Combining Various Offshore Renewable Energy Sources in a Multi-source Park for Climate Mitigation, Energy Security and a Reduced Impact on the Ecosystem

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Abstract. Europe and the world are currently in a poly-crisis. Firstly, anthropogenic climate change leads to an increase in extreme weather conditions while increasing the pressure on an already weakened ecosystem. Secondly, the biodiversity crisis as a follow up of pollution and reduction of natural habitats causes unstable eco systems . Thirdly, the geopolitical order and energy security for many (European) countries is getting jeopardised by the Russian attack on Ukraine and the ongoing trade-wars. This work shows how the build-out of offshore renewable energy in multi-source parks combining offshore wind, wave and offshore solar energy can tackle multiple of those crises. A tool, called Multi-Source Offshore Renewable Energy (MultiORE) is used for the layout, energy profile and economics of such a combination of technologies wave, wind and solar energy resources. The MultiORE simulation of a 600 MW wind – 210 MW wave – 900 MW solar park at this North Sea location resulted in an 21% increased energy density compared to the wind-only scenario. The increase in energy density is possible without any delay on site characterisation and grid infrastructure build-out as well as only minor expected impacts on construction time, critical for the **climate crisis.** The increased energy density requires less areas for offshore renewables leaving more space for natural ecosystems. To achieve the same yearly energy output as the wind-only park, the multi-source park would require about 18% less space helping to mitigate the **biodiversity crisis**. The model further shows an increase of the capacity factor from 52% (Wind only) to 63% (Wind/Wave/Solar) while also reducing low production hours (<20% of export capacity) by almost 60% compared to wind-only. The longest duration of low production hours was reduced from 144 consecutive hours to 39 hours. This overplanting at the same time did not lead to significant curtailment, as only 5% of the total energy produced could not be exported indicating improved **energy security**.
Even though multi-source parks can have several positive impacts on above described crises they also come with difficulties like varying maturity of different technologies having a higher risk profile and cost . An economic assessment showed that a positive bussiness case, calculated via a net present value (>0), is possible, considering learning rates on the Levelised Cost of Electricity (LCOE) provided by industry as part of the Horizon 2020 EU-SCORES project.

1. Introduction

Europe and the world are in a polycrisis with climate change, biodiversity loss and geopolitical uncertainty on the forefront (Pörtner, et al., 2023). Those crises do not exist in a vacuum but impact and often foster each other. For example, the climate crisis is expected to be a major driver in the degradation of European wetland ecosystems increasing the biodiversity crisis (J.E., et al., 2016). At the same time, the loss of forests, wetlands, and other ecosystems reduces the planet's capacity to capture and store carbon, making it harder to mitigate climate change (Pörtner, et al., 2023). The geopolitical uncertainty increased spending in military capabilities. This funding is not available for climate change or biodiversity crisis mitigation actions anymore. Additionally, active conflicts have a large likelihood of destroying local ecosystems and are generally increasing carbon emissions. The Initiative on GHG Accounting of War publishes a yearly insight into the emissions caused by Russia's attack on Ukraine. In the period of February 2022 until December 2025, those carbon emissions are expected to reach 230 MtCO2e (Klerk, et al., 2025). This comes close to the 250 $MtCO_2$ emissions per year of a medium sized advanced economy like Spain. The same conflict also showed that Europe requires a greater energy independence utilising local resources instead of relying on Russian or other imported gas.

As funding and attention are limited, solutions are required which have a synergetic effect on those crises. Preliminary studies on the combination of different offshore renewable energy technologies with a focus on wave, solar and wind energy showed that those can have this synergistic effect. Several of them found cost reductions, improved power output stability, resource complementarity and strengthened operational efficiency. All of which are contributing to reducing the climate, biodiversity and security crises described above if they can be achieved in a cost-efficient manner.

The combination of multiple renewable energy sources has shown a significant improvement on the power output stability due to resource complementarity with and without the addition of storage units (Gao, et al., 2023). Combined wind-wave parks with energy storage systems show improved stability and reduced LCOE compared to standalone wind parks. The complementarity of wind and wave resources allowed for a 32% reduction in energy storage CAPEX for combined energy parks compared to standalone wind parks (Gao, et al., 2023). Lavidas and Venugopal (2018) found that wind and wave hybrid stations can contribute significant amounts of clean energy while reducing spatial constraints. They noted that co-located wind-wave solutions could complement a significant amount of non-operative wind turbine production hours, highlighting the potential for wave energy to fill gaps in wind energy production (Lavidas & Venugopal, 2018).

For a hybrid wind-wave park in Norway, there was a lag of approximately 3 hours between wind and wave energy peaks. This temporal offset contributes to a smoother combined power output and reduces the frequency of low-production periods (Rönkkö, Khosravi, & Syri, 2023). Rönkkö estimated reductions of 12-14% in capital costs and 12% in operational costs for their hybrid wind-wave park in Norway. These cost reductions were primarily attributed to shared infrastructure and operations, indicating improved operational efficiency (Rönkkö, Khosravi, & Syri, 2023). Van der Zant et al (2024) showed the high complementarity of offshore wind and solar, increasing the capacity factor on the cable significantly for a Dutch wind park (VanderZant, et al., 2024). Other studies showed power smoothening effects on a subhour scale (Moore & Iglesias 2025).

It is important to note that the complementarity of resources can vary depending on the specific location and the combination of technologies used (Faraggiana, et al., 2023). For instance, wave energy in the Atlantic Ocean shows a very consistent and wind independent output while wave energy in the Baltic Sea is dominated by the local wind resources. Solar resources in the south of Europe are generally having a higher capacity factor but cost reductions and technology progression is making them suitable for wider geographic regions.

All those studies show individual benefits of the combination of offshore wind with wave and solar energy. This paper is taking their results one step further. It is complementing them with additional analysis on a planned wind park and showing the concrete positive impact offshore multi-source parks can have on the three above-described crises. In the context of the climate crisis, this study shows that multi-source parks can lead to a 21% increase in renewable electricity exports and a 183% higher capacity installed in roughly the same amount of time if building multi-source parks instead of offshore wind only. On the biodiversity crisis, the paper highlights that multi-source parks can save 19% of offshore space and reduce environmental impact compared to wind-only. And in regards to the geopolitical crisis, the security of continuous energy supply is explored. The study shows that the capacity factor of the export infrastructure could be increased by eleven percentage points and hours of low production (<20% of export capacity) could be reduced by almost 60%. Altogether, the case for multi-source parks is supported by economic considerations showing the feasibility of this proposition.

2. MultiORE methodology

2.1 MultiORE

MultiORE is a modelling tool that allows for the techno-economic and -financial analysis of hybrid offshore energy parks. Hybrid parks in this context include any combination of offshore wind turbines, wave energy converters, offshore storage technologies and offshore solar. MultiORE's analyses are based on hourly timesteps and evaluated in statistical assessments across a number of parameters to determine the **power flow**, **storage capacity** and **techno-financials** (Figure 1). Through iterative procedures it is possible to assess different aspects of a multi-source offshore renewable energy park (see below). The model is currently at TRL 6-7 for the combination of offshore wind, wave, and offshore solar.

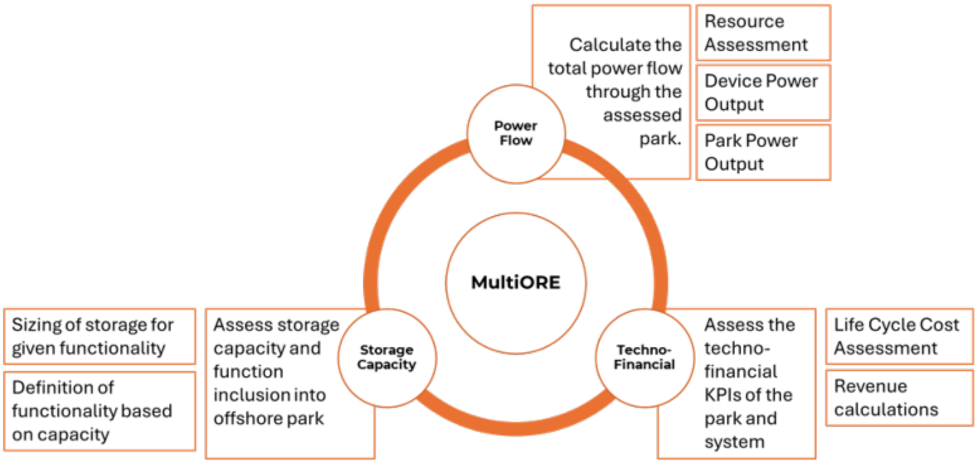

Figure 1 DMEC's MultiORE and its different modelled aspects

The **power flow** functionality forms the foundation of the tool. Here the user of MultiORE calculates the electricity production of different offshore renewable energy sources at the given location using characteristics of specific power generating devices and configurations. Based on resource availability, it calculates individual device output, system generation output and assesses the exported electricity based on the power flows through the export infrastructure (sub-station, export cables etc.). The model considers losses such as wake effects, temperature dependency of PV cells and losses due to device and system efficiency factors such as energy **storage capacity** round-trip efficiency. In the **techno-financial** section of the tool, KPIs are calculated to give an overview of the park's technical and financial feasibility. It takes into consideration costs of project development, components, installation and operation, the electricity produced, and the potential revenues of the entire park. The main KPIs of the model are levelised cost of electricity (LCOE), net present values (NPV), internal rate of return (IRR), and (discounted) payback period ((d)PBP).

2.2 Case study

The case study is performed for the planned 700 MW offshore wind park *Ten Noorden van de Waddeneilanden* (TNW), located in the Dutch North Sea, about 67 kilometres offshore at an average water depth of 35 meters. The wind park area extends over 120 km^2 (RVO, 2025). Different configurations of co-located offshore renewable energy parks are simulated. Next to the baseline scenario of wind-only (W), two configurations with one additional technology are simulated: wind-solar (WS) and wind-wave (WW).

Based on the available space, considering mooring lines and exclusion zones two solar scenarios with a medium (600 MW) and high (900 MW) capacity were simulated. The former was selected for the WS case study, the latter capacity was used for the WWS case. Since wave conditions in the North Sea are strongly correlated with wind, the limited capacity which could be extracted in the lower wave climate and the uncertainty about exclusion zones around wave energy parks with multiple devices, only a portion of the wind park's installed capacity was added for the wave energy park. The two capacities modelled for wave energy include 210 MW and 390 MW with the former having a better overall performance. Over several iterations a wind-wave-solar (WWS) park with a wind capacity of 600 MW, a wave capacity of 210 MW and a solar capacity of 900 MW was selected (Table 1).

The resource data for the wind-wave simulations was retrieved from ResourceCode ranging from 2005 to 2020. For the wind-solar case, the resource data ranged from 2018 to 2023 and was retrieved from Solcast. As no source has data for offshore wind, wave, and offshore solar at their disposal, different sources for overlapping years were combined. For the WWS scenario, wave and wind resources were taken from Resource Code and offshore solar data from Solcast for the years 2018-2020.

Table 1 Different case studies and parks selected for further analysis

Case	**wind [MW]**	**solar [MW]**	**wave [MW]**	**park [MW]**	**export infrastructure [MW]**
W	705	-	-	705	700
WS	705	600	-	1305	700
WW	705	-	210	915	700
WWS	600	900	210	1710	700

For wind, the IEA 15-MW Offshore Reference Turbine with a unit power rating of 15 MW, a rotor diameter of 240 meters, and a hub height of 150 meters was selected. A total of 47 turbines and their published power curves were used in the simulation to account for 705 MW installed wind capacity (NREL, 2020). Regarding solar, the technology of Oceans of Energy is modelled as 50 MWp offshore solar islands floating on the ocean surface. A panel efficiency of 22% was assumed. The point absorber of CorPower Ocean was modelled according to its power matrix for the wave simulations, with each device having a capacity of 0.4 MW (Satymov, Bogdanov, Dadashi, Lavidas, & C., 2024). Compared to the other three cases, the installed wind capacity in the WWS scenario is slightly decreased to 600 MW to decrease the dominance of wind and leave more physical space in the park and export capacity on the export infrastructure for wave and solar energy to achieve more synergistic effects between the technologies. Throughout all cases, the export infrastructure was assumed to be able to support a maximum export power of 700 MW as this is the planned capacity for the offshore wind park by the grid operator TenneT. Transmission losses of 3% are applied before the export infrastructure (TenneT, 2022).

The following layout of the TNW park below including 600 MW of offshore wind, 210 MW of wave energy and 900 MW of offshore solar was constructed to show that it is possible to allocate all three resources in the park area given the exclusion zones of the technologies and cables (Figure 2). Overall, this layout increases the installed capacity from 705 MW in the W case to 1710 MW in the WWS scenario. The wave park is located on the Northern side as the dominant wave direction. To minimise wake effects in the consecutive wave energy converters rows, the number of rows is kept minimal, while extending the array along the edge of the park. The solar islands of 50 MWp each were placed in between the turbines where the most space was available.

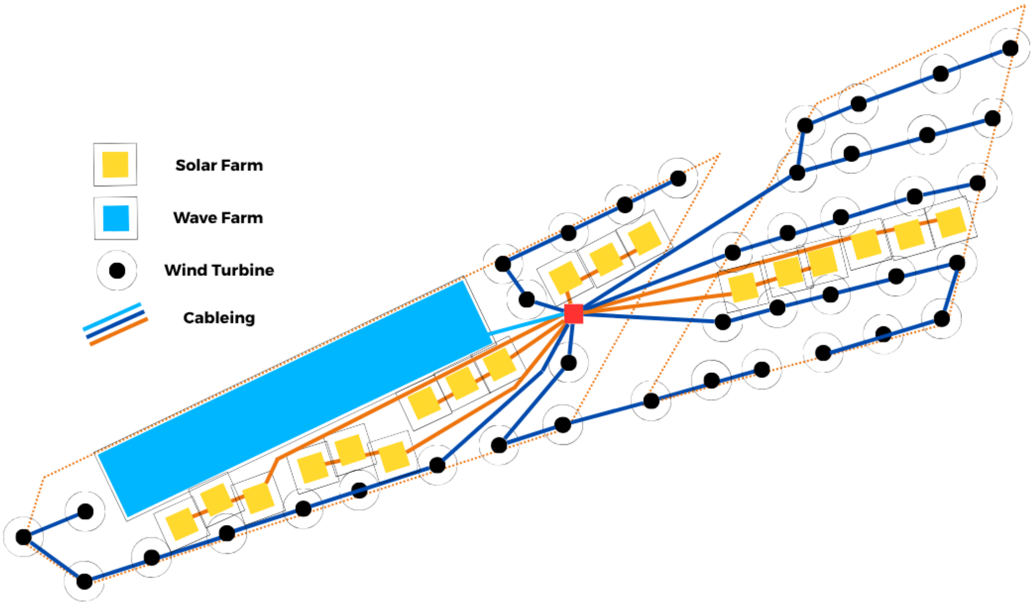

Figure 2 Layout for the chosen (TNW) case

3. Results & Discussion

3.1 Climate crisis

To mitigate the climate crisis, which is largely driven by anthropogenic carbon dioxide emissions from fossil energy generation, it is crucial to increase the generation of electricity from renewable energy sources. Co-located offshore renewable energy parks leverage the complementarity of resources by exporting more clean electricity via the same export infrastructure. Hence, more renewable electricity is available for society without requiring an enlargement of the export infrastructure like export cables and substations, which are not only expensive but which also have long lead times. Delays in grid connection are a main bottleneck for the finalisation of renewable energy projects and the availability of clean electricity.

As the offshore energy park described in this work combines three different sources, it is essential to model the different combinations of technologies to see their individual impact (Table 2). For the decision on which electricity generation technology to curtail, the following prioritisation is applied: 1 wind, 2 solar, 3 wave. Wind always has priority to export electricity because of the favouring offshore wind policy frameworks including the dedication of the zone at question as a wind-search-area. As offshore solar has a lower complementarity with wind than wave, electricity generated from offshore solar is prioritised over electricity from wave energy.

The simulation of an offshore wind-solar (WS) park shows that adding almost the same capacity installed of offshore solar to a wind-only (W) park can increase the annual electricity exported (AEE) by almost 15%, exporting more than 400 GWh of additional clean electricity. At the same time, the annual electricity curtailed (AEC) only increases by 80 GWh. In the wind-wave (WW) scenario, AEP is higher than in the WS case even though the installed capacity of wave energy is lower than that of offshore solar in the WS case. This increase of AEP in the WW case is due to a higher capacity factor of wave energy (35%) compared to solar (10%) in the North Sea. Simultaneously, the AEE of wave energy is smaller than that of offshore solar. This is because wave resources in the North Sea are primarily produced by local winds. It, therefore, correlates more with wind than solar does. This pattern is manifested in the capacity factor (CF) of the export cable, which is slightly higher for WS than WW. Adding both wave and solar to the TNW wind park, while slightly reducing the wind capacity to 600 MW to create space and limit curtailment, the AEE can be increased by 21%. The curtailment share stays low at 5% of the AEP. The capacity factor of the export infrastructure is increased by 11 percentage points, bringing the CF to 63%.

Table 2 Overview of the annual electricity produced, curtailed and exported for the various selected case studies

Case	**Technology**	**Annual Electricity Produced (AEP)** (without transmission losses) **[GWh]**	**Annual Electricity Exported (AEE) [GWh]**	**Annual Electricity Curtailed (AEC) [GWh]**	**AEC / AEP [%]**	**Capacity factor of export infrastructure (CF) [-]**
W	wind	3,360	3,170	0	0%	0.52
WS	wind	3,360	3,170	0	0%	-
	solar	520	420	80	16%	-
	park	3,670	3,590	80	2%	0.59
WW	wind	3,360	3,170	0	0%	-
	wave	620	390	210	35%	-
	park	3,770	3,560	210	6%	0.58
WWS	wind	2,780	2,690	0	0%	-
	wave	620	490	110	19%	-
	solar	770	650	100	13%	-
	park	4040	3,830	210	5%	0.63

Simulating the AEE per month and scenario and plotting it over a full year shows significant differences between the seasons (Figure 3). In summer, the exported wind electricity is lower due to lower wind speeds during these months. The strong correlation between wave and wind is shown in the light blue graph representing the WW case, which closely follows the pattern of the wind scenario. It also becomes apparent that in summer, offshore solar has a higher yield while also being able to use free capacity on the export infrastructure and contribute to filling the dip caused by wind energy. Comparing only the winter months, offshore solar (WS) does not add a lot of electricity to the mix but wave energy (WW) increases the export mix greatly. The most consistent case is the one which combines wind, wave and solar (WWS).

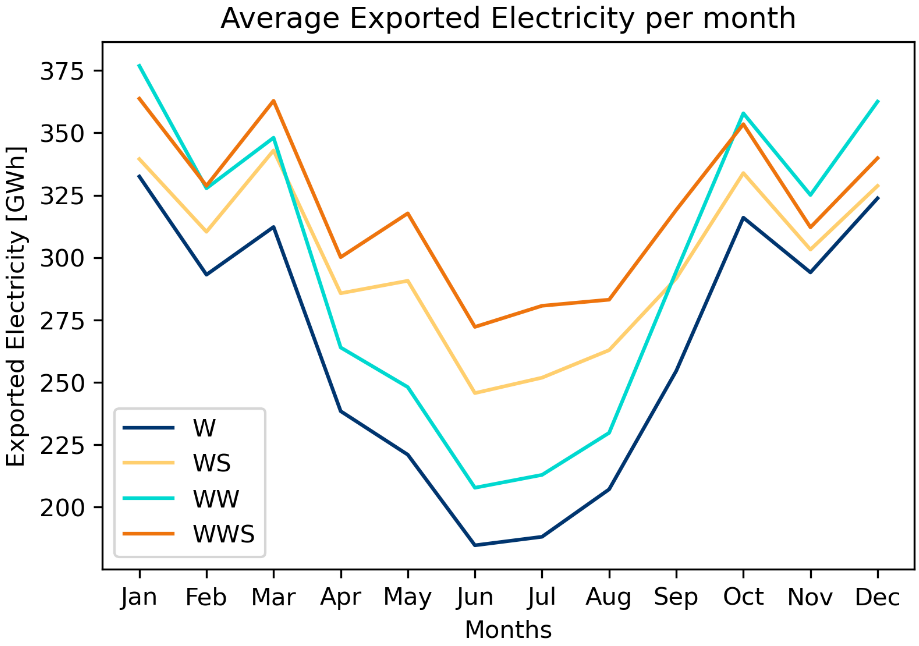

Figure 3 Average exported electricity per month plotted over an exemplary year for four different cases

The curtailment share for WW is the highest of all scenarios due to the correlation of wind and wave energy. As the AEP for both is increased during winter also the curtailed electricity is larger between November and March (Figure 4). On the contrary, driven by greater solar resources during summer, scenarios that include offshore solar show greater curtailment shares in spring and summer. On an annual scale however, the percentage of curtailed electricity is lower for WS than for WW. Similar to the average monthly exported electricity, also the average monthly curtailed share of a WWS park is relatively consistent. The decreased wind capacity lowers the curtailment to 5% for the WWS scenario compared to 6% for the wind-wave case. All scenarios are characterised by overplanting, although due to the transmission losses of the the interarray and export cable included in all parks, the total exported electricity is decreased. In the wind-only case, this leads to a maximum power exported of approximately 684MW.

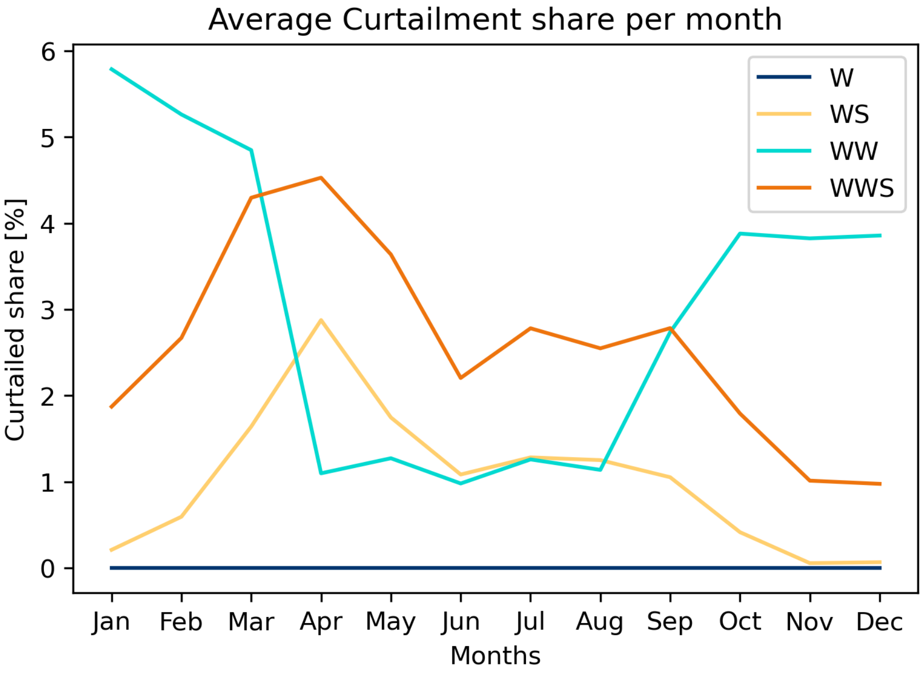

Figure 4 Average curtailment (in % of electricity produced) per month in an exemplary year

The improved capacity factor, higher energy density and acceptable curtailment amount demonstrates that a WWS park can deliver more clean electricity to society while making significantly more efficient use of the export infrastructure. Beyond contributing to climate change mitigation, this improved efficiency can also help build public support for offshore renewable energy projects. By co-locating technologies, the costly infrastructure is used more effectively, thereby reducing the societal cost of transporting each unit of electricity. At the same time, co-located parks can increase the deployment speed of renewables, as the main bottleneck is often the export infrastructure and as the construction time of the park is not expected to increase significantly.

3.2 Biodiversity crisis

The increase in energy density of co-located offshore renewable energy parks compared to wind-only parks can help mitigate the biodiversity crisis by requiring fewer space to achieve the goals of the energy transition. As such, more space is available for nature conservation and restoration.

The wind park TNW extends over an area of 120 km^2. The space required to accommodate 1 MW varies per technology. Wind requires 0.05 km^2, whereas wave needs 0.04 km^2 and solar only 0.03 km^2 per installed MW. This shows that wind has the lowest density and solar the highest density when considering the installed capacity. However, when evaluating the energy density of the different park configurations, the different capacity factors of the technologies need to be considered which influence the power output. Furthermore, it is not the power output that is of relevance, but the exported energy, which is determined by the capacity of the export infrastructure. Due to the overplanting of the park in all cases, power output will need to be curtailed when the production exceeds the export capacity.

The table below shows the energy density as the AEE per area, always assuming the entire park area can be used for energy generation (Table 3). Even though the installed capacity in WS is almost twice as high as in W, the AEE per area only slightly increased, despite offshore solar's high energy density regarding the installed capacity per area. This can be explained by the relatively low capacity factor of offshore solar in the North Sea. The WW case performs almost as good as WS, even though the added wave energy capacity is only one third to the added solar capacity in WS. This can again be explained by the higher capacity factor of wave energy (Table 2).

Table 3 Park-level energy density per area for the four different cases

Case	**Annual Electricity Exported / Area [GWh/km^2]**	**Installed Capacity / Area [MW/km^2]**
W	26.4	5.9
WS	29.9	10.9
WW	29.6	7.6
WWS	32.0	14.3

With the chosen assumptions, an offshore solar installation in the North Sea is able to export 17.6 GWh/km^2 per year while for a wave energy installation this amounts to 68.5 GWh/km^2 per year and for wind energy to 85.3 GWh/km^2 per year (Table 4). The high exported energy for both wind and wave, however, faces the issue that the devices cannot be built too close together while at the same time minimizing wake effects. Therefore, once more the combination of different technologies is beneficial. The energy density of WWS regarding the AEE is 21% higher than for a wind-only park, showing that the area needed to achieve the same exported energy can be decreased a lot when adding solar and wave energy to a wind park. The increase in efficient use of the park area has positive effects for biodiversity, as fewer space is needed for clean energy generation. This positive effect can further be enlarged by maximizing the utilisation of mitigation technologies and nature inclusive designs appropriate for the local ecosystem.

Table 4 Energy density per technology

Technology	**Annual Energy Exported technology / Area technology [GWh/km^2]**	**Total Area technology [km^2]**
wind	85.3	37.1
solar	17.6	24.0
wave	68.5	5.7

3.3 Energy security crisis

A challenge for a successful energy transition and a country's energy security is the intermittency of renewable energy sources. This results in fluctuations of available clean electricity and poses challenges for fulfilling baseload power requirements with renewable sources at any time. In co-located offshore renewable energy parks, the combination of different energy sources with varying power output profiles can provide a more stable energy output. The more anti-correlated the resources are, the more complementary they are and the better they can produce a stable power output.

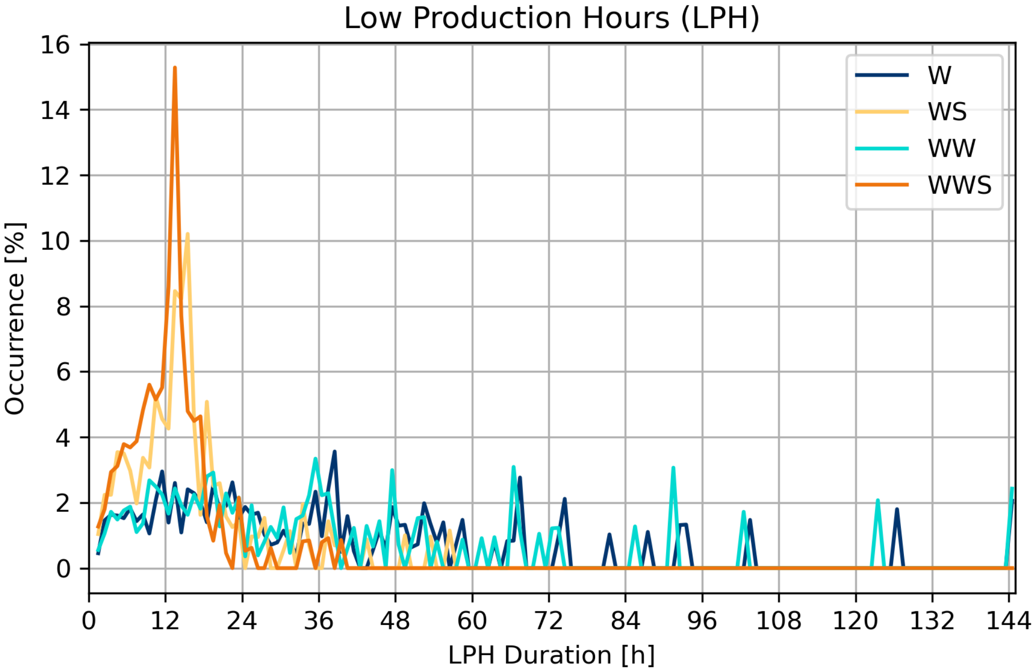

Figure 5 Histogram of low production hours (below 20% of export capacity) in the W, WS, WW and WWS cases

A metric to assess the generation of baseload electricity are low production hours (LPH). Those are defined as the hours during which the energy output of the park is below a certain threshold of the export infrastructure. This threshold was set to 20% of the export capacity, meaning that if the park produces less than 140 MW (20% of 700 MW) it cannot fulfil its baseload requirement. In the W scenario, during almost 30% of the time, the park is not generating enough power output to fulfil baseload requirements, as shown in the table below. During the longest period of 144 consecutive hours, which equals 6 days, baseload could not be achieved. Even when adding wave energy, the longest low production period could not be shortened as it occurs in summer where wave energy, such as wind energy, have lower outputs. Nevertheless, in the WW case, the share of LPH could be decreased to 25% of the time. This shows that despite the correlation of wave and wind, wave can still contribute to decreasing LPH, but only moderately and without reducing the longest low production period. In contrast, offshore solar shows a much greater potential to reduce both overall LPH and the duration of the longest low production events when added to a wind-only park. In the WS case, the time during which the park output is not generating baseload power could be decreased from almost 30% to 20%. The WS park also shows a remarkable reduction of the longest low production period to 56 hours, or 2.3 days, equalling a reduction of over 60% compared to wind-only. At the same time, shorter periods of low production increase notably when adding solar to the park. The most drastic reduction is once more seen in the WWS case with the longest low production period being shortened to 39 hours, 1.6 days, compared to six days in the wind-only case. Both cases including solar show an occurrence peak around 12 hours coinciding with a full night. The peak of the WWS shows the strongest shift to the left indicating a strong improvement in energy security (Figure 5).

The occurrence of the longest low production period is moved from summer (mid-July) in the W and WW scenarios to late winter (mid-February) in the WS case, when the solar output is not yet large enough to contribute to baseload power and to spring (early-April) for the WWS case. Regarding the contribution of a co-located park to energy security, the table below shows the substantial decrease in low production hours by 12 percentage points when adding both wave and offshore solar to the TNW wind farm, equalling a decrease by more than 40%. Also, this emphasizes the role that co-located offshore renewable energy parks can play in providing baseload power and contribution to energy security.

Table 5 Low production hours occurrence and timing

Case	Share Low Production Hours [-]	Longest Low Production Hour [h]	Start date of longest low production hour [month-day]
W	0.29	144	18-07
WS	0.20	56	19-02
WW	0.25	144	18-07
WWS	0.17	39	03-04

3.4 Business case

After having demonstrated the benefits of adding offshore solar and wave energy to a Dutch offshore wind park and how the co-located park is better equipped to tackle the climate, biodiversity and energy security crises, the following section provides a techno-financial analysis to inform about the economic feasibility of the WWS case compared to wind only.

The offshore wind park TNW was originally planned to become operational in 2031therefore, , 2031 was selected as the start year for the simulations. The modelled lifetime for all cases is 25 years, as this is the expected lifetime for offshore solar and wave energy parks and the cost data were chosen based on previous work, market data and simulations (EU-SCORES, 2024). As future electricity prices remain greatly uncertain, several different prices ranging from 80 EUR/MWh to 120 EUR/MWh were simulated (Table 6). The electricity prices were simulated as constant prices, representing two-sided Contracts for Difference (CfD) or Feed-in tariffs (FiT).

Table 6 Cost assumptions & techno-financial input used for the different technologies modelled in this study

	wind	**solar**	**wave**
CAPEX (MEuro/ MW)	2	1.5	2.5
OPEX (kEuro/ MW year)	40 (2%)	22.5 (1.5%)	200 (8%)
DEVEX (MEuro)	220		
Discount rate (-)	0.1		
Electricity price (PPA, FiT) (Euro/ MWh)	80/100/120		
Lifetime (y)	25		

The results of the techno-economic analysis shown in the table below show that the W scenario has a positive business case for all three electricity prices modelled. For the WWS case, a positive net present value (NPV) could only be achieved for the highest electricity price. As wave and offshore solar energy are not yet mature technologies (around TRL 6-7 in 2025), this is not surprising. Wave and solar will require governmental support to become commercially viable, as is the case for many innovative technologies that have not yet reached economies of scale. The results also show that as electricity prices increase, the differences in internal rate of return (IRR) between the W and WWS scenarios decrease. Regarding the depreciated payback period (dPBP), with an electricity price of 120 €/MWh, the dPBP for the WWS case can compete with the dPBP of a wind-only park at lower electricity prices.

While the wind-only configuration outperforms the WWS case in the techno-economic assessment, not combatting the crises also comes at a significant price, as damage due to natural disasters caused by the climate crises, a reduction in agricultural productivity and general declining ecosystem balance caused by the biodiversity crisis, and sky-rocking energy prices as well as higher need for energy independence following the war of Russia on Ukraine have shown.

Table 7 Output of the financial analysis including net present value (NPV), internal rate of return (IRR) and depreciated payback period (dPBP)

Case (electricity price in €/MWh)	NPV (M€)	IRR (%)	dPBP (y)
W_80	412	13	14
WWS_80	-826	6	N/A (13 non discounted)
W_100	987	17	6
WWS_100	-130	9	N/A (10 non discounted)
W_120	1561	21	5
WWS_120	566	13	15

4. Conclusion

The comparison of the W, WW and WS cases and their effects on the climate, biodiversity and security crises showed the strengths of combining different renewable energy sources in combating those crises. To take advantage of the beneficial characteristics of all three technologies, one scenario that includes offshore WWS with 600 MW wind, 210 MW wave and 900 MW offshore solar has continuously shown the best results . It can be argued that the increase in additionally exported clean electricity using the same electrical infrastructure can help mitigate climate change, as more carbon-free energy can be provided without delaying the realisation of the offshore energy parks. Furthermore, the smaller spatial claim of co-located offshore energy parks compared to single-source parks due to their greater energy density, reducing the space needed for producing the same amount of electricity by 21%, can relieve the biodiversity crisis, leaving more space available for marine protected areas. This can contribute to achieving the international 30x30 target of the Global Biodiversity Framework, aiming to conserve 30% of the marine space by 2030. Lastly, the continuous supply of electricity is strongly improved in co-located parks, reducing intermittency and helping to balance the grid, which contributes to energy security as it provides more certainty on the availability of clean electricity. The economics of a multi-source park combining wind, wave and solar remain to this date challenging as both offshore solar and wave are still in an early stage so that economics of scale could not yet materialise. However, the crises mitigation potential showcased throughout this work should be sufficient motivation on the positive contribution of WWS parks on climate change mitigation, the biodiversity crisis and providing energy security and compel governments to support the roll-out of co-located offshore renewable energy parks. The paper builds on the intermittency of renewable energy as a key characteristic of the technologies and hence any fully decarbonised energy system. This characteristic results in both, a need for overplanting in order to meet a continuous energy demand, as well as curtailment in times of high production due to congestion in the power grid. A combination with a storage system, allows to mitigate some of these effects, by for example shaving production peaks or by providing power output during periods of low or no generation. The combination of offshore wind with solar and wave energy already reduces these events and hence the need for storage capacity, significantly. On the other hand however, the overplanting results in curtailment peaks of up to 402 MW for wind-solar farms, 126 MW for Wind-Wave farms and 700 MW for wind-wave-solar farms. Designing a storage system to mitigate these is possible, but not desirable. As these overproduction periods usually represent periods of high renewable saturation in the energy system and therefore either low (or even negative prices) or even grid side curtailment. It is therefore not desirable to absorb all of this energy on site, as cheap electricity is ubiquitous on the day-ahead or intra-day market. Instead, future studies could analyse the ability of a renewable + storage hybrid system to shift power outputs towards demand peaks in order to benefit from high energy prices. In this way a focus could be on the match of a wind-only as opposed to a wind-wave-solar power output against such a demand profile (duck curve).

Data access: The wind and wave data is open access: https://resourcecode.ifremer.fr/ The solar data was purchased from: https://solcast.com/ Please contact the corresponding author to request data and more information.

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