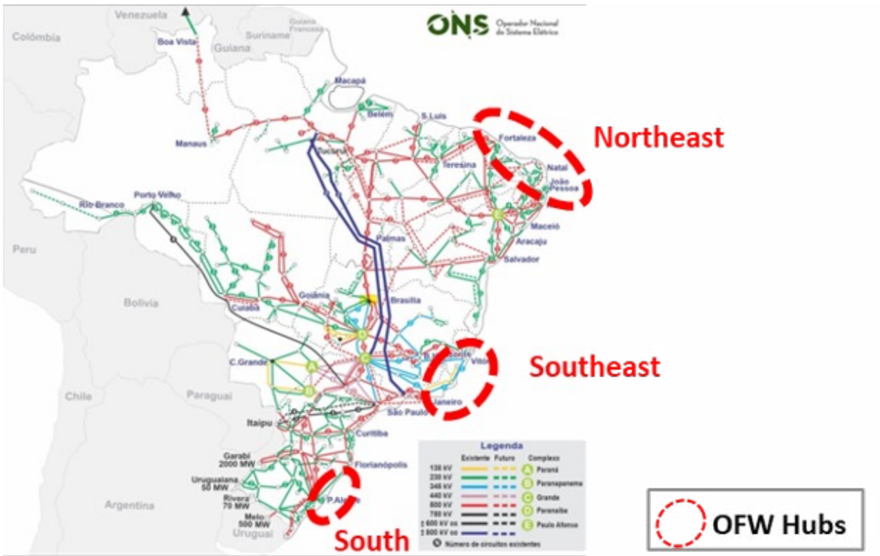


Figure 1: The three Offshore Wind hubs in Brazil
Source: Operador Nacional do Sistema (ONS)

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.

2. The value proposition for Offshore Wind

The final results indicate that offshore wind (OSW) operates as a systemic asset, offering value across three pillars: operability, economic optimisation, and market diversification.

Offshore wind helps offset fluctuations in hydropower, working as a hydrological hedge . In some regions, increased wind generation closely aligns with lower inflows into hydroelectric dams, meaning it produces more electricity when hydropower produces less..The analysis indicates that wind production increases during dry months in the main river basins, allowing the National Interconnected System (SIN) to better manage reservoir levels, especially under climate change scenarios. Additionally, OSW 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-fuelled thermal dispatch.

While offshore wind involves increased initial capital expenditure (CAPEX) compared to onshore alternatives, it facilitates grid optimisation. The study shows that locating generation near consumption centres 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 OSW 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 OSW relies on regional strategies tailored to infrastructure constraints and the general characteristics of regional markets.

Northeast Hub: Despite possessing the most significant wind resource and complementary timeseries, the region faces severe transmission bottlenecks and acute competition with onshore wind, 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. The expansion of renewable energy supply in this submarket is primarily driven by biomass and solar photovoltaic, as onshore wind power lacks potential and hydropower has already exhausted its exploitation. Therefore, offshore wind power becomes an important vehicle for expanding regional supply in large-scale projects.

South Hub: Features a robust transmission margin (~6.0 GW) and a constant generation profile over the 24-hour cycle. In contrast to the Northeast's severe bottlenecks and acute grid competition, the South's abundant transmission headroom accommodates the coexistence and expansion of both offshore wind and its established onshore wind resources. Peak wind speeds occur during the winter, which coincides with the region's highest energy demand, facilitating the balance between regional supply and demand.

To support project bankability, the study identifies the Contracts for Difference (CfDs) as an interesting benchmark to be evaluated in the local context. 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 revenue stacking required to make offshore projects financially viable.

3. Baseline 2050: Growth Exacerbates the Need for System Flexibility

Electricity demand projections play a central role in power system planning, guiding both the expansion of generation capacity and the long-term operation of the Brazilian power system. Accordingly, demand forecasting was incorporated into this study as a key input for the system simulations.

Brazil's gross electricity demand is projected to increase substantially over the coming decades, reaching an average load of 218 GW by 2050, approximately 2.7 times current levels. This growth reflects an optimistic macroeconomic outlook, with an average annual GDP growth rate of 3.2%, together with the accelerated electrification of end-use sectors and the emergence of new electricity-intensive loads, particularly green hydrogen production and data centres.

At the same time, the rapid deployment of distributed solar photovoltaic (PV) generation is expected to fundamentally reshape the system's load profile. Net demand projections, which incorporate the expected expansion of distributed generation through an econometric-statistical model, indicate a pronounced deepening of the "duck curve". While distributed PV reduces daytime net demand, it also creates significantly steeper load ramps during the late afternoon and evening, increasing operational challenges for the Brazilian Interconnected System (SIN).

The projected increase in electricity demand will require a substantial expansion of the country's generation fleet. However, meeting future demand will not be solely a question of adding new capacity. The combination of strong demand growth and the increasing penetration of distributed solar generation means that the SIN will require significant volumes of fast-responding flexible capacity to reliably manage steep evening ramps and maintain system security. As a result, future planning will need to prioritize not only renewable energy deployment but also investments in flexibility resources—including energy storage, demand-side response, transmission expansion, and complementary dispatchable technologies.

In this context, offshore wind can play a strategic role. Compared with solar PV, offshore wind typically exhibits a more complementary generation profile, with higher production during evening and nighttime hours in many regions. When combined with battery storage and enhanced transmission infrastructure, offshore wind can contribute to increasing system reliability, reducing net load variability, and supporting Brazil's transition toward a more resilient, flexible, and low-carbon electricity system.

Figure 2: Electricity demand adjusted scenario[1]

1 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 2055 TNZ (Net Zero Transition) – 3.2x growth
PNE 2055 TA (Elongated Transition) – 2.9x growth
PNE 2055 TC (Continued Transition) – 2.1x growth

4. Grid Integration and Regional Dynamics

The assessment considered 31 candidate substations associated with the main offshore wind hubs currently under environmental licensing (15 in the Northeast, 7 in the Southeast, 8 in the South, and 1 aggregated node in the North). Under the planned transmission reinforcements already included in the PDE, the system is estimated to accommodate up to 18 GW of offshore wind capacity, distributed as 9.5 GW in the Southeast, 6.0 GW in the South, and only 2.5 GW in the Northeast.

The results reveal a marked regional imbalance in available transmission capacity. Although the Northeast hosts the country's largest offshore wind pipeline, transmission margins are already close to saturation across several substations, meaning that large-scale deployment would require additional grid reinforcements beyond those currently planned, including synchronous compensation and network upgrades. By contrast, the Southeast and South retain significantly higher connection margins, making them the most attractive regions for the first wave of offshore wind projects from a grid integration perspective.

These findings suggest that transmission capacity, not only wind resource quality, will shape the geographical trajectory of offshore wind development in Brazil. They also highlight the importance of aligning concession auctions with grid availability to avoid concentrating projects in areas where connection capacity is already constrained. While the South offers substantial connection headroom, its comparatively lower wind capacity factors and greater distance from major demand centres should be balanced against the Southeast, which combines stronger transmission availability with proximity to the country's main electricity load.

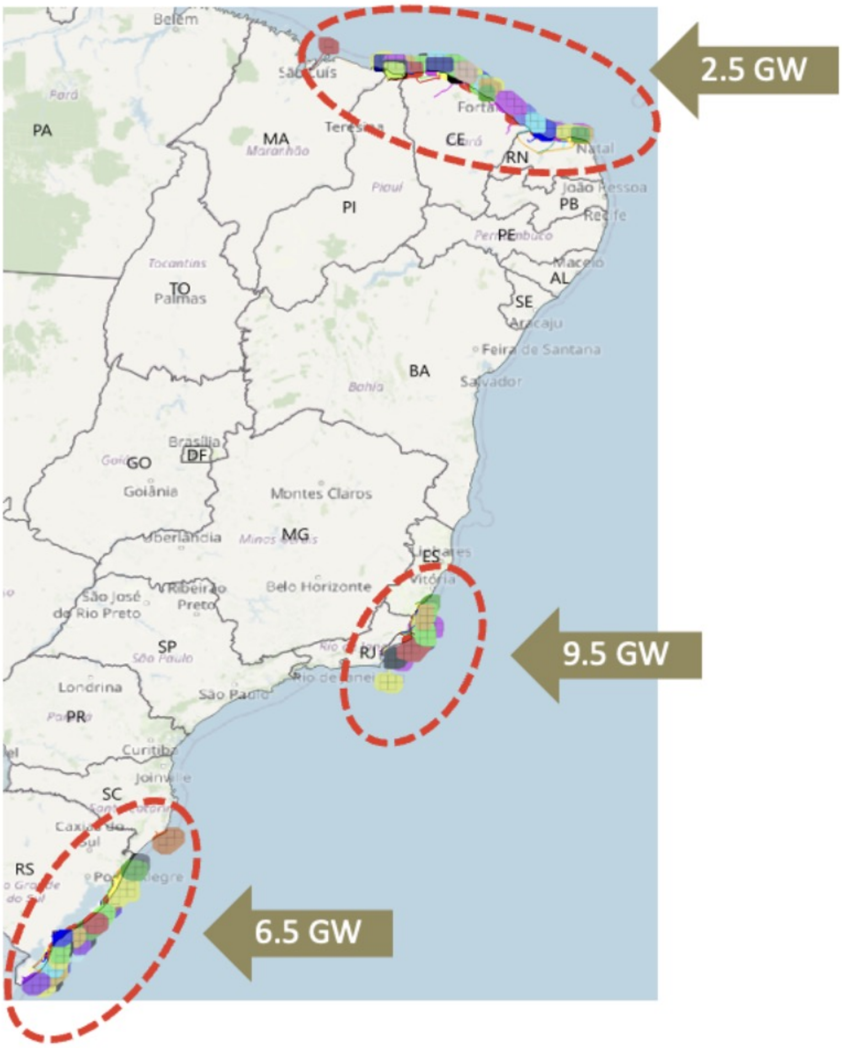


Figure 3: Regional transmission availability[2]
Source: Ibama/ MME map - environmental licensing

The integration of offshore wind generation can contribute not only to system reliability but also to a more balanced allocation of transmission costs across Brazil. Simulations using ANEEL's nodal transmission tariff (TUST) model indicate that locating offshore wind projects closer to the country's main load centres—particularly in the Southeast and South—reduces regional tariff disparities by improving the utilization of the transmission network and redistributing the Annual Permitted Revenue (RAP) more evenly.

2 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.

Under current conditions, the Northeast faces the highest transmission tariffs due to the high concentration of renewable generation and increasingly saturated transmission corridors. Without offshore wind, transmission tariffs in the South correspond to only **42%** of the Northeast's TUST level. With the strategic deployment of offshore wind in the Southeast and South, this ratio increases to **65%**, substantially reducing regional asymmetries while preserving the economic signals that encourage efficient project siting.

These results suggest that offshore wind can generate system-wide efficiency gains beyond electricity production alone. By injecting generation closer to major demand centres, offshore projects reduce pressure on long-distance transmission corridors, improve network utilization, lower electrical losses, and promote a more balanced distribution of transmission costs. Although local power injections slightly increase transmission charges in the South and Southeast, both regions remain highly competitive relative to the Northeast, reinforcing their attractiveness for future offshore wind development.

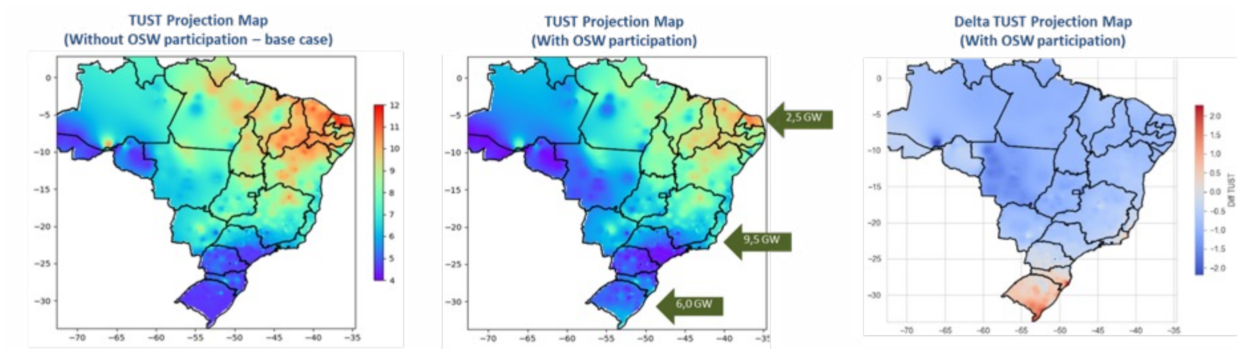


Figure 4: Offshore Wind promotes TUST redistribution

5. The Natural Advantage: Multi-Resource Complementarity

The complementarity analysis assessed the interaction between offshore wind generation and other renewable resources by calculating hourly and monthly correlation matrices using representative generation profiles for offshore wind, onshore wind, solar PV and hydropower.

Table 1: Data-set details for timeseries complementary analysis[3]

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.

3 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.

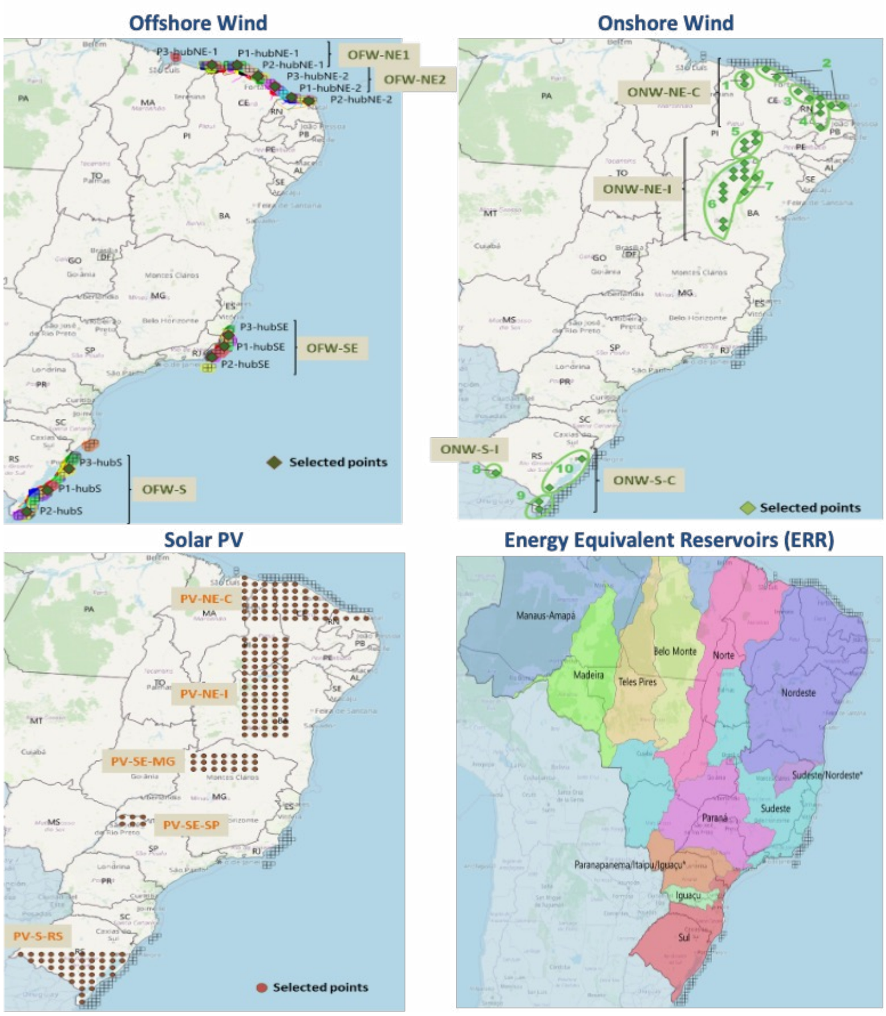


Figure 5: Map identifying typical profiles for complementarity analysis

The collection, processing, and analysis of various ERA-5 data points in the regions of OSW 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.

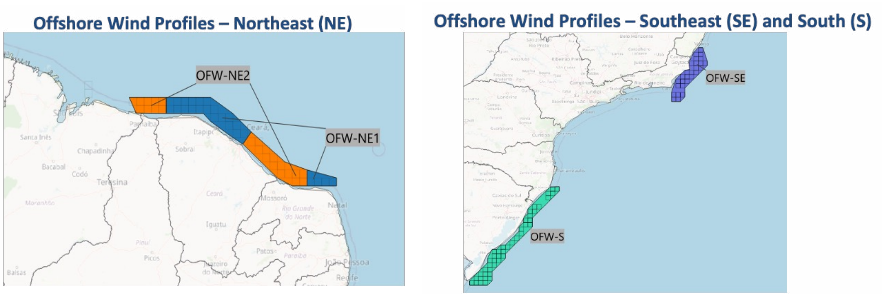
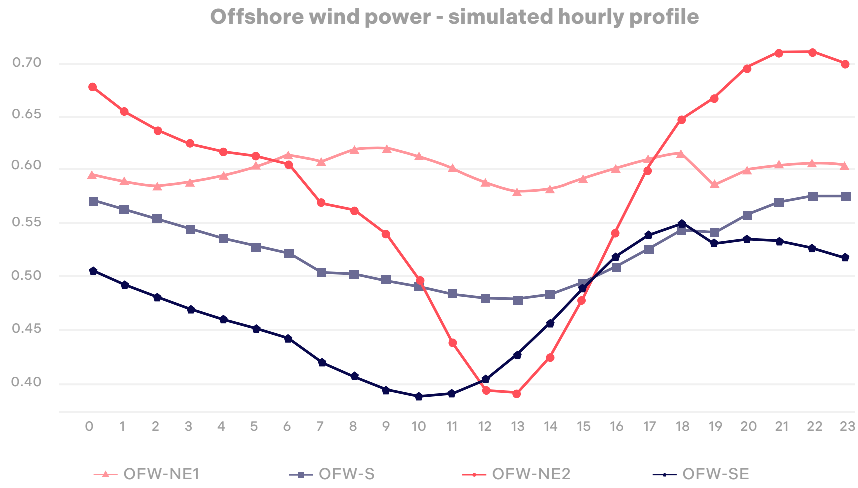


Figure 6: Offshore Wind Profiles in the Brazilian hubs

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).



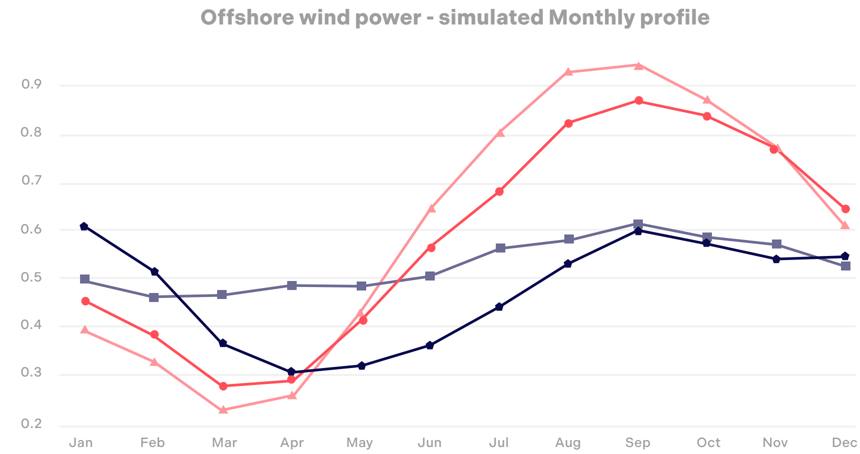


Figure 7: Offshore Wind profiles correlation (hourly and monthly profile)

Offshore and onshore wind generation show predominantly positive correlations, reflecting the similar wind regimes found along the Brazilian coast where most onshore wind farms are located. A few regional exceptions with negative correlations indicate that geographic diversification can provide additional balancing benefits. Although both technologies share similar seasonal patterns, offshore wind consistently achieves higher capacity factors, particularly in the Northeast, resulting in significantly higher firm capacity during critical dry-season months.

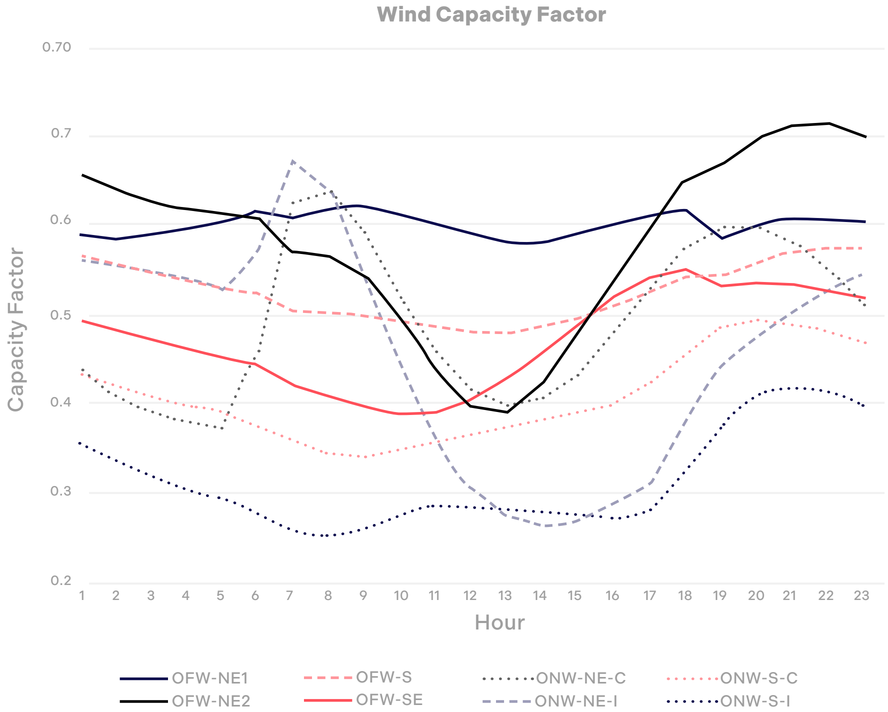


Figure 8: Offshore and Onshore Wind profiles correlation (hourly)

Offshore wind presents a strong hourly negative correlation with solar PV generation. While solar output declines during the late afternoon, offshore wind generation typically increases, helping to mitigate the evening net-load ramp ("duck curve"). This complementary behavior improves system flexibility, increases the utilization of transmission assets and enhances renewable penetration without requiring additional dispatchable generation.

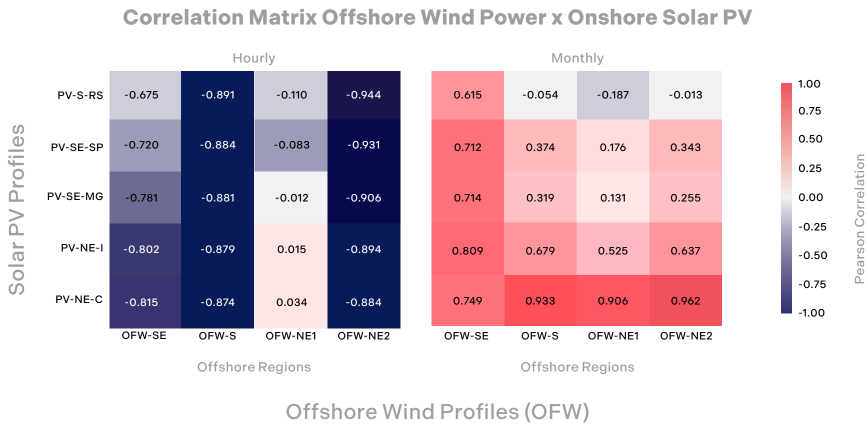


Figure 9: Offshore and Solar PV correlation (hourly and monthly profile)

The complementarity analysis of Offshore Wind and Hydro generation reveals high negative correlations (except in the South ERR and part of the OFW-SE), indicating a significant level of hydro-wind complementarity on 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. Periods of lower hydroelectric availability generally coincide with stronger offshore wind resources, allowing reservoir preservation, reducing curtailment risks and lowering system operating costs. These results confirm offshore wind as an effective hydrological hedge for the Brazilian power system.

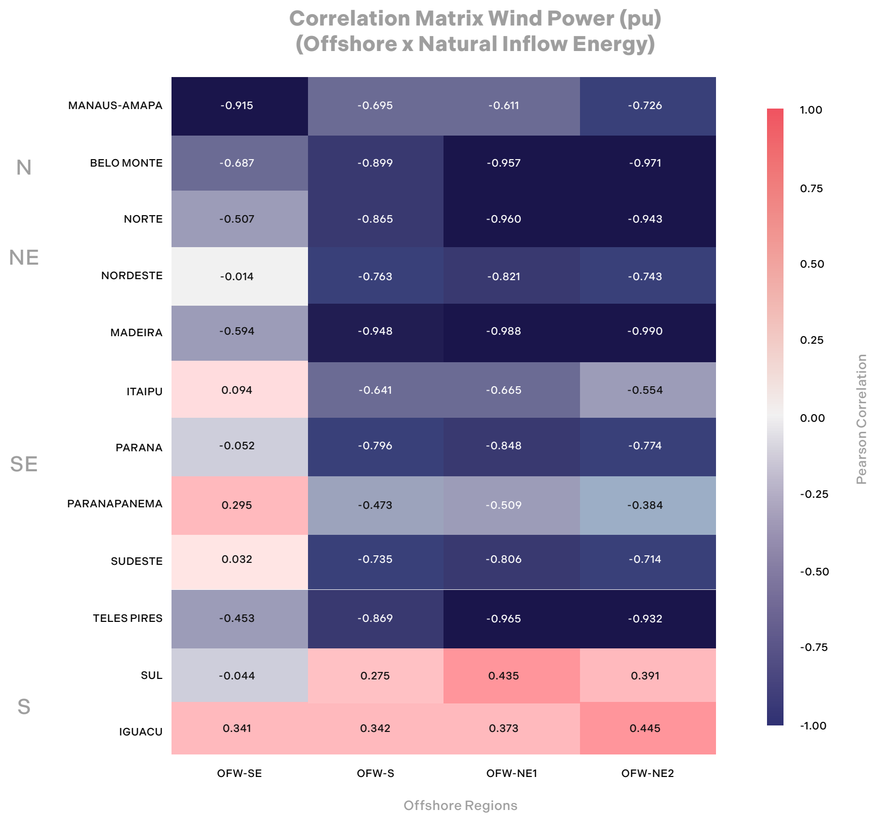


Figure 10: Offshore and Hydro correlation (monthly profile)

Although offshore and onshore wind exhibit similar seasonal generation patterns, offshore wind consistently achieves substantially higher capacity factors, particularly in the Northeast submarket. During the critical dry season (August–October), offshore wind provides nearly twice the reliable firm capacity of onshore wind in the Northeast, highlighting its superior contribution to system adequacy. In contrast, solar PV provides a relatively limited contribution to peak demand due to the mismatch between its generation profile and evening load peaks. Offshore wind also presents a slight advantage over solar PV in the South and Southeast regarding peak-load support. Overall, offshore wind demonstrates significant capacity value, with peak contribution reaching up to 71% in the Northeast, reinforcing its strategic role in enhancing system reliability and supporting security of supply.

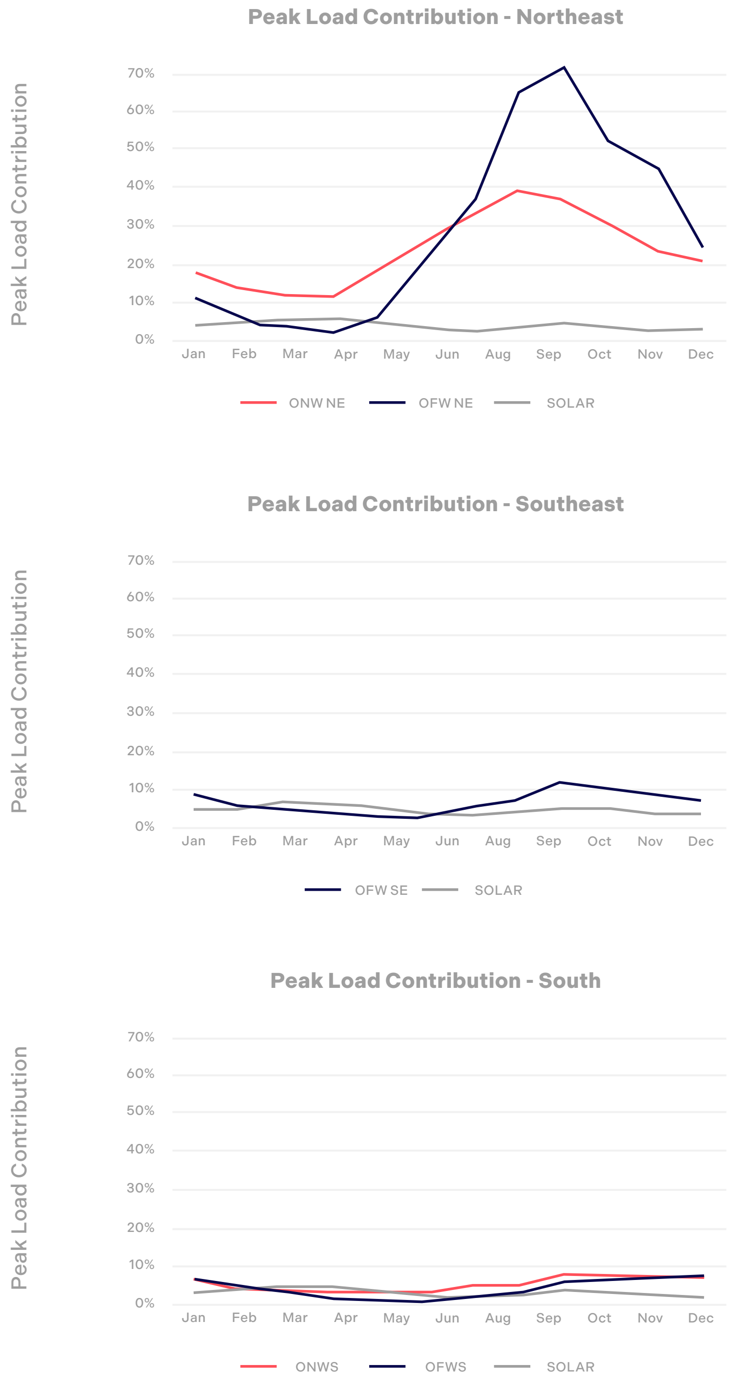


Figure 11: Offshore Outperforms Onshore Wind in Peak Contribution

6. Capacity Expansion: Strategic Scenarios

Eight expansion scenarios were developed using an integrated modeling framework[4] that combines long-term investment optimization with detailed hydrothermal operation simulation. This approach ensures that each scenario is both economically efficient and operationally feasible under the characteristics of the Brazilian power system.

Technology cost assumptions reflect expected 2050 learning curves. Offshore wind is assumed to reduce its capital cost by approximately 30% relative to current values, improving its competitiveness as the technology matures. Onshore wind and solar remain the lowest-cost renewable options, while thermal technologies maintain higher operating costs despite their flexibility. Transmission expansion costs are explicitly represented in the optimization, meaning that generation located farther from load centers must also justify the additional investment required for interregional grid reinforcement.

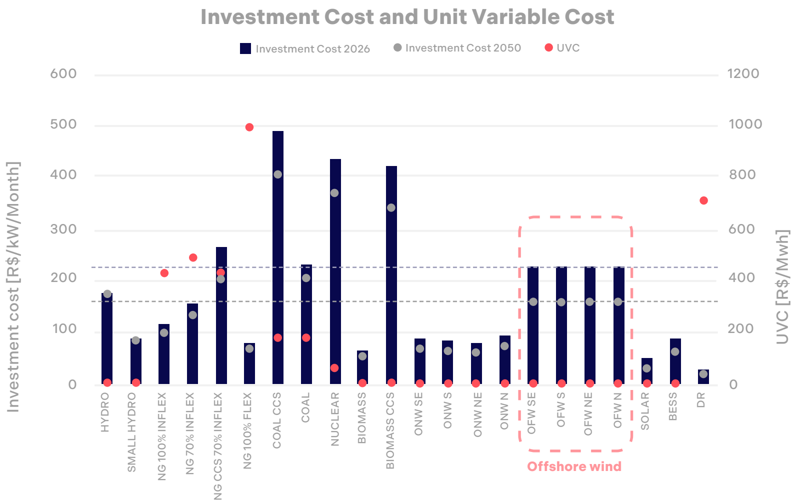


Figure 12: Investment Cost Expectations for Various Sources

4 The analysis follows an iterative two-step process. First, a Python optimization model identifies the least-cost expansion of generation and transmission while satisfying energy balance and firm capacity requirements. Technology-specific annual expansion limits are imposed for each submarket based on historical deployment, technology maturity, regional resource potential, and assumptions consistent with EPE planning studies. The optimized portfolio is then simulated in NEWAVE to capture seasonal variability, reservoir operation, hydrothermal dispatch, and Marginal Operating Costs (CMO). Operational constraints identified in NEWAVE are subsequently incorporated back into the optimization model, and the process is repeated until the target reliability criterion (90% power adequacy) is achieved. Alternative scenarios follow the same methodology, ensuring that all scenarios are compared under an identical reliability standard.

Battery Energy Storage Systems (BESS) are modeled primarily as a capacity resource rather than an energy source. In the optimization model, BESS[5] provides firm capacity while contributing only a limited amount of net energy.

Based on the methodology described, eight scenarios were developed to evaluate the role of offshore wind in the future Brazilian electricity system under different technical, economic, and environmental assumptions. All scenarios were assessed using the same optimization framework and, except where explicitly stated, were calibrated to satisfy an identical system reliability criterion, ensuring that the results are directly comparable.

5 During the NEWAVE simulations, storage is represented through a calibrated high variable operating cost, ensuring that it is dispatched only during the most critical peak-load periods. This methodology preserves a near-zero net energy contribution while fully capturing the reliability, flexibility, and peak-support value of storage, enabling the model to estimate its economically optimal participation in the future generation mix.

Table 2: Scenarios overview[6]

Scenario	Name	Detailed Description
Reference		
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		
Scen 2	18 GW OFW	Designed to assess the impact on total system cost considering the addition of 18GW of offshore wind (OFW) capacity. This amount is the result of the Connection Margin Study, which defined the maximum capacity for each hub.
Scen 6	34 GW OFW	Considers the gradual integration of 34GW of OFW capacity into the generation mix among 2040 and 2050.
Cost Sensitivity		
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 the 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		
Scen 7	Emission 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 compensary scenario with the addition of OFW capacity.***

6 * 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.

The scenarios are organized into four groups according to their analytical objective: (i) the Reference Scenario, which defines the least-cost expansion portfolio; (ii) Additional Capacity Scenarios, which assess the impacts of increasing offshore wind deployment beyond the economically optimal level; (iii) Cost Sensitivity Scenarios, which evaluate the influence of offshore wind investment costs on system expansion decisions; and (iv) Environmental Scenarios, which investigate the effects of greenhouse gas minimization and long-term climate change on the optimal generation mix.

A comprehensive description of the modeling assumptions, optimization parameters, and detailed results for each individual scenario is provided in Appendix 1. The Appendix presents the complete set of assumptions adopted for each case, together with the corresponding expansion portfolios, operational outcomes, and sensitivity analyses that support the results discussed throughout this report.

The scenario analysis demonstrates that the value of offshore wind extends well beyond energy production. Although the technology still requires higher upfront investment than other renewable sources, its contribution to transmission optimization, system reliability, and climate resilience makes it a strategic component of Brazil's long-term electricity mix.

A key finding is the role of offshore wind as a generation-at-load resource. Replacing part of the onshore wind expansion in the Northeast with offshore projects in the South and Southeast reduces dependence on long-distance power transfers, optimizes power flows across the National Interconnected System (SIN), and alleviates curtailment risks in the Northeast by bringing generation closer to the main load centers. This also reduces transmission losses and strengthens overall system resilience.

This geographical redistribution translates into significant transmission savings. Integrating 18 GW of offshore wind reduces transmission expansion costs from BRL 10.4 billion to BRL 7.3 billion, while high-penetration scenarios (33.7 GW) reduce these investments by nearly 60%, releasing capital for other strategic investments in the power sector.

Despite the additional CAPEX associated with offshore wind, total system operating costs remain broadly unchanged. Rather than displacing the existing thermal fleet, offshore wind primarily substitutes the need for major transmission expansion, improving overall system economics without increasing operating expenditures.

The benefits become even more pronounced under climate stress. In scenarios assuming a 20% reduction in hydro inflows, the approximately BRL 70 billion investment in offshore wind is fully offset by lower thermal dispatch costs and the avoidance of energy deficits, effectively transforming offshore wind into a strategic hedge against hydrological risk.

Operationally, offshore wind exhibits strong seasonal complementarity with hydropower, delivering its highest output during the late dry season (August–October). This allows more conservative reservoir operation, preserving stored energy (EARM) for periods of greater hydrological uncertainty.

Although offshore wind still requires CAPEX reductions of approximately 42% to 62% to become fully competitive based solely on generation costs, its system value is substantially greater than indicated by energy costs alone. During peak demand, offshore wind provides nearly twice the firm capacity of onshore wind in the Northeast, reaching a Peak Load Contribution of up to 71%, supporting remuneration mechanisms based on reliability and capacity services.

Finally, the long-term scenarios indicate that the Brazilian power system can successfully accommodate a large offshore wind fleet. Even in the 33.7 GW scenario, the variation in Net Present Value (NPV) is only 1.8% relative to the reference case, demonstrating that large-scale offshore deployment can be achieved with limited impact on total system costs, provided that transmission planning is coordinated with coastal connection hubs.

Overall, the results show that offshore wind enables a structural shift in Brazil's expansion strategy by partially decoupling future load growth from the need for large Northeast–Southeast transmission corridors, resulting in a more balanced, efficient, and climate-resilient electricity system.

7. Market Design: Ancillary Services and Regional Business Models

The economic viability of offshore wind should not be assessed solely through electricity sales. International experience demonstrates that successful projects rely on diversified revenue streams combining energy commercialization with ancillary services, environmental attributes, and long-term contractual arrangements that improve project bankability. Among these opportunities, reactive power support represents one of the most immediate applications for Brazil. Modern offshore wind farms are inherently capable of providing voltage control through power electronic converters, requiring only limited regulatory adaptations. The Dogger Bank Offshore Wind Farm in the United Kingdom, for example, secured a 10-year fixed contract for reactive power provision, illustrating how ancillary services can become a stable source of secondary revenues.

Table 3: Ancillary Services and Remuneration

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

Different remuneration mechanisms have been adopted worldwide to reduce investment risk and accelerate offshore wind deployment. Contracts for Difference (CfDs) have become the dominant support mechanism in Europe by reducing market price uncertainty while preserving competitive market signals. At the same time, Corporate PPAs, ancillary service contracts and Renewable Energy Certificates (RECs) have expanded the range of revenue sources available to developers. Brazil successfully developed its onshore wind industry through competitive auctions, gradually transferring market risks to generators as the sector matured. Offshore wind, however, presents a different risk profile due to its higher capital intensity, suggesting that the first Brazilian projects may require contractual arrangements that provide greater revenue stability while avoiding excessive risk allocation to consumers.

Law 15.097/2025 establishes the legal framework for offshore wind development through competitive auctions for maritime concession areas, requiring concessionaires to pay signature bonuses, occupation fees and royalties. While these instruments create public revenues, international experience shows that high upfront concession costs without corresponding revenue stabilization mechanisms may compromise project bankability. Recent experiences in Germany, the Netherlands, the United Kingdom and the United States have demonstrated that concession models based on significant upfront payments are being reconsidered due to higher interest rates, increased supply-chain costs and narrower project margins. For Brazil's first auction rounds, particular attention should therefore be given to calibrating concession prices according to market maturity, designing appropriate contracting mechanisms, and encouraging complementary revenue streams such as ancillary services and environmental certificates in order to reduce the risk of unsuccessful auctions.

Brazil also presents a unique opportunity to develop offshore wind through region-specific business models, rather than adopting a single nationwide approach. The diversity of energy resources, industrial activities and electricity demand across the Northeast, Southeast and South creates distinct opportunities that should be reflected in public policy and market design. Business models include Power-to-Grid, supplying electricity directly to the National Interconnected System (SIN); Power-to-Load, serving large consumers such as data centers and offshore oil and gas platforms; Power-to-X, enabling the production of green hydrogen, ammonia and synthetic fuels; and hybrid configurations integrating offshore wind with Battery Energy Storage Systems (BESS) and solar PV to improve grid utilization and operational flexibility.

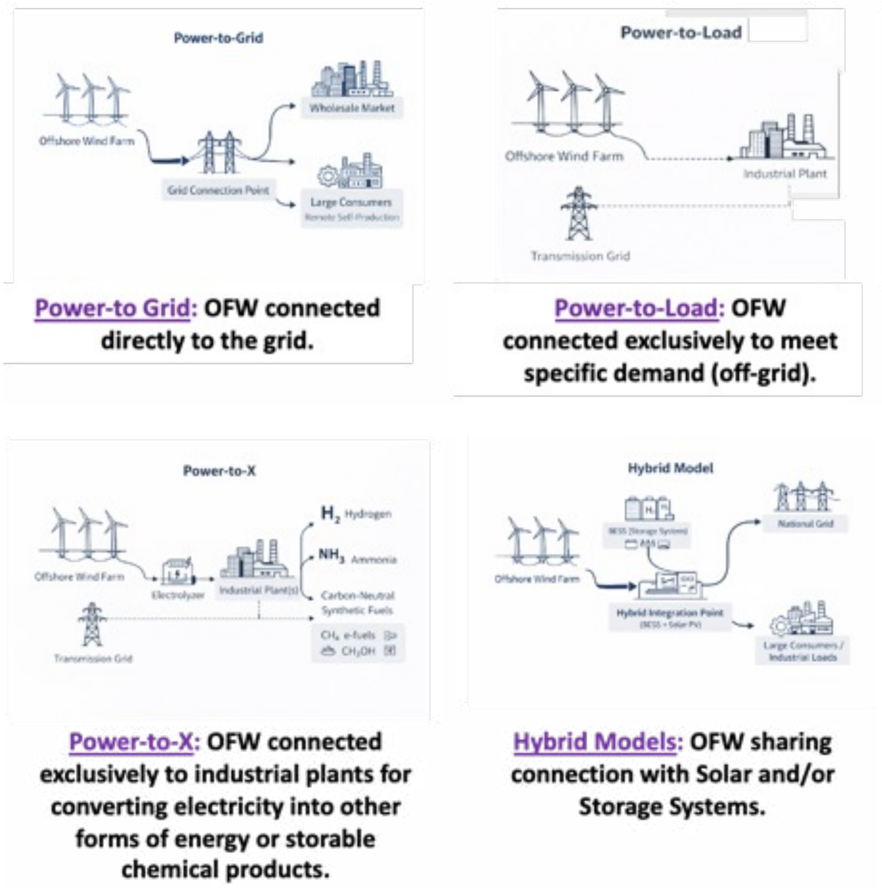


Figure 13: Business Models with Offshore Wind Participation

There is no single business model suitable for all offshore wind hubs in Brazil. Instead, development strategies should leverage the comparative advantages of each region. The Northeast is particularly well positioned for large-scale renewable generation and Power-to-X industries; the Southeast combines proximity to major load centers with industrial demand and offshore O&G activities; while the South benefits from strong system integration, industrial consumption and seasonal complementarity with hydropower. Once connected to the SIN, offshore wind can also provide ancillary services that strengthen system operation and reliability

Table 4: Regional Business Models as per Qualitative Assessment

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.	**O7G & 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 internatiinal 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.	**Meeting the load;** lower yields are offset by direct load proximity and O&G synergies.	**The balanced play;** offers the most favorable grid conditions and unique cross-border integration opportunities. The Southern region appears more promising for initial projects (compared to the Southeastern), considering the general conditions analyzed in this study.

Overall, offshore wind should be viewed not only as a new source of renewable electricity, but as a strategic infrastructure capable of supporting industrial decarbonization, enabling the production of higher value-added green products, supplying large electrical loads with clean energy, and delivering valuable ancillary services to the Brazilian power system. Designing regulatory frameworks and business models that recognize these multiple sources of value will be essential for establishing a competitive and sustainable offshore wind market in Brazil.

8. Conclusions

This study demonstrates that offshore wind can become a strategic component of the Brazilian electricity system by contributing not only to renewable energy expansion but also to transmission optimization, system reliability, operational flexibility, and industrial decarbonization. Its value extends beyond energy production, particularly when evaluated from a system-wide perspective that incorporates avoided transmission investments, complementary generation profiles, and resilience under future climate conditions.

The results show that the development strategy for offshore wind should be region-specific. The Northeast possesses Brazil's largest offshore wind resource but faces severe transmission constraints, with an estimated remaining grid integration margin of approximately 2.5 GW. Consequently, large-scale deployment in this region should be accompanied by local consumption strategies, particularly Power-to-X applications for green hydrogen and derivatives, as well as Power-to-Load projects serving large electricity consumers such as data centers. These approaches reduce dependence on new export transmission corridors while creating opportunities for industrial development and the production of higher value-added low-carbon products.

The Southeast presents the largest transmission integration margin, approximately 9.5 GW, together with proximity to the country's largest electricity demand centers. These characteristics reduce transmission distances, associated losses and expansion costs, making the region particularly suitable for Power-to-Grid projects. The Southeast also offers significant opportunities for Power-to-Load applications through the direct electrification of offshore oil and gas platforms, contributing to the decarbonization of petroleum production.

The Southern Hub offers an available transmission margin of approximately 6.0 GW and exhibits a highly stable wind profile throughout the day. In addition, offshore wind production reaches its seasonal maximum during winter months, coinciding with periods of higher regional electricity demand. Although further cost reductions are required to improve competitiveness, these characteristics make the South an attractive region for supplying industrial loads and strengthening regional security of supply.

From a system operation perspective, offshore wind provides important complementarities with Brazil's hydrothermal system. Generation during dry periods allows hydroelectric reservoirs to preserve stored water for future use. Under unfavorable hydrological conditions, the addition of 34 GW of offshore wind is projected to maintain reservoir storage (EARM) in the Southeast/

Central-West subsystem up to 7.3% above the reference scenario. Offshore wind also reduces the need for thermal generation, shortens transmission distances by locating generation closer to load centers, and complements solar PV by increasing production during the evening period when solar output rapidly declines.

Although offshore wind requires higher initial investment than other renewable technologies, its overall impact on system expansion costs is limited once avoided transmission investments are considered. The scenarios evaluated indicate that the total expansion Net Present Value (NPV) remains only approximately 1.5% above the reference case, while international learning curves suggest significant additional cost reductions through technology maturation, equipment standardization and local supply-chain development.

The study also highlights that offshore wind should be supported by diversified business models and appropriate regulatory mechanisms. Power-to-Grid, Power-to-Load, Power-to-X, and hybrid projects integrating offshore wind with solar PV and Battery Energy Storage Systems (BESS) offer complementary pathways depending on regional characteristics. In addition to electricity sales, offshore wind projects can generate additional revenues through ancillary services, such as voltage and frequency support, which are already remunerated in mature markets including the United Kingdom.

Finally, the success of the Brazilian offshore wind market will depend not only on resource quality, but also on the design of its commercial and regulatory framework. While Law 15.097/2025 establishes the legal basis for offshore wind development, the first concession rounds should carefully balance the application of concession fees with the demand for those concessions. This will be based on competition driven by the underlying need for offshore wind in Brazil which this study has shown. Additionally, the potential for mechanisms that improve revenue stability, such as Contracts for Difference (CfDs), will also drive competition and its important that route to market auctions are held at an appropriate time when development risk that underpins price setting has been addressed sufficiently so no risk premiums are applied-

About Ocean Energy Pathway

Ocean Energy Pathway accelerates global offshore wind growth through programmes which support the energy transition, enhance marine ecosystems and empower local communities. We provide expert, independent support to governments and key decision makers to fast-track offshore wind worldwide. Through collaboration with leaders in policy, industry, and conservation, we help shape sustainable solutions for the long-term growth of offshore wind. Ocean Energy Pathway owns the offshore wind POWER Library, in collaboration with Climate Policy Radar, to help policymakers easily find curated reports and policies related to offshore wind. Headquartered in the UK, we work in Australia, Brazil, Colombia, India, Japan, Mexico, the Philippines, South Korea, and Vietnam with ongoing projects in several other countries.

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Founded in the early 1990s, MRTS Consultoria is a leading Brazilian consultancy specializing in power system planning, energy modelling, electricity market regulation, and transmission planning. With partners bringing around 40 years of experience in the Brazilian power sector, the company provides high-level technical support for decision-making through advanced analytical methods, proprietary tools, and internationally recognized modelling platforms.

MRTS combines strong market expertise with close ties to academia. Its multidisciplinary team of engineers, researchers, and university professors has an extensive publication record and delivers innovative, evidence-based solutions across energy planning, reliability assessment, regulatory studies, economic analysis, and research and development projects.

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