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Executive summary

This document presents a comprehensive assessment of hybrid offshore renewable energy systems, focusing on integrating wind with wave and solar PV technologies. The study evaluates various configurations' performance, curtailment, and complementarity, with specific case studies at WindFloat Atlantic (for wind) and Aguçadoura (for waves).

Key findings reveal that each renewable technology exhibits distinct energy profiles. Wind energy is highly variable and intermittent, while wave energy offers, theoretically, a higher capacity factor with stable short-term output but significant seasonal variations. Solar PV, in contrast, follows a predictable diurnal cycle with production confined to daylight hours, resulting in a lower capacity factor and minimal standalone curtailment. These differing characteristics provide the basis for effective hybridization strategies, which can reduce overall curtailment and improve grid stability.

The analysis shows that hybrid systems combining wind with wave resources have the potential to reduce curtailment, when compared to standalone wind or wave configurations, despite a positive Pearson correlation indicating that these technologies often peak simultaneously. In contrast, the wind and solar PV hybrid exhibits lower curtailment and a negative Pearson correlation, highlighting strong complementarity between wind and solar generation profiles. In scenarios where export cable capacity is a limiting factor, modest increases in capacity (from 25 MW to 29 MW for wind+solar and to 27 MW for solar-only) can eliminate curtailment, further underscoring the importance of aligning infrastructure with generation profiles.

The document also explores operational and economic aspects of hybrid systems, noting that hybridization enables shared infrastructure, joint operations, and improved maintenance strategies. In addition, the emerging potential of wave energy, despite its current high cost per MWh, is expected to benefit from technological advancements and integration with other offshore renewables. Future research directions include enhancements in grid infrastructure, advanced forecasting techniques, energy storage, and hydrogen production—each critical to supporting the expanding role of hybrid offshore renewable energy systems.

Overall, this study confirms that strategic hybridization, tailored to local resource characteristics and infrastructure constraints, significantly enhances renewable energy production, minimizes curtailment, and supports the stable operation of future grids, paving the way for more economically viable and resilient offshore energy solutions.



List of abbreviations

WEC: Wave Energy Converter.

RES: Renewable Energy Sources.

WFA: WindFloat Atlantic, offshore floating wind farm near Viana do Castelo in Portugal.

H2: (di)hydrogen.

CAPEX: Capital Expenditure.

OPEX: Operational Expenditure.

EU-SCORES: European Scalable Offshore Renewable Energy Source.

O&M: Operation & Maintenance.

REN: Rede Eléctrica Nacional.

NPV: Net Present Value, the difference at a given time (in this case, at the end of the project) of the cash inflow, and the cash outflow.

LCOH: Levelized Cost of Hydrogen, roughly translates to the cost of the hydrogen for the producer, taking all expenses, revenues and discount rate into account.

LCOE: Levelized Cost of Energy, roughly translates to the cost of the energy for the producer, taking all expenses, revenues and discount rate into account.



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1 Introduction and Objectives

1.1 Context and Motivation

As nations set ambitious targets for carbon neutrality, the energy landscape is shifting from conventional sources toward renewables. Renewable energy—primarily hydro, wind, and solar—is already reshaping power generation. Yet, challenges such as grid stability and intermittency remain. Hydropower is geographically limited and weather-dependent, whereas solar exhibits significant diurnal and cloud-induced variability, and wind energy, while promising, is inherently stochastic [1].

In this context, wave energy emerges as a potential complement. While historically less mature than wind energy, wave power offers advantages in predictability and lower variability over time [2]. With the European Union targeting at least 1 GW of ocean energy (excluding wind) by 2030 [3], a rigorous analysis of resource complementarity is crucial as the European renewable energy portfolio is diversified.

Wave energy is one of the most potent yet underutilised renewable resources. Literature currently estimates that the annual global potential for wave energy production is approximately between 500 to 17,500 terawatt-hours (TWh) [4]. This value would be enough to cover the global final electricity consumption in 2023 of 25,278 TWh [5], about 12% of which corresponds to Europe's total annual electricity consumption of 2,917 TWh [6].

Europe aims to install between 178 and 494 MW of wave energy by 2030, reflecting its growing commitment to harnessing the power of the ocean for sustainable energy. This investment can result in lower levelized costs of energy (LCOE) of 110 €/MWh to 150 €/MWh (high versus low growth scenarios) [7], which are still higher than the LCOE of more established renewable generation sources such as Solar PV (LCOE=41€/MWh), onshore wind (LCOE=31€/MWh), offshore wind (LCOE=69€/MWh) and hydropower (LCOE=53€/MWh). However, this change represents a significant improvement, and costs should continue to decrease as wave energy technologies mature and become more competitive [4] [8].

As wave energy is influenced by wave height, speed and frequency, this technology is most suitable for islands or coastal areas and particularly offshore (since offshore wave energy density is higher than nearshore). This becomes particularly relevant as more than 40% of Europe's citizens live in coastal regions and can have their energy needs met using these technologies [9].

A powerful solution for maximizing renewable energy production is hybridizing offshore wind and wave energy, as these power sources complement each other: while wind energy is highly variable, wave energy is more consistent, providing stability when wind speeds are low. When wind speeds are high, both systems ensure a steady, reliable energy supply, helping reduce reliance on other fuel sources, such as fossil fuels.

Furthermore, offshore infrastructure such as platforms and cables can be shared by wind and wave energy technologies, combining in a more efficient use of these resources, and reducing construction and maintenance costs, while minimizing environmental impacts. This solution results in high grid stability and scalability for future expansion, making it a great opportunity to increase the resiliency of the entire energy generation process.



2 Wave Energy: Fundamentals, History and Technology

2.1 Introduction to Wave Energy

Wave energy represents the conversion of kinetic energy from water surface undulations into electricity. Unlike wind, which is primarily characterized by wind speed, the potential of wave energy is mainly governed by two parameters: wave height and wave period. This dual parameter dependency introduces additional complexity in resource assessment but also offers opportunities for more predictable output when averaged over time. The exploitation of wave energy dates back to the late 18th century, with early experiments in France. In the 19th century, various devices attempted to harness raw mechanical power directly from waves.

A major breakthrough came during the 1970s oil crisis with the development of innovative concepts such as the “Salter’s Duck” [10]. Although interest waned when oil prices dropped, modern advances in materials science—particularly the use of composites and advanced machining—have renewed the prospect of economically viable WECs.

Additionally, regarding the energy conversion fundamentals, waves are the visible manifestations of energy moving through water. The energy content of waves can be approximated by a formula that incorporates water density (ρ), gravitational acceleration (g), significant wave height H_{mo} (not the height of a single wave, but rather a statistical measure describing the distribution of the sea state), and wave energy period T_e (reflects the wave energy flux differently from other wave period definitions such as mean zero crossing).

$$E = \frac{\rho \times g^2 \times H_{mo}^2 \times T_e}{64\pi} \quad 1-1$$

Concerning the technological approaches, unlike wind power, which has largely standardized around the three-blade horizontal-axis turbine, wave energy conversion is pursued through various technological pathways, such as:

- **Oscillating Water Columns:** these systems harness water motion to displace air, which then drives a turbine. Example: Mutriku Wave Energy Plant in Spain, one of the world’s first commercial wave energy plants, seen in Figure 2-1 [11]. In this 296 kW project, wave motion is used to compress and decompress air, which then drives 16 turbines to supply clean energy.
- **Overtopping WECs:** similar in concept to air-flow devices, these use the moving water directly to activate a turbine. Example: the Wave Dragon project uses overtopping waves via a concentrator upwards ramp to channel water utilising the small head different to drive appropriate Kaplan turbines to generate electricity similarly to the principles of a one way hydroelectric dam, a functional and visual similarity as seen in Figure 2-2 [12].
- **Terminators:** here, the relative motion between two bodies drives hydraulic fluids that power turbines. Example: the Oyster Wave Energy Converter, seen in Figure 2-3, uses waves’ motion to pressurize a fluid using hydraulic pistons [13]. The high-pressure fluid is later used to drive an onshore turbine.
- **Point Absorbers:** these devices convert the relative motion directly into electrical energy via mechanical or electromagnetic converters. Example: the Archimedes Waveswing, which can be viewed in Figure 2-4, a fully submerged device that uses pressure differentials to move the device’s upper part up and down [14]. CorPower’s solution also fits in this category, as it is a point absorber WEC that is floating on the surface of the water. This drives a linear generator to produce electricity without using fluids or air compression.



- Attenuators: these solutions have high power harnessing potential related to their extended proportions, allowing for large-scale generation applications. Example: measuring 180 meters in length, 4 meters in diameter and weighing about 1350 tonnes, the Pelamis P2 prototype seen in Figure 2-5 was comprised of 5 sections whose movement was harnessed by hydraulic rams at the joints to drive electrical generators [15].



Figure 2-1 Mutriku wave energy plant [11].



Figure 2-2 Wave Dragon device [12].

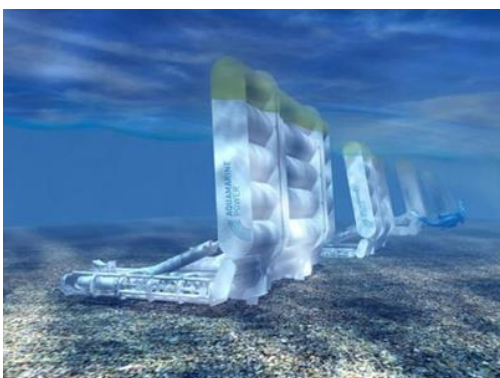


Figure 2-3 Oyster wave energy converter [13]

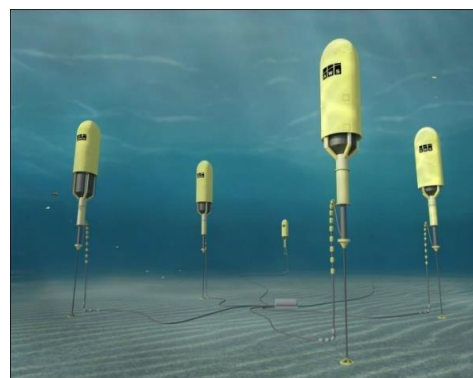


Figure 2-4 Archimedes Waveswing buoys [14].



Figure 2-5 Pelamis P2 attenuator [15].

Each approach has a distinct operational profile, influencing factors such as the range of effective wave heights, power output characteristics, and CAPEX/OPEX considerations. Below, in Figure 2-5 and Figure 2-6 the power matrix that retrieves the power output (in kW) of both a CorPower buoy and Pelamis' semi submerged attenuator, given the wave height (H_s)



and period (T_p), is illustrated [4]. Even though the Figures have different axis, one of the most important characteristics of the WECs is shown: the ability to operate in different conditions.

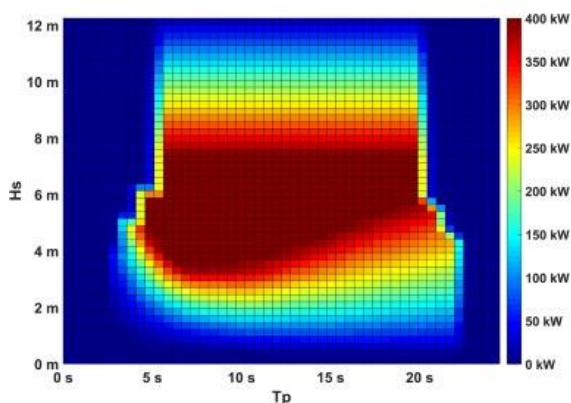


Figure 2-6 - CorPower WEC power matrix [4]

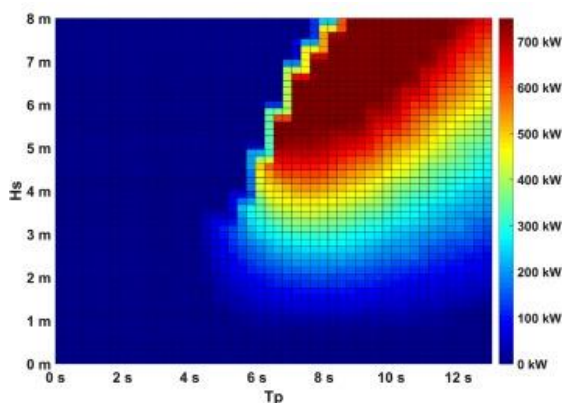


Figure 2-7 - Pelamis WEC power matrix [4]

By analysing Figure 2-6, it is possible to conclude that the CorPower Buoy has a broader power output for a large range of wave height and period, thus can theoretically attain a much higher capacity factor than the Pelamis WEC in Figure 2-7. A higher capacity factor means that more energy is generated relative to the device's rated capacity, even in less-than-ideal maritime conditions, improving both revenue potential and stability (lower downtime and variability). Consequently, in this case, CorPower's device's power take-off system and control strategies might be more optimized at efficiently capturing and converting wave energy across varying sea states.

A Floating two-body heaving converter's power matrix is represented in Figure 2-8 [16]. This device, inspired by the WaveBob, has a peak power output of 1000 kW and is typically designed for smaller-scale energy production. The optimal working conditions are with wave heights of 5-7 meters and 7-12 seconds peak periods, a small area of optimal operation thus translating to a low capacity factor. Since it does not require extremely high waves to achieve the best energy capture values, this device is best suited to be used in moderate sea states.

The 3D power matrix of a floating oscillating water column (F-OWC) is seen in Figure 2-9 [16]. With a higher power output of over 2800 kW and optimal conditions of wave heights between 5.5 to 7 meters and peak periods of 9 to 17 seconds, this technology's capacity factor is much higher than the floating two-body converter's. The steep incline of power output indicates this device's power generation capacity has a high dependence on wave height.

A bottom-fixed oscillating flap (B-OF), which has its power matrix displayed in Figure 2-10, can reach peak power output values of almost 3200 kW, meaning it has the best power output of the 3 displayed devices [16]. This WEC also has the highest capacity factor of the 3, as its optimal working conditions are in wave heights of 4.5 to 7 meters and peak periods of 7 to 17 seconds. In a similar fashion to the Floating Oscillating Water Column, power output increases significantly in wave heights above 4 meters with its highest output values with waves of 7 meters, with a more gradual increase than the latter.



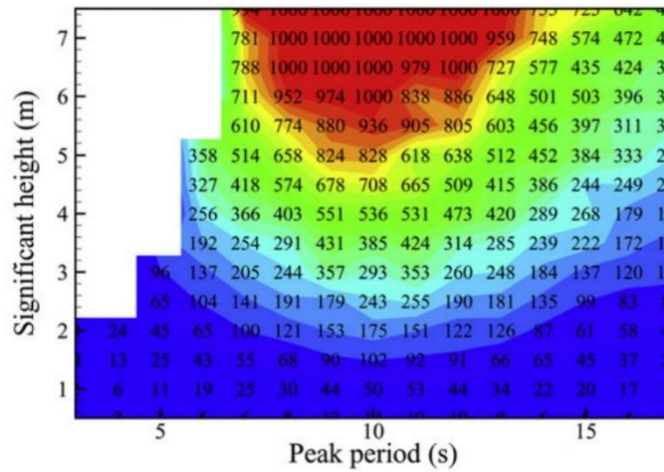


Figure 2-8 Power matrix of a floating two-body heaving converter [16].

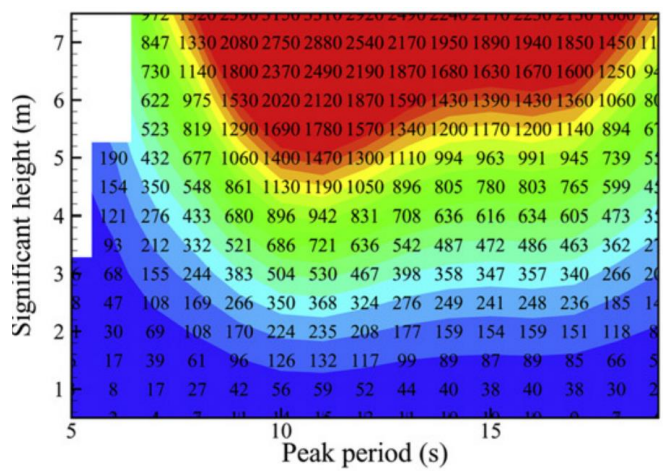


Figure 2-9 Power matrix of the floating oscillating water column (F-OWC) [16].

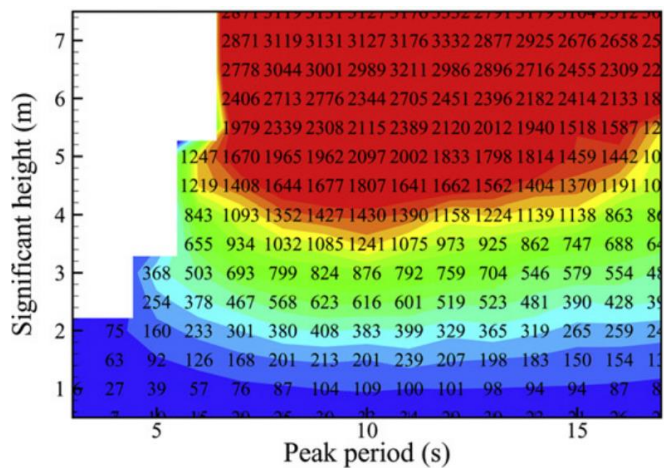


Figure 2-10 Power matrix of the bottom-fixed oscillating flap (B-OF) [16].



In conclusion, the displayed WECs have very distinct performance parameters based on their power output and optimal operating conditions which should be carefully examined to optimize resource allocation and energy output.

2.2 Review of Existing WEC Technologies

Since the early conceptual designs such as Salter's Duck, numerous demonstration projects have been initiated. Despite the technical challenges and economic hurdles—often linked to the harsh marine environments—the sector is experiencing renewed interest.

Several near-future WECs were compared for study in the region along the Galician coast. Their WEC types, the mode to extract energy, the maximum value in the power matrix (P_{max}) and the power take-off system (PTO) are all represented in Table 2-1. The resulting average LCOE of each of these WECs considering all CapEx ranging from 1.5 M€/MW to 5 M€/MW with an increment of 0.5 M€ are displayed in Figure 2-11 for a discount rate of 10% [17]. This graph shows the consistent competitiveness of the RM5, Atargis and Oyster projects with the lowest LCOE values, thus displaying strong economic potential. On the other hand, the Pelamis, Pontoon, OceanTech and Wave Dragon projects resulted in the highest LCOE values, reflecting greater cost challenges.

Each of the presented technologies operates at different power capacities, depths and energy conversion methods. Large-scale solutions, such as Wave Dragon and Pelamis are mostly high-capacity, while smaller point absorbers like Aqua Buoy have lower power ratings but may be easier and less costly to deploy and maintain.

Most of the presented WECs operate in deep water of depths between 50 and 100 meters and tend to operate with hydraulic or pneumatic systems (e.g., Pelamis, Aqua Buoy, Wave Bob, and OR Buoy), while only a few like Oyster and Wave Roller Type operate in shallow water and usually rely on direct water flow or surge mechanisms (<20m depth). Technologies like Ceto and Wave Dragon are used in nearshore deployments that vary between 20 and 50 meters of water depth.

The most common energy modes are heave and surge-based technologies. Heave-based devices move up and down with the waves, while surge-based ones use the water's horizontal motion. The overtopping system used in Wave Dragon stands out as a unique, high-power device that collects wave water at a higher level and releases it through turbines, thus producing energy.

Depending on the deployment conditions, available infrastructure, system requirements, different solutions may stand out: if high power is required, Wave Dragon or Pelamis can be used; if the system is required to operate in shallow waters, solutions like Oyster or Wave Roller Type could be ideal. Hydraulic systems are efficient although they may result in higher OpEx, while air flow solutions have less moving parts, reducing the required upkeep.

Table 2-1- Main characteristics of selected WEC technologies [17].

WEC	Type	Energy mode	Max Power (kW)	Dimensions	Weight	PTO System
Aqua Buoy	Point Absorber	Heave	150	44 m (L) x 11 m (diameter) [18]	-	Hydro turbine



Atargis	Terminator	Heave and Surge	2530	60 m (L) [19]	-	Hydro turbine
Ceto 5	Point Absorber	Heave	240	6 m (H) x 20 m (diameter) [20]	-	Hydro turbine
OE Buoy	Oscillating water column	Oscillating pressure differences	2880	40 m (L) x 20 m (W) 16 m (H) [21]	600 tonnes [21]	Pneumatic air turbine
Oceantec	Attenuator	Pitch	500	-	-	Pneumatic air turbine
Oyster	Oscillating Surge	Surge	290	18 m (L) x 12 (H) [22]	-	Hydro turbine
Pelamis P1	Attenuator	Heave and sway	750	140 m (L) x 3.5 m (diameter) [23]	750 tonnes [23]	Hydraulic motor
Pontoon	Point absorber	Heave	3619	-	-	Hydro turbine
RM5 SeaPower	Oscillating Surge Attenuator	Surge	360	45 m (L) x 29 m (W) x 19 m (H) [24]	800 tonnes [24]	Hydraulic motor
Wave Bob	Point Absorber	Heave	1000	-	-	Hydraulic motor
Wave Dragon	Overtopping	Overtopping	7000	140 m (L) x 95 m (W) [25]	237 tonnes [25]	-
Wave Roller	Oscillating Surge	Surge	3332	30 m (L) x 25 m (W) x 5 m (H) [26]	3000 tonnes [24]	Hydraulic motor

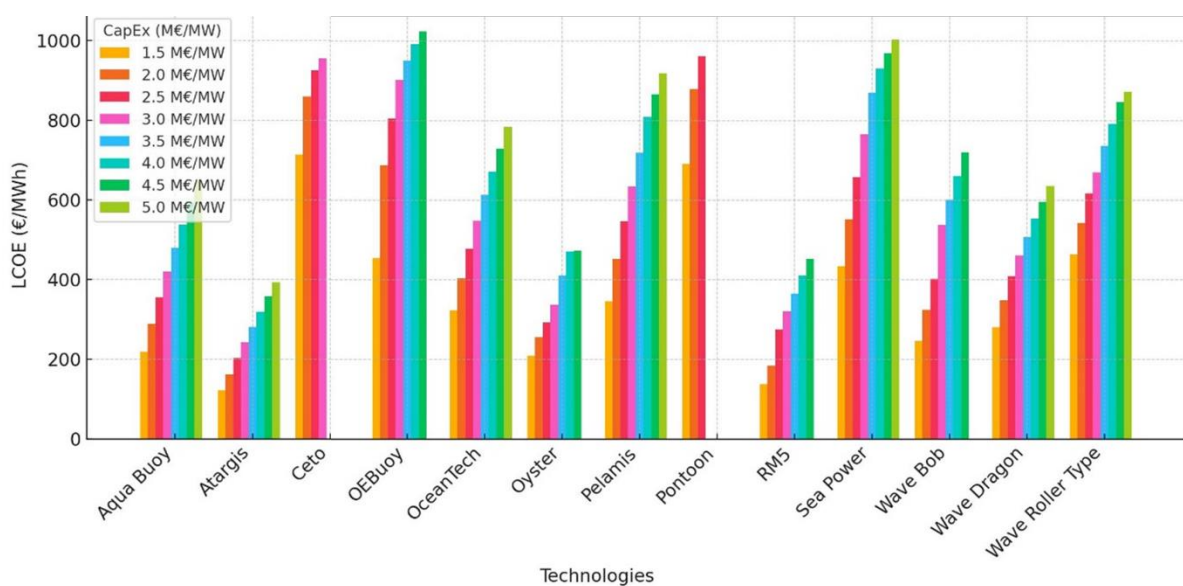


Figure 2-11 LCOE (€/MWh) per WEC based on CapEx (M€/MW), for a discount rate of 10%. Adapted from [17].

This considered dataset highlights a wide range of WECs and each of them has advantages and trade-offs. The diversity in WECs that are currently being developed is a great indicator of the progress in this field. Continuous innovation, optimization and adaptation to various working conditions ensure that wave energy can contribute significantly to the global energy mix in the future.



2.3 Market Trends and Learning Curves

Electricity markets operate on an hourly basis, involving suppliers, consumers, transmission system operators, distribution network operators, and regulators. These markets vary geographically, functioning at national, regional, or even cross-border levels, as seen with the integrated market of Portugal and Spain. The core principle of market operation is balancing supply and demand in real time, with electricity prices fluctuating hourly. When energy supply is abundant and demand is low, prices drop—sometimes even turning negative—whereas high demand and limited supply drive prices up. Many renewable energy sources are variable and depend on accurate weather forecasts, though some—such as hydroelectric with reservoir storage or biomass—are dispatchable. Dispatchable generation, traditionally dominated by fossil fuels, enhances grid stability but, in the case of fossil fuels, generally entails higher economic and environmental costs [27].

The energy crisis triggered by the Russia-Ukraine conflict in 2022 led to unprecedented electricity price surges, particularly in gas-dependent nations. In the Iberian Peninsula, average grid prices rose from around 50 €/MWh before 2021 to 167 €/MWh in 2022, before stabilizing at 63 €/MWh in 2024. Italy experienced a sharper increase, with prices escalating from 55 €/MWh in 2021 to 320 €/MWh in 2022, then settling at 130 €/MWh in 2024. Projections suggest a gradual decline in electricity prices, particularly in countries with significant renewable energy capacity. By 2035, estimated market prices are expected to be 60–70 €/MWh in Portugal, Spain, the Netherlands, and the United Kingdom, 70–80 €/MWh in France, and 100 €/MWh in Italy [19] [28].

Regarding the learning rates and future costs for offshore wind and wave technologies, there is already a compilation study and market projection done within the EU-SCORES project. The LCOE of floating offshore wind is expected to be between 121 and 170 €/MWh by 2030 and between 32 and 48 €/MWh by 2050, with a LCOE learning rate of 14.1%, as seen in Figure 2-12. For wave energy, public reports project that in Europe by 2030, between 178 and 494 MW of wave energy will be deployed, leading to an LCOE estimate of 110 and 150 €/MWh, and Corpower Ocean's current LCOE model and sales forecast as an LCOE estimated of 154 €/MWh in 2030, 53 €/MWh in 2040 and 34 €/MWh in 2050. The learning rate of wave energy is estimated to be between 15% and 18.6%. Another conclusion from this analysis is that if 10% of predicted floating offshore wind global capacity is hybrid farms, LCOE reduces on average by 51% for wave energy between 2020 and 2050 [21] [29].



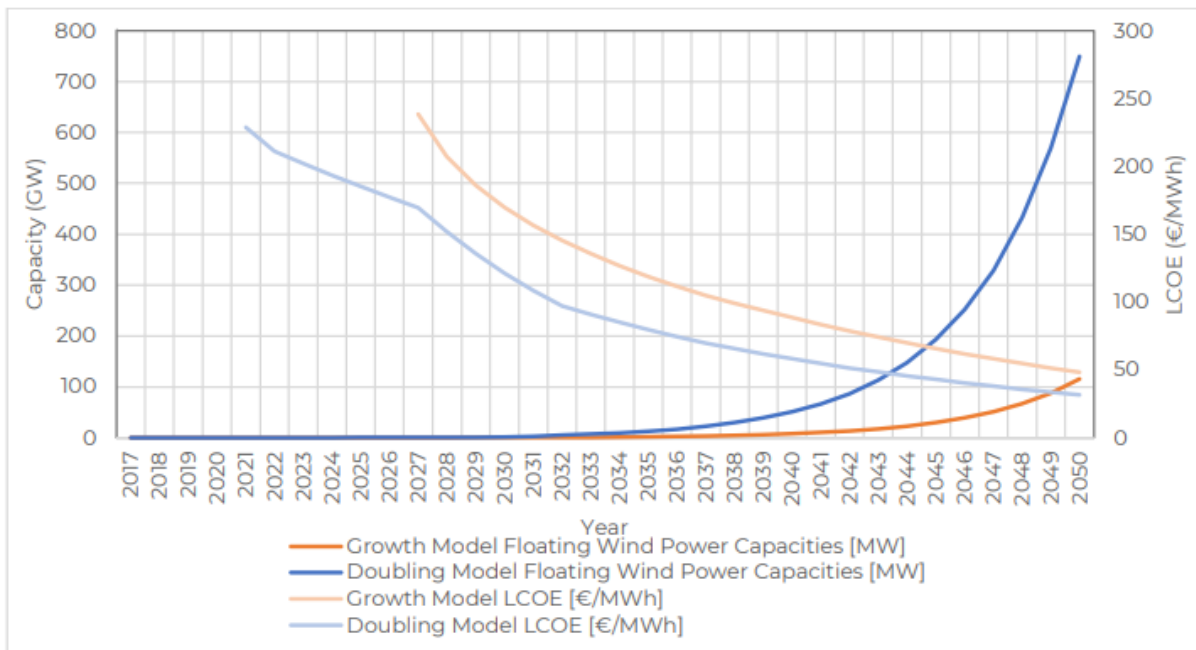


Figure 2-12 - Projected floating offshore wind capacities and corresponding LCOE using reference technology fixed offshore wind, growth and doubling models. Source:[28].



3 Hybrid Offshore Renewable Projects

3.1 State of the Art

Wind energy has been moving offshore due to several reasons, such as:

- Stronger and more consistent wind patterns, leading to increased and more consistent energy production and higher capacity factors when compared to onshore wind energy production.
- Decreased usage of land, especially significant in densely populated regions in which visual and noise impacts are greater.
- Less environmental impact.
- Much larger turbines can be used to harvest even more energy, since land-based space restrictions do not apply. Floating wind devices are starting to appear as a solution for energy production in deep waters, where even stronger winds exist.

Wind turbines' rotor diameter and hub height have increased significantly over the last 2 decades, along the rising power production capacity. From having less than 50m in diameter in the late 1990s, rotors in 2025 have reached more than 275 meters in diameter. Larger rotors harness more energy from the wind as the useful area increases, thus also increasing energy output and maximizing energy yield per turbine and reducing the number of needed turbines in a wind farm. Hub heights have had a slower increase rate when compared to rotor diameters, however, these have also increased significantly to over 100 meters in recent years. As turbines are placed higher above the water surface, they are exposed to stronger and more consistent wind speeds, reducing turbulence and improving production efficiency [30].

The previously mentioned factors have paved the way for the power rating per turbine (nameplate capacity) to grow steadily from under 1 MW in 2000 to having installations of 12 MW turbines with 15 MW prototypes turbines under prototyping in 2023.

Major investment in clean energy translated in the evermore competitiveness of offshore wind energy production. In the past decade the cost of offshore wind energy has decreased from over 250€/MWh to under 80€/MWh, making them now on par with coal [31].

Hybrid renewable energy projects combine different energy generation methods within a system to achieve higher efficiency, reliability, and economic viability. By diversifying the amount and type of energy sources, it is possible to synergise complementary characteristics these might have. As wind energy benefits from being installed in an offshore environment, hybridising wave energy with offshore wind is a promising approach to overcome the variable and intermittent nature associated with standalone technologies. This approach is particularly attractive for coastal regions and island grids.

Hybrid offshore wind and wave systems combine offshore wind turbines that capture energy from varying wind speeds at heights of over 100 meters with WECs that are characterized by having more consistent production patterns than wind. Thus, by integrating both solutions these systems can benefit from a more consistent energy production which increases grid stability and decreases these investments' LCOE.

As previously mentioned, one key advantage of combining offshore wind and wave energy is reducing power output fluctuations. Offshore wind power is highly variable due to the uncertainty related to harnessing energy from the wind. However, waves can persist even when wind speeds are low, always ensuring continued energy production. In fact, the combination of wind-wave systems can reduce power variability by 30-40% when compared to standalone wind solutions [20] [32]. Reduced swings in generation and smoother power



outputs reduce the need for battery storage or using grid support mechanisms. However, when paired with storage solutions there is potential for dispatchable power to be used as a service.

Wave energy converters (WECs) can be integrated into planned or even existent offshore wind farms leading to notable cost reductions by sharing significant infrastructure, such as:

- Mooring and foundation structures, which can include floating platforms that support both systems.
- Grid connections, namely underwater electrical cabling.
- Maintenance staff and equipment, reducing maintenance costs by 20-30% [33].

The characteristics of a shared system design can reduce the capital cost per installed MW and can reduce the LCOE of the entire project, when compared to investing in independent installations.

Choosing the most suitable WECs to integrate these hybrid projects is vital to optimize the possible synergies that can be created. The best WEC options for wind offshore hybridization are described below and summarised in Table 3-1.

Table 3-1 - Comparison of different wave energy converters in hybrid systems.

Parameter	Point Absorbers	Oscillating Water Columns (OWCs)	Attenuators
Footprint	Small	Medium	Large
Structural Integration	Can be moored independently or on floating platforms	Can be integrated into turbine foundations	Requires large mooring system
Power Output	Up to 1000 kW [34]	Up to 1000 kW [35]	Up to 1000 kW [36]
Suitability for Floating Wind	High	High (Stabilizes platform)	High (Shares mooring, reduces wave impact)
Suitability for Fixed Wind	High	High (Integrates into foundations)	High (Requires floating platforms)
Dimensions	Up to 20 m (diameter) [37]	Up to 50 m (length), 30 m (width) and 12 m (height) [38]	Up to 180 m (length) and 5 m (diameter) [39]
Weight	Up to 70 tonnes [40]	Up to 500 tonnes [38]	Up to 1350 tonnes [39]

3.2 Review of Existent EU-Funded Projects

Different offshore solutions are gaining attention due to their potential to increase energy reliability, optimize resource allocation, and reduce costs. Across Europe, several pioneering projects have started to explore offshore wind energy's potential to the fullest, aiming to provide more stability in power generation, shared infrastructure and improve the overall efficiency and profitability of these investments.

POSEIDON

The POSEIDON project aimed to advance Floating Power Plant's wind-wave hybrid device. With a total budget of €1,634,500 and a project duration of nearly two years, this project used Floating Power Plant's P80 platform, a hybrid floating platform that integrated an 8 MW wind turbine with multiple point absorbers. The P80 device underwent extensive testing, including



This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

1:44 scale model trials at Aalborg University for performance and design improvements. With a 600 GW market potential in Europe, this solution validated the feasibility of wind-wave energy and demonstrated the potential for lower LCOE compared to standalone wind or wave systems, enhancing energy output, reducing costs, and improving grid stability [41].

UPWAVE

The UPWAVE project developed and installed a 1 MW wave energy converter, the WAVESTART C6-1000. The project did not directly implement wind energy generation, but rather focused on integrating WECs within existing offshore wind farms. This initiative focused on industrializing the WEC with efficient manufacturing processes, automation and optimization while significantly reducing the cost of wave energy to approximately 15 cents per kWh, making it aligned with the cost of offshore wind [42].

VALID

The VALID project developed a hybrid testing platform to improve the reliability of WECs and lower energy costs. Combining virtual and physical tests, the project helped establish new standards for wave energy technology, enhancing design processes and accelerating market entry, pushing this sector closer to large-scale deployment [43].

PROMOTioN

The PROMOTioN project focused on advancing High Voltage Direct Current (HVDC) offshore transmission grids to connect offshore wind farms in Europe. It proposed to tackle high converter costs, lack of protection systems and regulatory barriers. The results of PROMOTioN pave the way for the European grid to be better prepared for the large-scale integration of renewable energy, improving its stability, and increasing cross-border electricity trading while lowering overall costs [44].

Carbo4Power

The Carbo4Power project aimed to develop advanced, lightweight, and high-strength materials for offshore wind and tidal turbine blades. The objective of this project was to deliver the new generation of nano-engineered materials to increase their mechanical properties, including self-healing coatings and anti-fouling surfaces, all this using modular blade designs which reduced material waste by 20% and achieved a recyclability of up to 95% [45].

MARINA PLATFORM

The MARINA PLATFORM developed multi-purpose platforms integrating offshore wind energy and wave energy converters. The project evaluated several offshore energy combinations to achieve optimal efficiency and costs in platforms suited for deep-sea deployment. The large-scale marine renewable energy deployment was also supported with cost-benefit analyses and policy recommendations for EU systems [46].

Table 3-2 Summary of the existent projects.

Acronym	Description	Duration (months)	Total Cost (€)
POSEIDON	Developed and matured a floating wind-wave energy device for commercial deployment.	24	1,634,500.00
UPWAVE	Demonstrated a 1-MW wave energy converter integrated into an offshore wind turbine farm.	60	28,866,787.50
VALID	Developed a hybrid testing platform to improve the reliability and cost-effectiveness of wave energy converters.	42	4,993,651.25



PROMOTiON	Advanced meshed HVDC offshore grids to integrate large-scale offshore wind energy into Europe's grid.	57	42,691,662.81
f	Developed next-generation, lightweight, and recyclable offshore turbine blades using nano-enabled materials.	48	7,831,707.49
MARINA PLATFORM	Designed multi-use offshore platforms combining wind, wave, and tidal energy for efficient deep-sea deployment.	54	12,761,220.93

3.3 Hybrid Projects within EU-SCORES

Portugal, with its extensive coastline and unobstructed exposure to both wind and waves, is an ideal location for hybrid projects, hence fitting very well into the EU-SCORES project. The country's ambitious climate and energy autonomy goals—transitioning from a net importer to a potential exporter by 2050—underscore the strategic importance of such initiatives.

Within the EU-SCORES framework, this study focuses on two projects located approximately 60 km apart:

- WindFloat Atlantic: A floating offshore wind farm near Viana Do Castelo, operational since 2020, with 3 turbines delivering a total of 25 MW (8.4 MW each).
- Aguçadoura Wave Farm: A pilot project featuring a 300 kW floating buoy that was demonstrated offshore for 3 months in 2023. This installation not only serves as a testbed for wave energy conversion but also provides valuable production data for future scalability studies.

The location of both WindFloat and Aguçadoura site can be found in the Figure 3-1.

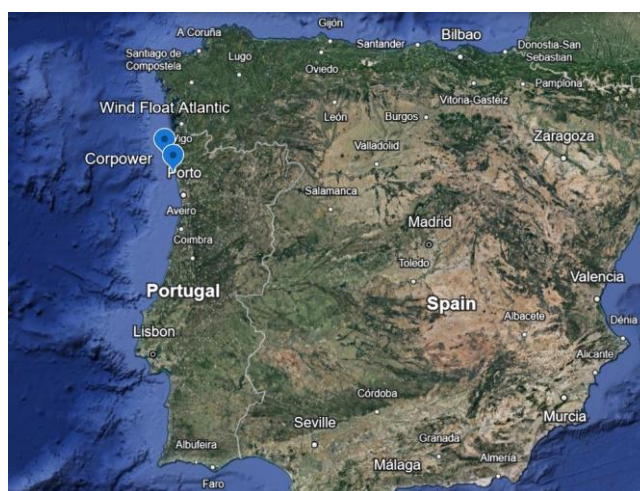


Figure 3-1 - WindFloat Atlantic and Corpower's buoy location

3.4 Data used for the Simulations

In this study, we analyze the complementarity between wind and wave energy resources by leveraging extensive datasets and specific equipment characteristics. To capture the inherent variability and ensure robust conclusions, we utilize hourly data spanning from 2013 to 2022, amounting to 87,600 data points for each energy source.

Meteorological data is sourced from the ERA5 dataset, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) as part of the Copernicus Climate Change Service. ERA5 provides hourly estimates of atmospheric, land, and oceanic parameters



This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

globally, with a spatial resolution of approximately 11 km for land and 27 km offshore. For this analysis, we extract parameters such as mean wave period, significant wave height, and wind components at 100 meters altitude, aligning with the hub height of the wind turbines under consideration [47].

The wind energy assessment employs data from the Vestas V164 turbine series. Initially rated at 8.0 MW, the V164's capacity has been increased in subsequent iterations, with further developments reaching up to 10.0 MW. The turbine features a rotor diameter of 164 meters and a swept area of 21,124 m². Each blade measures 80 meters in length and weighs approximately 35 tonnes. The turbine is designed to operate at wind speeds ranging from a cut-in speed of 4 m/s to a cut-out speed of 25 m/s, with rotational speeds between 4.8 and 12.1 rpm. The nacelle, housing key components such as the gearbox and generator, weighs around 390 tonnes. Given that the WindFloat Atlantic (WFA) project utilizes a modified version of this turbine, we apply linear interpolation to the available power curves to estimate the specific performance characteristics accurately.

For wave energy production, we utilize a power matrix provided by our project partner, CorPower. This matrix correlates wave characteristics—such as significant wave height and energy period—with the expected power output of the wave energy converters. By applying this matrix to the wave data extracted from the ERA5 dataset, we estimate the hourly power outputs of the WECs.

To ensure uniformity in our time series data, we pre-processed the datasets to address complications arising from leap years and daylight-saving time adjustments. Specifically, we standardized each year's data to start on January 1st at 00:00, with each subsequent row representing the next hour. This approach ensures a consistent time index across all years. Additionally, data corresponding to February 29th in leap years was excluded, resulting in uniform datasets of 8,760 hours for each year. This method aligns with best practices in time series analysis to mitigate irregularities caused by varying day lengths and leap years.

By integrating these datasets and equipment specifications, and by standardizing the temporal data, we aim to conduct a comprehensive analysis of the temporal alignment and variability of wind and wave energy resources. This approach assesses the potential benefits of their combined deployment in enhancing the reliability and stability of renewable energy supply.

3.5 Pearson correlation

The Pearson correlation factor, also known as Pearson's correlation coefficient, is defined as a statistical measure that quantifies the strength and direction of the linear relationship between two continuous variables. It is denoted by the symbol “r” and ranges from -1 to +1. A value of +1 indicates a perfect positive linear relationship, meaning that as one variable increases, the other variable also increases proportionally. Conversely, a value of -1 indicates a perfect negative linear relationship, where one variable increases as the other decreases. A value of 0 suggests no linear relationship between the variable [48].

The formula for calculating the Pearson correlation coefficient is given by Equation 3-1:

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad 3-1$$

Where x_i and y_i are the individual data points, and \bar{x} and \bar{y} are the mean of the variables x and y .



Within the present analysis, the Pearson correlation is used to measure the complementarity of the technologies. Positive Pearson correlation values suggest that the technologies will have production values within the same windows of production. On the other hand, negative Pearson correlation values are also interesting, as they can provide insights on how to stabilize grid production, since technologies produce in different windows of opportunity. Average Pearson correlation values will also be studied with different granularities since hourly values are different from season values.



4 Hybridization between Wind and Wave

4.1 Study of Individual Resources

Regarding the hybridization between wind and wave, the hourly average production of wind and wave between 2015 and 2025 was plotted and is shown below, in Figure 4-1.

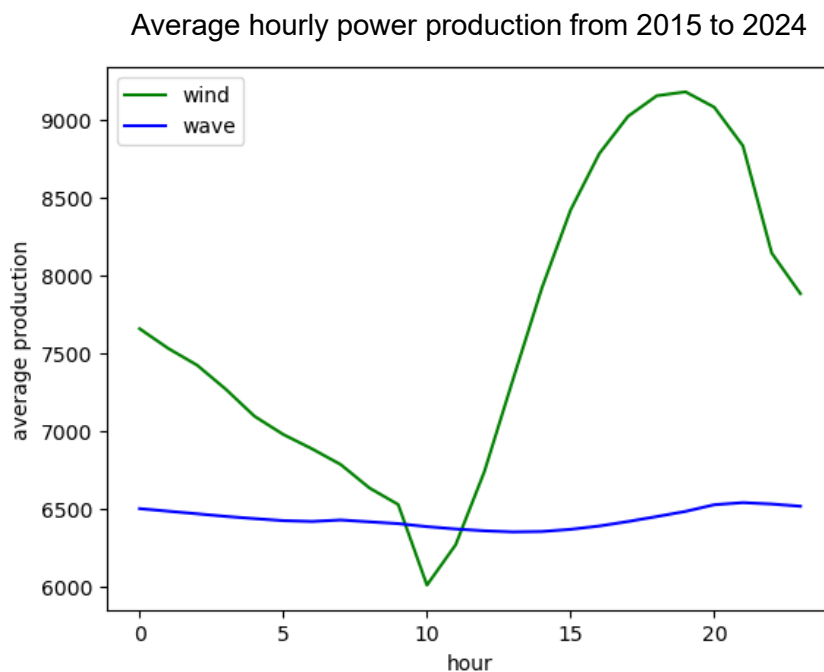


Figure 4-1 - Aggregated hourly average power production of wind and wave, assuming 100% availability and no maintenance.

The plot shows the hourly average production of wind (green) and wave (blue) over a typical day, aggregated from data spanning 2015 to 2025 (assuming 20 MW of installed wind capacity and 10 MW of wave capacity). Wind power exhibits a clear diurnal pattern, with production dipping in the late morning hours and rising substantially in the afternoon and early evening. This fluctuation is likely driven by meteorological and thermal factors that affect wind speed over the course of the day. In contrast, wave power remains comparatively steady, with only minor variations throughout the 24-hour cycle, due to the nature of the data used for these simulations.

The stability of wave energy underscores its potential to complement wind's more pronounced daily oscillations. During periods when wind output is lower—around mid-morning in this case—wave energy can help maintain a baseline level of generation. Conversely, when wind production peaks in the late afternoon, the total output can exceed what wind or wave alone would provide. By combining both sources, in this study, the offshore system achieves a more balanced and predictable power profile over the course of the day, thereby enhancing overall grid stability and reducing the intermittency typically associated with standalone wind or wave power. Additionally, the capacity factor of both these technologies was also plotted and can be found below, in Figure 4-2 and Figure 4-3.

Figure 4-2 and Figure 4-3 illustrate the capacity factor trends for wind and wave energy between 2015 and 2024, for the same power mix described above.



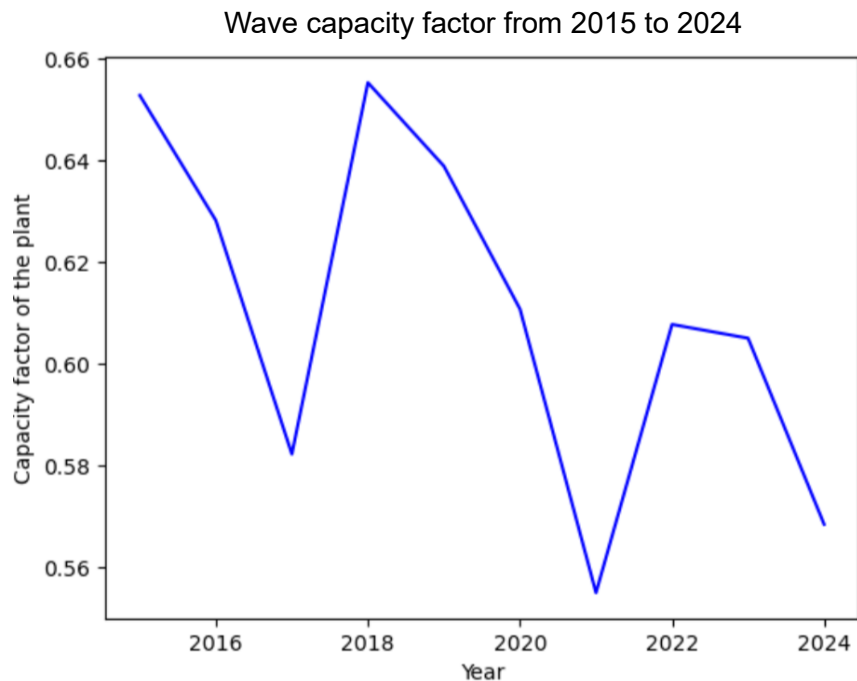


Figure 4-2 - Wave Capacity factor between 2015 and 2024.

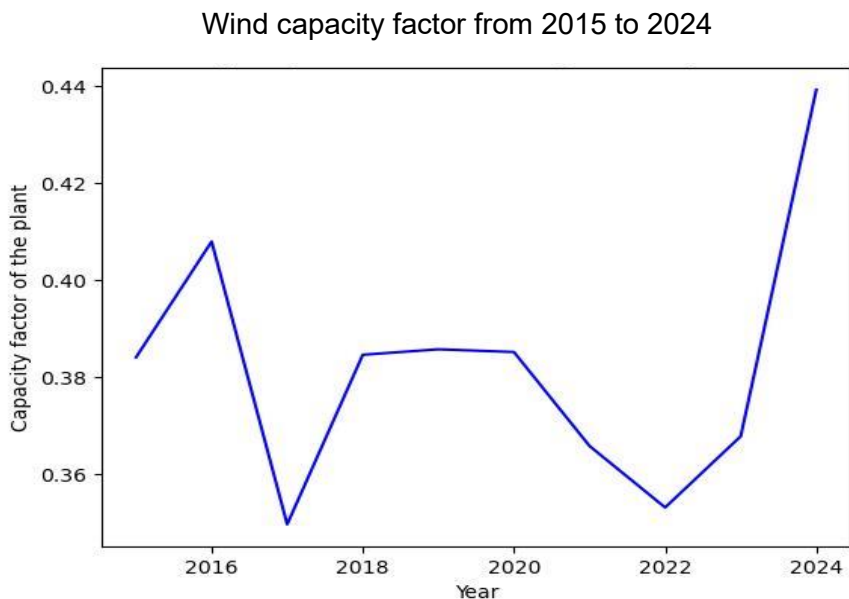


Figure 4-3 - Wind Capacity factor between 2015 and 2024.

A key observation is that wave energy consistently exhibits a higher capacity factor than wind energy. While wave energy fluctuates, mostly between a range of 0.55 to 0.66, wind energy shows lower values, varying between 0.35 and 0.45. This suggests that wave energy generally provides a higher proportion of its installed capacity over time compared to wind.

Figure 4-4, which represents the normalized power output for wind and wave energy at the test site (assuming the power mix described above), further supports these observations. The



wind power output curve reveals significant variability, with rapid fluctuations between high and low production periods. On the other hand, wave energy results suggest a smoother and more stable output distribution, producing more consistently across different hours of the year, considering the theoretical power matrix.

These findings highlight the complementarity between the two energy sources. While wind power experiences more frequent fluctuations, wave energy provides a steadier contribution. This complementarity is particularly beneficial in reducing overall variability, ensuring that when wind energy production is low, wave energy can still supply a significant portion of the total output.

Normalized wind and wave power output from 2015 to 2024

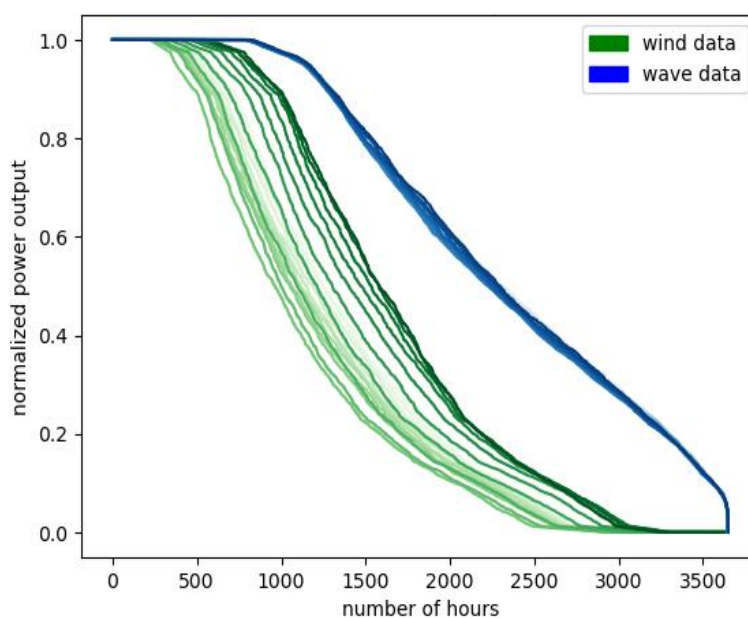


Figure 4-4 - Wind and Wave normalized power output in the WindFloat Atlantic.

Figure 4-5 plots illustrate how wind and wave power output fluctuate on daily and hourly timescales, providing further insight into their respective levels of variability and potential complementarity.

In the first plot, which focuses on the relative hourly variation, both wind and wave exhibit more frequent fluctuations within each day. However, the amplitude of these changes is still typically greater for wind than for wave. Wind power may spike or drop sharply in response to passing weather systems or shifts in wind speed, whereas wave power tends to show more gradual rises or dips due to the inertia inherent in ocean wave formation and propagation.

In the second plot, which shows the relative daily variation, wind power (green) displays larger swings in output from day to day compared to wave power (blue). Wave energy appears more stable overall, with fewer extreme changes. This steadier profile underscores why wave energy often achieves a higher capacity factor, as it tends to remain closer to its mean output even when conditions shift. When considered alongside the capacity factor analyses, these observations reinforce the notion that wave and wind resources can effectively balance one another. The steadier wave power output can help compensate for the higher volatility in wind production, reducing overall intermittency in a combined system. On days or hours when wind energy falls off abruptly, wave energy is likely to maintain a relatively higher output, thereby



smoothing the aggregate production curve. This synergy becomes particularly valuable in regions — like the WFA, located in Viana do Castelo, Portugal — where both resources are sufficiently abundant. By leveraging these complementary patterns of variability, operators can design hybrid wind-wave farms that deliver a more stable and reliable supply of renewable energy over multiple timescales.

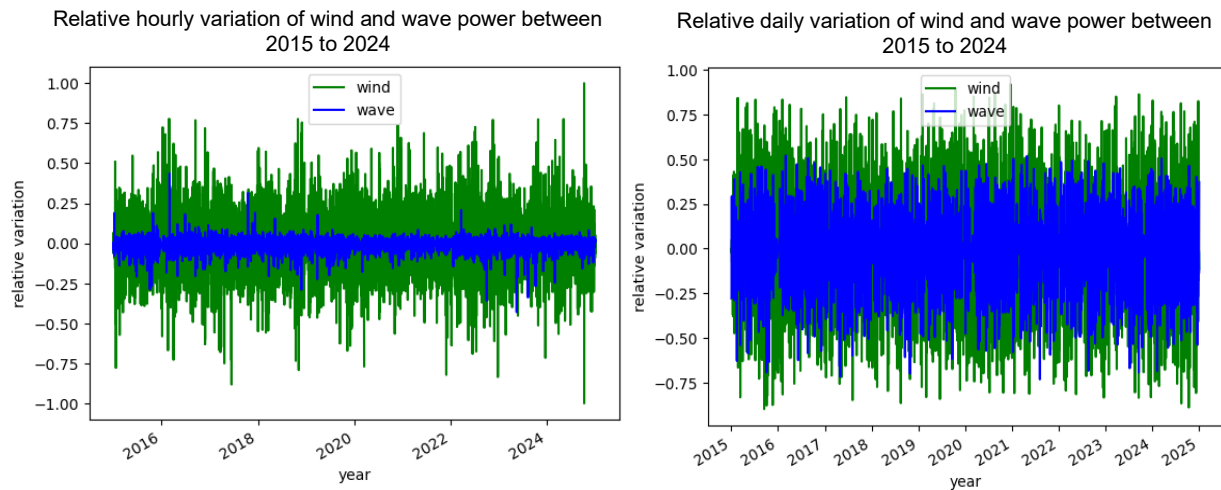


Figure 4-5 - Relative hourly and daily variation of wind and wave power.

4.2. Study of Combined Resources

After analyzing each resource individually, a study regarding the combination of both wind and wave as a hybrid farm was carried out. To that end, the seasonal and aggregated hourly Pearson correlation between both technologies was plotted and is presented in the Figure 4-6 and Figure 4-7.

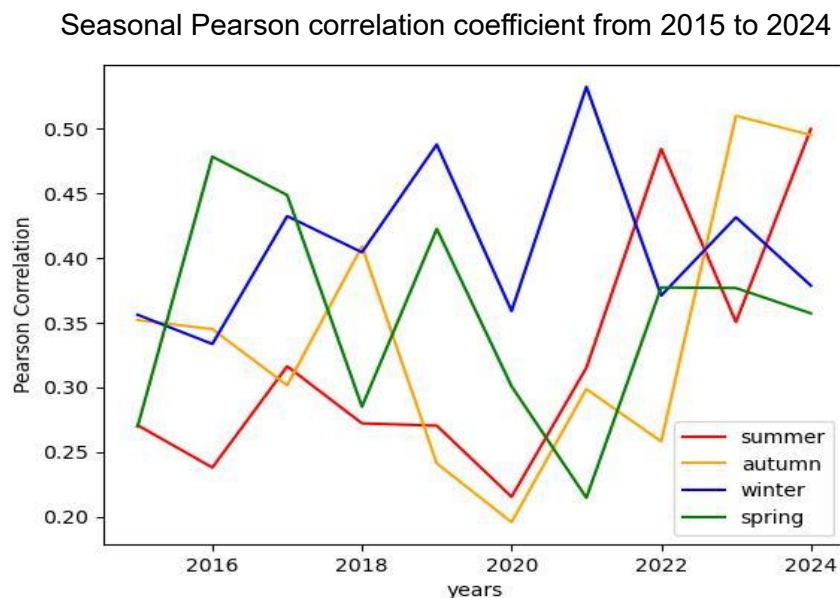


Figure 4-6 - Seasonal Pearson correlation between wind and wave.



Hourly Pearson correlation coefficient from 2015 to 2024

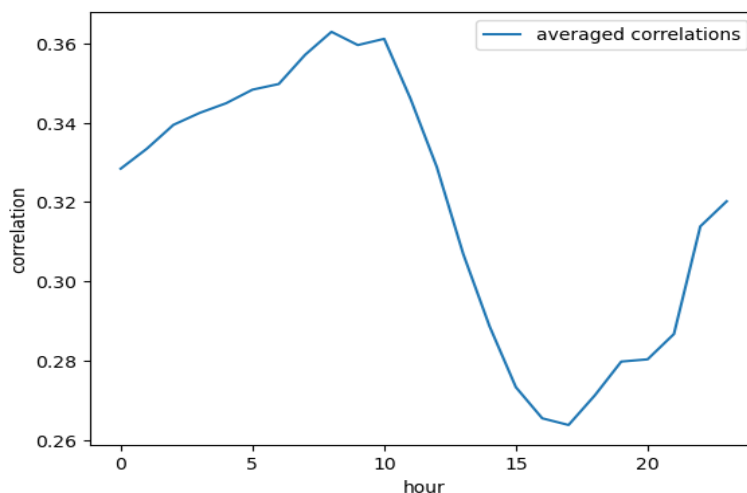


Figure 4-7 - Hourly Pearson correlation between wind and wave.

Figure 4-6 illustrates the seasonal Pearson correlation between wind and wave production at the WFA. The correlation coefficient serves as a proxy for how similarly the two resources fluctuate over time. A value closer to 1 indicates that wind and wave output tend to peak simultaneously, reducing their overall complementarity. Conversely, lower (or negative, in other cases) values signify that one resource often compensates for the other—exactly the condition desired for effective hybrid operation. As shown, the correlation varies from season to season, implying that certain periods of the year naturally exhibit higher synergy (i.e., lower correlation) than others. For example, if the correlation drops during winter months, it suggests that when wind speeds are high, wave heights may be lower (or vice versa), thereby helping smooth total power output. During seasons with a higher correlation, both technologies are more likely to ramp up or down together, offering fewer benefits from a balancing perspective.

Figure 4-7 provides insights into the hourly average correlation over the course of a typical day. This diurnal trend highlights how wind and wave resources may align or diverge at different hours. Notably, the correlation can shift significantly between early morning and late afternoon, indicating that wind speeds and wave conditions do not remain synchronized on a 24-hour cycle. Periods with lower correlation values (for instance, in the early morning or late evening) suggest times when wave output may remain relatively stable while wind output fluctuates—or vice versa—offering a beneficial balancing effect. In contrast, any spikes toward higher correlation imply that both resources are moving in tandem, reducing the potential for complementary power generation.

From a project planning and operational standpoint, these findings underscore the importance of analyzing both seasonal and hourly patterns to maximize the advantages of hybrid offshore wind-wave farms. By identifying when correlation is lowest, operators can schedule maintenance, optimize energy storage strategies, or align power purchase agreements to leverage periods of enhanced complementarity. Conversely, understanding the times and seasons with higher correlation allows for more accurate forecasting of total power output and better grid integration strategies.



5 Hybridization between Wind and PV

5.1 Study of Individual Resources

In order to strengthen the conclusions of the benefits of the complementarity between different offshore technologies, a study between offshore wind and PV was also carried out. Figure 5-1 below shows the aggregated hourly average production of wind and solar between 2015 and 2024.

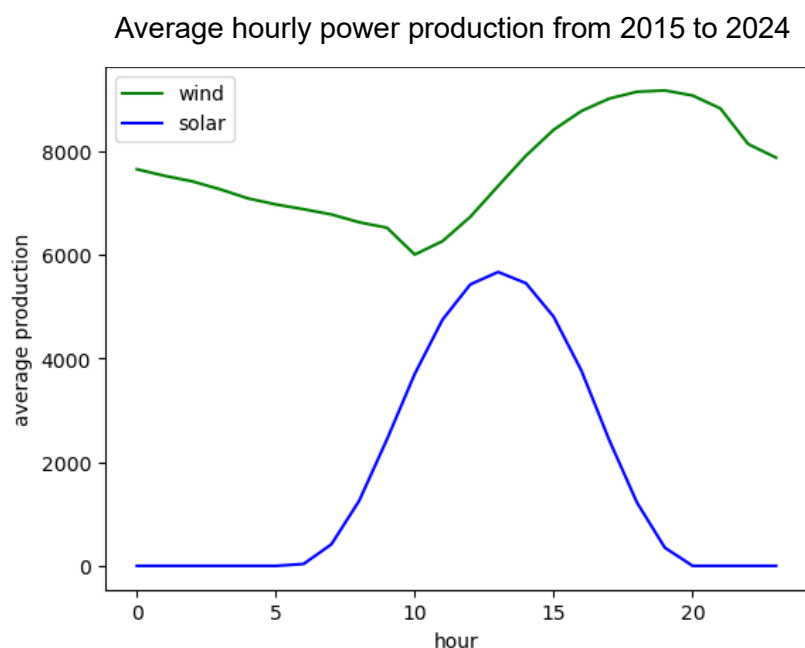


Figure 5-1 - Aggregated hourly average power production of wind and solar in a farm with 20MW of wind and 10MW of solar power.

The plot illustrates the hourly average wind and solar energy production between 2015 and 2024. Solar energy production follows a clear diurnal pattern, starting at zero during nighttime and increasing sharply after sunrise. It peaks around midday to early afternoon, between 12:00 and 15:00, before gradually declining and returning to zero after sunset. In contrast, wind energy production exhibits a more stable profile throughout the day, with relatively smaller fluctuations compared to solar energy. There is a noticeable dip in production around midday, followed by a steady increase in the late afternoon, reaching its highest values in the evening and nighttime. This complementary behaviour highlights a key advantage of hybrid wind-solar systems, as solar power dominates during daylight hours while wind production remains significant at night, ensuring a more continuous energy supply throughout the day.

5.2. Study of Combined Resources

The hourly and seasonal Pearson correlation between these technologies, for the years 2015 until 2024, was also studied and is illustrated in Figure 5-2 and Figure 5-3 below.



Hourly Pearson correlation coefficient from 2015 to 2024

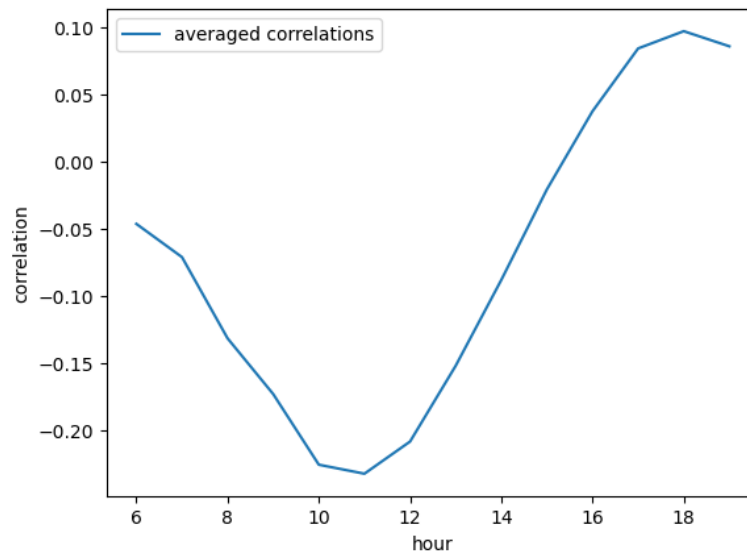


Figure 5-2 - Aggregated hourly Pearson correlation between wind and solar.

Seasonal Pearson correlation coefficient from 2015 to 2024

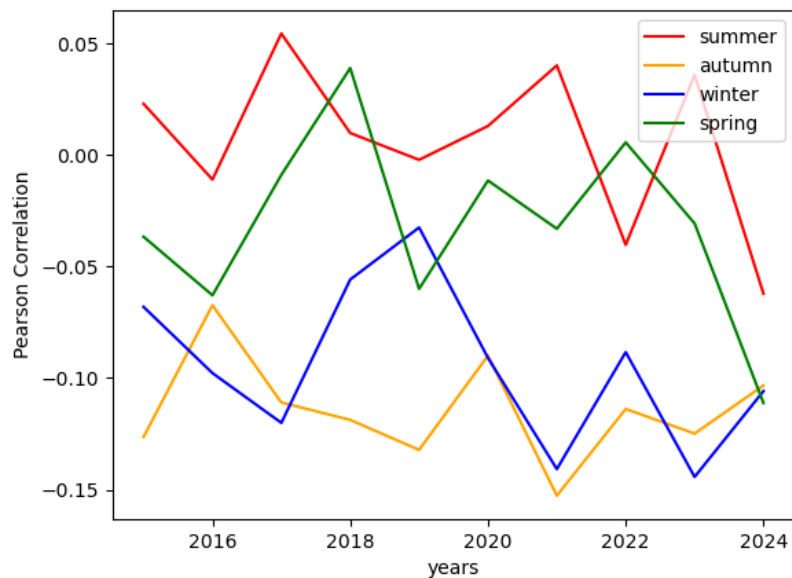


Figure 5-3 - Seasonal Pearson correlation between wind and solar.

The correlation analysis between wind and solar power generation provides valuable insights into their potential complementarity when integrated into a hybrid energy system. The first plot illustrates the hourly average correlation between wind and solar power output over the period from 2015 to 2024. A clear diurnal pattern emerges, where the correlation is negative in the early morning and mid-day hours and becomes slightly positive in the late afternoon. The most negative correlation occurs around midday, approximately between 10:00 and 12:00, when solar power production is at its peak and wind power output is at its lowest. Conversely, in the late afternoon and early evening (16:00–18:00), the correlation turns positive, suggesting that



wind power begins to increase as solar production declines. This inverse relationship indicates that solar and wind can complement each other in a hybrid system, mitigating fluctuations and enhancing overall energy supply stability.

The second plot delves deeper into the seasonal dynamics of the wind-solar relationship, showing the Pearson correlation coefficient for different seasons across multiple years. The seasonal variation in correlation highlights distinct patterns depending on the time of year. In summer, the correlation is slightly positive, meaning that both solar and wind energy tend to follow similar trends, although the relationship is not particularly strong. In winter, however, the correlation is predominantly negative, reinforcing the idea that these resources operate in an alternating fashion—when solar is high, wind is low, and vice versa. This suggests that a hybrid wind-PV system can be particularly effective in winter, helping to offset the variability of each individual source. Autumn and spring exhibit more intermediate behaviors, with the correlation fluctuating over the years, but generally showing negative or near-zero values.

Compared to the wind-wave hybridization discussed in the previous subsection, the key difference lies in the nature of variability and complementarity. Wave energy, as shown in previous analyses, tends to have a higher capacity factor and lower variability, making it an effective buffer against wind fluctuations. In contrast, solar power follows a predictable diurnal cycle but can be highly intermittent due to weather conditions. The negative correlation between wind and solar, particularly in winter and midday hours, underscores the potential benefits of combining these two sources in a hybrid farm. By integrating solar with wind, operators can reduce the dependency on energy storage solutions and grid balancing mechanisms, as solar can provide energy during calm, sunny days while wind compensates during overcast or nighttime periods.

Overall, these results reaffirm the advantages of hybridization by showing how different renewable resources can complement each other over various timescales. The wind-solar hybrid model presents a strong case for diversified renewable energy systems, further enhancing grid stability and improving the overall efficiency of energy generation at offshore locations.



6 Hybrid Technologies Curtailment Analysis

A comprehensive comparison of curtailed energy across different offshore renewable configurations offers critical insights into how resource complementarities can reduce overall energy losses. Drawing on extensive operational experience, the table below summarizes the total curtailed energy for each 30 MW farm scenario — ranging from standalone wind, wave, and solar to hybrid wind–wave and wind–solar systems — under a 25 MW export cable capacity.

Table 6-1 – Curtailed and Produced Energy over 10 years for a 25 MW cable.

	20 MW Wind + 10 MW Wave	20 MW Wind + 10 MW Solar	20 MW Solar + 10 MW Wave	30 MW Wind	30 MW Wave	30 MW Solar
Produced Energy (GWh)	1234	822.2	868.5	1005	1691	457.1
Curtailed Energy (GWh)	56.58	3.44	0.28	79.66	144.95	0.53
Percentage of curtailed energy (%)	4.59%	0.42%	0.03%	7.93%	8.57%	0.12%

In the wind+wave scenario, curtailed energy (56.58 GWh) is substantially lower than in either the 30 MW wind-only (79.66 GWh) or the 30 MW wave-only (144.95 GWh) cases. This underscores the beneficial synergy arising from combining two different, and often asynchronous, resources. Although wave power can have a very high capacity factor—leading to significant curtailment when deployed alone—it pairs well with the intermittency of wind. Because wave energy does not tend to drop to zero as frequently, it fills some of the gaps left by wind and avoids continuous overproduction when wind peaks align with moderate wave conditions. The net result is a marked reduction in curtailed energy compared to single-resource systems, confirming that hybridization can leverage the strengths of each source while mitigating their individual drawbacks.

The wind+solar configuration experiences 3.44 GWh of curtailment, a notable improvement over the wind-only scenario (79.66 GWh). However, the solar-only farm has the lowest curtailment of all, at 0.53 GWh, primarily due to its lower capacity factor and naturally constrained generation window (daytime only). Although adding wind to solar does slightly increase curtailment compared to solar alone, it dramatically reduces the curtailed energy relative to a wind-only project. The negative Pearson correlation between wind and solar—where wind production often ramps up at times when solar is decreasing—helps distribute generation more evenly throughout the day and thereby reduces the likelihood of exceeding the cable capacity. From a system-wide perspective, this complementary profile is highly beneficial for wind, though less impactful for solar given its already minimal curtailment.

The degree of complementarity, as evidenced by correlation analyses, differs significantly between the wind+wave and wind+solar pairings. Wave energy's high-capacity factor translates to more sustained production, which can sometimes exacerbate curtailment if combined with high wind outputs. Yet, as shown in the table, the hybrid wind+wave system still outperforms standalone wind or wave due to the partial offsetting of their respective peak generation periods. By contrast, solar's relatively low-capacity factor means that the



wind+solar hybrid rarely reaches the export cable limit simultaneously, minimizing total curtailment. These distinctions highlight the importance of matching resource profiles to local conditions and infrastructure constraints, as each technology’s intrinsic characteristics—whether wave’s stability or solar’s diurnal cycle—fundamentally shape curtailment outcomes.

When analyzing the total energy produced by each configuration, a clear pattern emerges that reflects the capacity factors of the technologies. The 30 MW solar-only farm, despite registering the lowest curtailment (0.53 GWh), generates the least energy overall (457.1 GWh). By contrast, the 30 MW wave-only installation produces the greatest amount of energy (1,691 GWh) but also has the highest curtailment (144.95 GWh). The wind-only farm sits between these extremes, with 1,005 GWh produced and 79.66 GWh curtailed. The hybrid systems follow the same ordering: the wind+solar combination yields 822.2 GWh with only 3.44 GWh curtailed, while the wind+wave hybrid delivers 1,234 GWh and curtails 56.58 GWh. These results directly reflect the relative capacity factors—wave energy’s high capacity factor drives both high production and higher curtailment, wind’s moderate capacity factor lands it in the middle, and solar’s low capacity factor leads to modest production with minimal curtailment.

Overall, these findings confirm that hybridization can reduce curtailed energy and optimize resource utilization compared to single-source projects. In locations where wave resources are abundant and capacity factors are high, pairing wave with wind can significantly lower the combined curtailment. Conversely, wind+solar systems offer a particularly strong solution in regions with high solar potential, given solar’s naturally limited generation window and the negative correlation between the two resources. In either case, careful planning of export cable capacity and infrastructure is crucial to fully capitalize on these complementary effects. By tailoring hybrid projects to the specific resource availability and market conditions of a site, offshore renewable developers can enhance both operational efficiency and economic viability in pursuit of a more sustainable energy future.

Figure 6-1 illustrate the relationship between export cable capacity and energy curtailment for two distinct offshore renewable configurations. One plot depicts the curtailed energy for a 20 MW wind plus 10 MW solar hybrid system, while the other shows the curtailed energy for a 30 MW solar-only system.

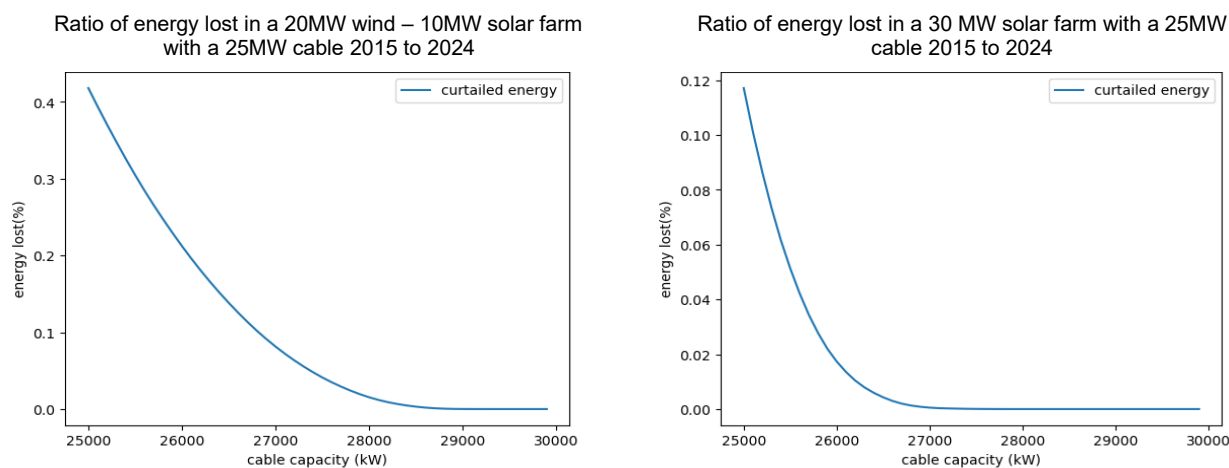


Figure 6-1 - Ratio of Energy lost vs cable capacity.

The above plot for the 20 MW wind plus 10 MW solar hybrid system clearly shows that if the export cable capacity were increased from 25 MW to 29 MW, curtailment would be completely eliminated. In this hybrid configuration, wind energy introduces a higher level of variability and



intermittency compared to solar PV, which in turn can cause occasional peaks in total generation. These combined peaks are more likely to exceed the 25 MW threshold, necessitating a higher cable capacity to capture the full potential of the hybrid system. Essentially, the presence of wind energy, with its capacity for sudden surges, demands a larger transmission margin, hence the requirement for a 29 MW cable to ensure that no generated energy is wasted.

In contrast, the plot for the 30 MW solar-only system indicates that increasing the cable capacity from 25 MW to only 27 MW would suffice to eliminate curtailment. Solar PV typically has a lower capacity factor, with production concentrated during daylight hours and virtually zero output at night. This more predictable and limited production pattern means that even during peak daylight, the instantaneous power output rarely exceeds the slightly higher threshold of 27 MW. The controlled, less variable nature of solar generation thus requires only a modest increase in cable capacity compared to the hybrid system.

From an operational perspective, these differences highlight the importance of tailoring export infrastructure to the specific generation profiles of the renewable technologies in use. In the hybrid wind+solar system, the unpredictable surges from wind demand additional capacity to accommodate intermittent high outputs, while the solar-only system's more consistent profile makes it less prone to overshooting the transmission limits. This nuanced understanding of resource behavior is critical for designing efficient offshore renewable projects that can minimize curtailment and maximize the use of available energy.



7 Future Works

Future research in hybrid offshore renewable energy systems should adopt a comprehensive approach that not only improves grid infrastructure, energy storage, and hydrogen integration but also explores novel aspects of technology interaction, maintenance, and economic viability. The concept of combining different renewable sources is still relatively new, and several additional elements have emerged from recent research that reinforce the potential of hybrid models.

One promising area is the synergistic effect of WECs within a floating hybrid farm. The installation of WECs can have the added benefit of dampening the size of incoming waves, thereby reducing wear and tear on other installed technologies. This passive wave attenuation may enhance the longevity and reliability of the entire farm by mitigating the harsh marine conditions that often lead to frequent maintenance and component replacement. Moreover, maintenance itself represents a critical challenge for offshore projects. Given that operations at sea require calm conditions for safe intervention, the naturally lower wave heights observed during summer months offer an ideal window for conducting heavy maintenance tasks. This seasonal variability not only facilitates smoother operations but also underscores the importance of designing maintenance schedules that align with environmental conditions.

In addition, the inherent reliability of WECs in terms of energy production suggests that hybrid systems might be particularly advantageous for island applications, where stable and predictable power output is essential. The possibility of joint O&M across different technologies within a hybrid farm further reduces downtime and overall costs, making these projects more economically attractive. With the ongoing evolution of energy market prices—driven by shifts in the energy mix and anticipated European market reforms—the economic landscape for renewable projects is poised to change dramatically. These market dynamics may further enhance the viability of hybrid systems, as more resilient and diversified generation portfolios become increasingly competitive.

From a technical perspective, future research should continue to develop and refine integrated simulation tools that model the interactions between multiple renewable sources, storage systems, and grid constraints. Such tools can help in optimizing export cable sizing, as even small increases in cable capacity have been shown to significantly reduce curtailment. Enhanced forecasting methods for wind, wave, and solar resources will also be critical in aligning generation with grid capacity, thereby minimizing energy losses.

Furthermore, the integration of hydrogen production offers a compelling route for storing excess renewable energy. Converting surplus power into hydrogen not only helps mitigate curtailment but also creates a versatile energy carrier that can be utilized for electricity generation, industrial applications, or transportation. Battery storage systems are also a good solution to stabilise the grid with the excess energy from this farm.

Overall, future work should embrace an integrated strategy that includes enhancements in grid infrastructure, energy storage, and renewable technology diversification, along with innovative approaches to maintenance and economic planning. By addressing these aspects, researchers and industry stakeholders can pave the way for more robust, efficient, and economically viable hybrid offshore renewable energy systems.



8 Conclusion

This work presents a comprehensive assessment of hybrid offshore renewable energy systems, focusing on integrating wind and wave resources — specifically at the WindFloat Atlantic for wind and Aguçadoura for waves—and, additionally, exploring wind and solar PV hybridization. The analysis demonstrates that each renewable technology exhibits distinct energy profiles, and when combined appropriately, these differences can be exploited to maximize overall system performance while reducing energy curtailment and enhancing grid stability.

The results indicate that wind farms, characterized by its variability, benefits significantly from hybridization with more stable energy sources. In the case of wind and wave hybridization, the wave component typically exhibits a higher capacity factor and a more stable short-term output — with extended periods of near-100% generation and almost no zero-power stages — yet it also experiences pronounced seasonal variations, for the analyzed location. These seasonal fluctuations underscore a key advantage: while wind resource can be highly erratic, the predictable stability of wave energy at short timescales can serve as a valuable asset for future grids. By mitigating short-term intermittency, wave energy can reduce the need for extensive flexibility and storage solutions, thereby contributing to overall grid reliability. However, the high-capacity factor of wave energy, despite lowering curtailment when combined with wind, tends to produce a positive Pearson correlation between the two, indicating that their outputs often peak simultaneously. This positive correlation reflects lower complementarity, even though the hybrid configuration still offers a reduction in curtailment compared to standalone systems.

In contrast, the hybrid wind and solar PV configuration leverages the complementary nature of solar PV's diurnal production pattern and wind's variable generation. The solar component, with its inherently low-capacity factor and a production profile that is largely confined to daylight hours, helps to mitigate curtailment when added to a wind system. Moreover, the negative Pearson correlation observed between wind and solar signals strong complementarity, as their generation peaks occur at different times of the day. This complementary interaction not only reduces curtailment relative to a wind-only system but also enhances the overall stability of energy production, even though the solar-only setup exhibits very low curtailment due to its limited production window.

Furthermore, the economic viability of wave energy projects remains a critical consideration. Given that wave energy is still an emerging technology, its current market price per MWh is higher than that of conventional renewable energy sources. Nonetheless, as the technology matures and benefits from progress in related offshore sectors such as floating PV (which is in a similar stage as wave energy, as it is not fully tested nor de-risked) and offshore wind, there is significant potential for cost reductions in both CAPEX and OPEX. Hybridization strategies, by sharing infrastructure such as anchors and grid connections and leveraging combined operational expertise, could prove pivotal in lowering overall project costs. Such synergies are essential for making wave energy economically attractive, especially if market mechanisms evolve to appropriately value its unique benefits — including its stability and potential for grid support.

Looking ahead, future research should focus on improving grid infrastructure and control strategies to better accommodate the complex interplay of hybrid renewable systems. This includes integrating advanced forecasting techniques, energy storage solutions, and hydrogen production via electrolysis to store surplus energy. Additionally, further studies in diverse locations with varying technological configurations are essential to fully assess the potential of hybrid offshore renewable energy systems across different environmental and market conditions.



Overall, this study confirms that strategic hybridization — by combining technologies with complementary profiles — can significantly enhance renewable energy production, minimize curtailment, and support the stable operation of future grids. The findings also highlight a critical nuance: while wind+wave hybridization offers lower curtailment than standalone systems, its positive Pearson correlation implies that the two resources tend to peak together, limiting their complementarity. In contrast, the wind+PV combination not only reduces curtailment relative to a wind-only system, but also achieves a negative Pearson correlation, indicating that their generation profiles are well-synchronized to complement each other, thereby optimizing energy output and grid stability.



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