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D5.10 Technical and Logistical Optimized Layout for Utility Scale Multi-use Parks

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Contents

1. Introduction

The Need for Space-Efficient and Grid-Resilient Renewable Generation

With growing commitments to climate-neutral energy systems, offshore renewable energy is expanding rapidly, particularly in the North Sea. However, this growth is met with spatial and ecological limitations. As offshore wind farms grow, competition for marine space intensifies among energy infrastructure, shipping, fisheries, and ecological preservation. Simultaneously, energy systems based on a single intermittent source (like wind) struggle with grid balancing, leading to the need for backup capacity or large-scale storage on the grid. Addressing both constraints requires solutions that make more efficient use of ocean space while improving the diversification of energy sources.

Benefits of Co-Locating Wind, Wave, and Offshore Solar

Combining multiple offshore energy sources in the same spatial footprint offers compelling advantages:

- **Energy smoothing**: Complementary production profiles reduce output variability across daily and seasonal cycles.
- **Higher energy density**: By utilizing the spacing between turbines and active perimeters for solar and wave energy, more power can be extracted per km².
- **Infrastructure sharing**: Co-located systems can use common export cables, substations, and maintenance vessels, reducing both CAPEX and OPEX.

Research suggests that these synergies not only increase total energy yield but also improve predictability supporting long-term grid stability.

The TNW Site as a Real-World Test Case

The Ten Noorden van de Waddeneilanden (TNW) wind farm zone, located north of the Dutch Wadden Islands, serves as a highly relevant and data-rich case study for multi-source offshore energy park design. This zone has been the subject of several in-depth planning and feasibility studies, including the 2018 Levelized Cost of Energy (LCoE) assessment by BLIX Consultancy for RVO [1]. That study evaluated multiple spatial variants of the TNW area, demonstrating how site boundaries and turbine spacing affect wake losses, energy yield, and ultimately the LCoE of offshore wind farms. For example, reduced site width or suboptimal layouts were shown to increase wake losses by up to 160%, leading to LCoE increases of nearly 10%, highlighting the need for spatially efficient designs.

Hinne et al. (2024) [2] provided the first comprehensive model of a multi-source park at TNW, quantifying benefits such as a 22% increase in energy density and an 86% reduction in hours of low output.

Building upon the findings of *Hinne et al. (2024) [2]*, which demonstrated the potential of co-locating offshore wind, wave, and offshore solar at the Ten Noorden van de Waddeneilanden (TNW) site, this deliverable advances the discussion by exploring layout scenarios for future multi-source parks. The original study highlighted the benefits of such integration in terms of energy density, output smoothness, and capacity factor. However, it was based on a single spatial design featuring 12 MW wind turbines with fixed assumptions on solar and wave allocation.

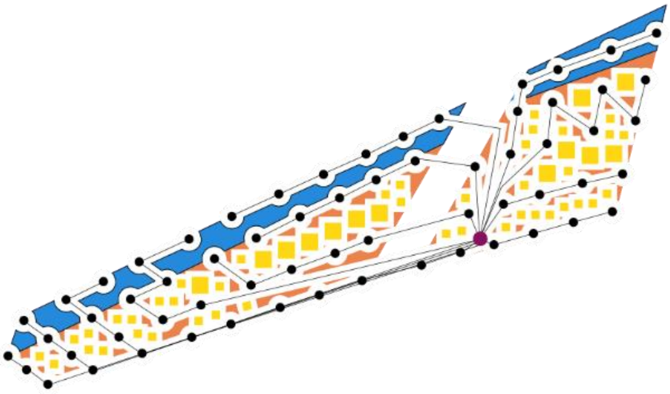

Figure 2: Proposed multi-source layout for Ten Noorden van de Waddeneilanden (TNW) based on Hinne et al. (2024)

The design features 63 offshore wind turbines of 12 MW each, one central offshore substation, and integrated zones for additional renewable sources. Offshore solar islands are placed between turbines using two sizes: 250 × 250 m units (~25 MW) and 500 × 500 m units (~50 MW). A designated northern perimeter (blue zone) is reserved for wave energy converters (WECs), aligned with the dominant wave direction to optimize capture potential.

As a more detailed study of the practicality of this design, this study investigates how spatial planning and technology assumptions impact park configuration and system performance. Using the TNW site as a blueprint, we simulate and visualize four distinct layout scenarios. These allow us to test trade-offs between turbine size, spatial constraints, and the inclusion of multiple energy sources. Each scenario represents a plausible future configuration, balancing power output, accessibility, and logistical feasibility:

- **Scenario 1**: Baseline layout using 12 MW turbines with solar integrated between turbine strings.
- **Scenario 2**: Same 12 MW turbine configuration including solar, but with the addition of wave energy converters (WECs) along the northern edge of the park.
- **Scenario 3**: Upscaled layout with 15 MW turbines and exclusion zones increased accordingly, solar is deployed between wider turbine spacing but without wave to test a pure wind-solar system.
- **Scenario 4**: Full multi-source concept with 15 MW turbines, offshore solar, and wave energy, testing the feasibility of maximum integration in the TNW spatial envelope.

These design scenarios were iteratively developed 2D design tools, incorporating realistic spacing rules, maintenance access corridors, and inter-array cabling strategies. The results provide both a visual demonstration of layout possibilities and a platform for discussing upscaling trade-offs for multi-source offshore parks worldwide.

2. Methodology and Design Approach

The methodology for this layouting exercise builds upon the framework developed by Hinne et al. (2024) [2], which modelled the spatial integration of wind and solar energy at the Ten Noorden van de Waddeneilanden (TNW) offshore wind farm. In the present study, this foundation is extended to explore future-oriented scenarios incorporating larger wind turbines, integrated wave energy, and alternative solar configurations. The overall process followed a three-step approach encompassing spatial layout design, electrical integration, and solar module configuration, as depicted in the methodology flowchart (Figure 3) below.

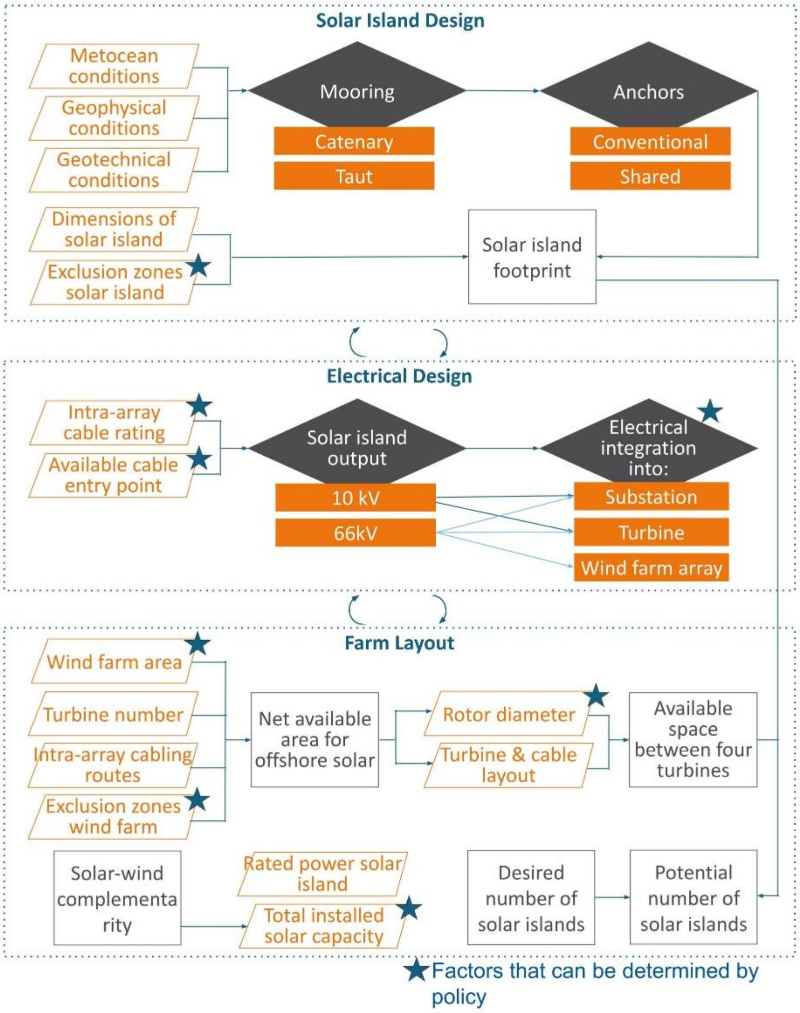

Figure 3: Overview of the three-step layouting methodology, covering wind farm layout definition, electrical integration options, and solar module design considerations for offshore solar deployment.

The first step established the solar island design to determine its physical footprint. This process began by analysing site-specific metocean conditions, geophysical data, and geotechnical characteristics of the seabed. These inputs informed the mooring and anchoring strategy for the proposed offshore solar platforms, which were defined as 500x500 meter units, each representing a 50 MW island. Mooring systems, including catenary configurations, were considered based on the hydrodynamic loads, water depth and platform mass. Correspondingly, anchor solutions were evaluated for soil compatibility, with options for both conventional and shared anchoring to secure the solar modules. The solar energy output was modelled using typical module efficiencies (20%) and performance ratios (0.77), with irradiance data from the PVGIS SARAH2 database. This initial design phase defined the fundamental solar island footprint used in subsequent planning.

The second step focused on electrical integration. The study evaluated how solar modules could be connected into the existing offshore wind array. Several integration strategies were considered, including connections directly through wind turbines, integration at inter array cables via T-connectors or routing solar output to the offshore substation through their own inter-array cable, landing via an additional J-tube. The placement of electrical equipment required for this integration was assessed for different locations, including mounting directly on the offshore solar islands, co-locating with offshore wind turbines, or situating the equipment on separate platforms. These options were evaluated against available intra-array cable ratings, connector availability, and redundancy considerations. A more detailed investigation into the electrical infrastructure is found in Section 7.

The updated layouts incorporated solar “branches” and radial structures where relevant, enabling a more modular and accessible string topology. This was particularly important in the 15 MW configuration, where the reduction in maximum turbines per string (from nine to eight) imposed new constraints on cable lengths and current capacities.

The final step determined the overall farm layout, integrating the solar island footprint with the wind farm characteristics. The base layout was updated from 12 MW to 15 MW turbines to reflect technology evolution, resulting in approximately 15% larger exclusion zones around each turbine. The net available area for offshore solar was calculated by considering these zones, maintenance corridors, and optimized intra-array cabling routes. Offshore solar islands were then placed within the available space between turbine strings. To determine the total installed solar capacity, assessments of solar-wind complementarity were considered to optimize the energy profile of the combined plant. This analysis, balancing the rated power of the solar islands with the available space, determined the potential number of solar islands that could be integrated. Updated layouts also included alternative arrangements, such as shorter solar strings and dedicated pure solar strings up to 150 MW. The northern perimeter of the site was retained as a designated zone for wave energy converters (WECs), in line with the original spatial allocation.

This methodology enabled the development and evaluation of four spatial scenarios at TNW, each reflecting a different combination of wind turbine capacity, solar layout, and wave energy integration. The results provide insights into how spatial design and infrastructure planning can support the upscaling of multi-source offshore parks under real-world constraints.

3. Layout Evaluation and Scenario Analysis

Using the spatial and technical considerations outlined in the previous section, the first step in the analysis was to replicate the layout from Hinne et al. (2024). The original layout was developed using the vector-based software Inkscape. However, for this study, the layouting work was conducted in Canva, a platform that proved more suitable for iterative design. Canva allowed for easier manipulation of layout elements, faster duplication of scenarios, and intuitive control over spacing and alignment—features that were particularly useful during the exploration of multiple layout variants.

The layout follows the original configuration of 63 wind turbines, each with a capacity of 12 MW, arranged within the designated TNW site boundaries. A central maintenance corridor was preserved across all scenarios to ensure accessibility for vessels and operational safety. One key modification was the relocation of the offshore substation to the western (left-hand) edge of the site, where a larger open area offers more flexibility for cable routing and the integration of solar and wave components.

All layout figures use a consistent set of visual symbols to represent key infrastructure elements. A legend is provided in Figure 4 for reference.

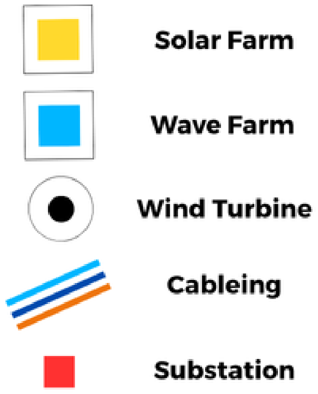

Figure 4: Symbol legend used throughout the layout figures. Icons represent wind turbines (black circles), solar farms (yellow), wave farms (blue), intra-array and export cabling (blue and orange lines), and substations (red squares).

Additionally, all the designs ensure that no individual cable string exceeds its capacity of approximately 150 MW. The 150 MW limit for a single cable string in an offshore wind farm isn't a universal law, but rather a widely adopted techno-economic benchmark for systems using the industry-standard 66 kilovolt (kV) intra-array cables. Exceeding this capacity introduces significant engineering and financial challenges.

Figure 5 shows the base layout without solar integration, preserving the turbine placement and spacing defined in the original model.

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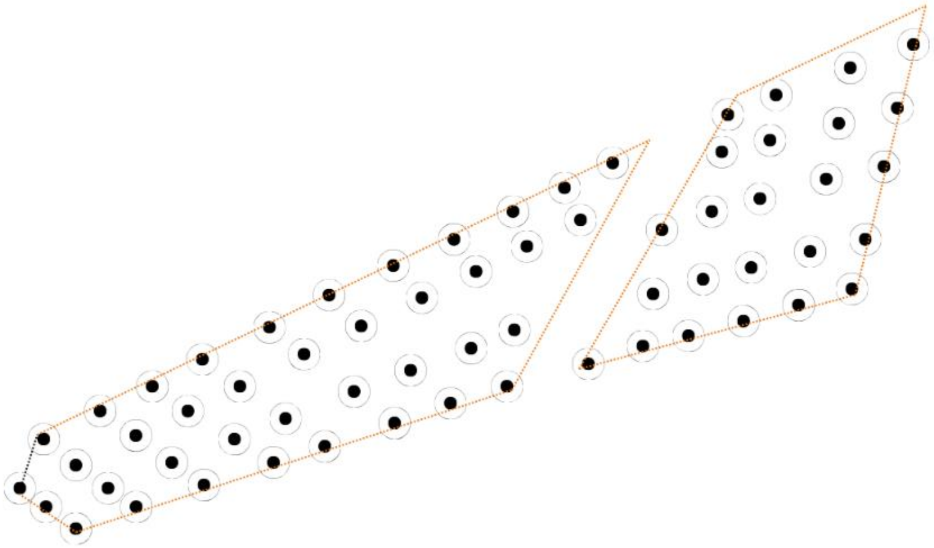

Figure 5: Base 12 MW layout

To further explore the implications of intra-array cabling, three different cable configurations were developed for this base layout. These illustrate the variety of interconnection options available when planning these cable routes. In a real-world development, cable routing decisions would be driven by a range of site-specific factors, including bathymetry, seabed conditions, the presence of obstructions such as debris or pipelines, and overall optimisation for capital expenditure (CAPEX). However, in the context of this study, the cable configurations in this study represent simplified models, each based on different core assumptions. These include direct point-to-point connections to minimize cable length and daisy-chain layouts to optimize the number of collection points. This approach allows us to effectively highlight the spatial and design implications of foundational routing strategies within a multi-source offshore energy park. Three cable iterations are shown below, Figure 6 and 7 are initial iterations not used for further assessment. Figure 8 is the base cable layout used for further assessment.

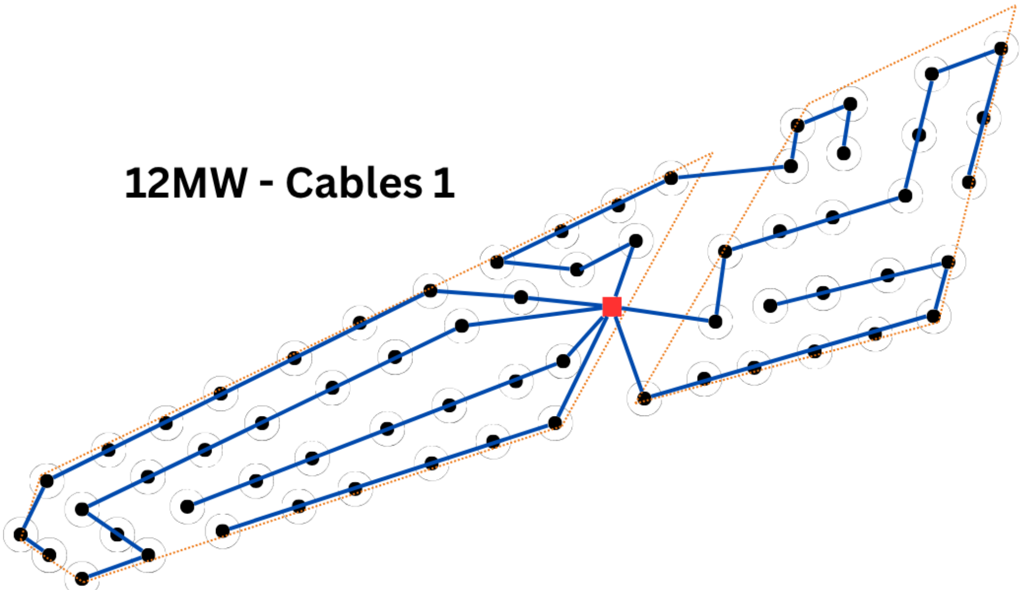

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Figure 6: 12MW Base with cable iteration 1

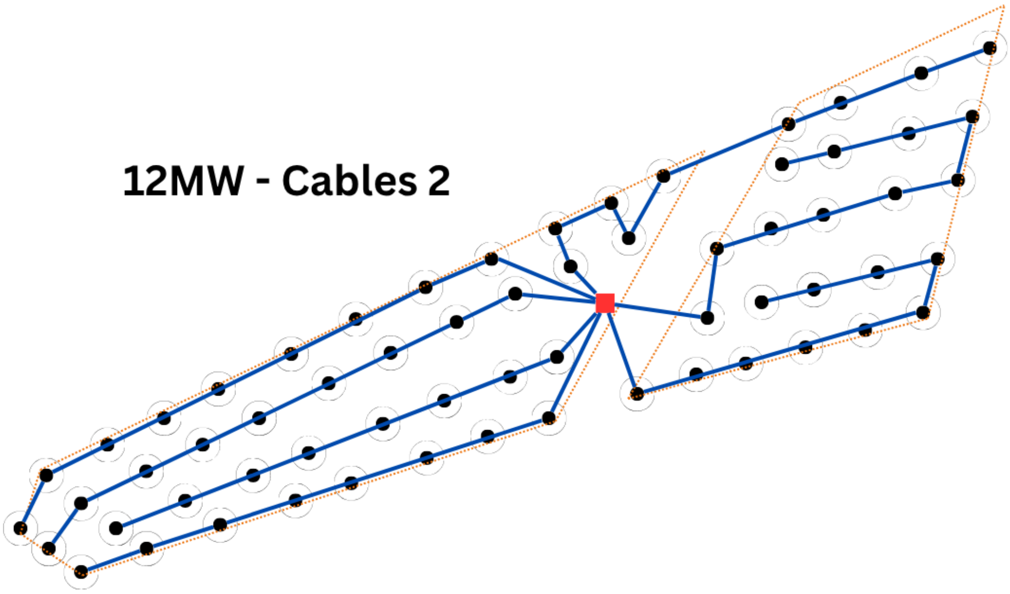

Figure 7: 12MW Base with cable iteration 2

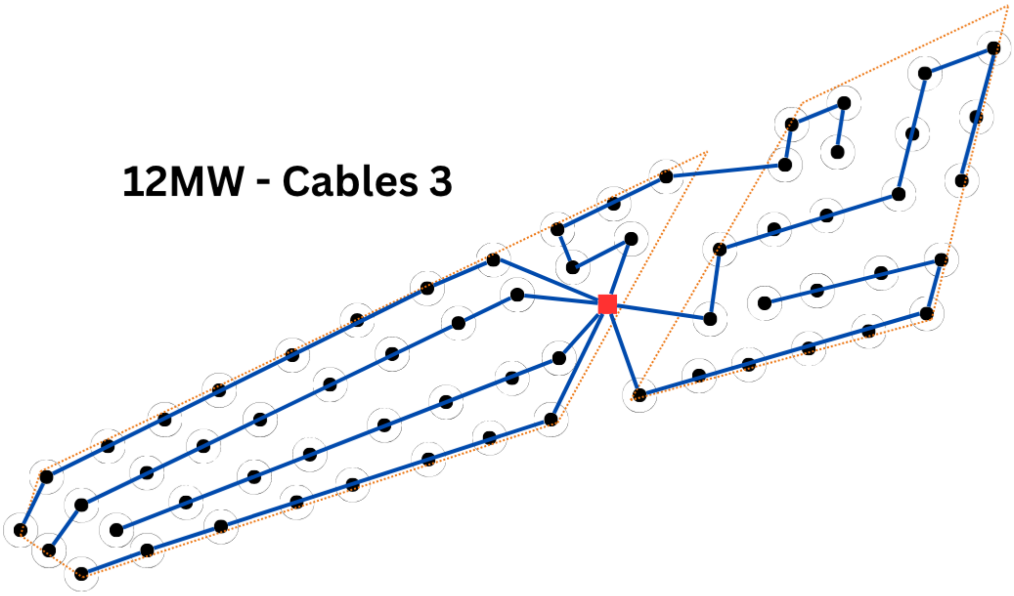

Figure 8: 12MW Base with cable iteration 3

Following the development of cable configurations, offshore solar platforms were introduced into the layout. These solar islands were scaled based on the module dimensions referenced in Hinne et al [2]., 500 × 500 meters (representing 50 MW). The platforms were visually overlaid between turbine rows in areas not obstructing exclusion zones or access routes.

The placement of the solar units was optimized based on a set of key technical requirements. This involved establishing access corridors for Operation & Maintenance (O&M) vessels to ensure unobstructed access to each wind turbine. Consequently, the solar arrays were positioned within the turbines' standard exclusion zones. This overlap is operationally acceptable because the low-profile, stationary solar arrays do not impede the critical O&M corridors, which are designed to restrict external vessel traffic rather than planned internal activities. Exclusion zones within a wind (or multi-use) park can overlap as their main purpose is to manage safety and access for vessel traffic. The rules for operating inside the farm are different to outside traffic.

Finally, the northern area of the farm was kept open to ensure the future installation of Wave Energy Converters in the area with the most favourable wave climate.

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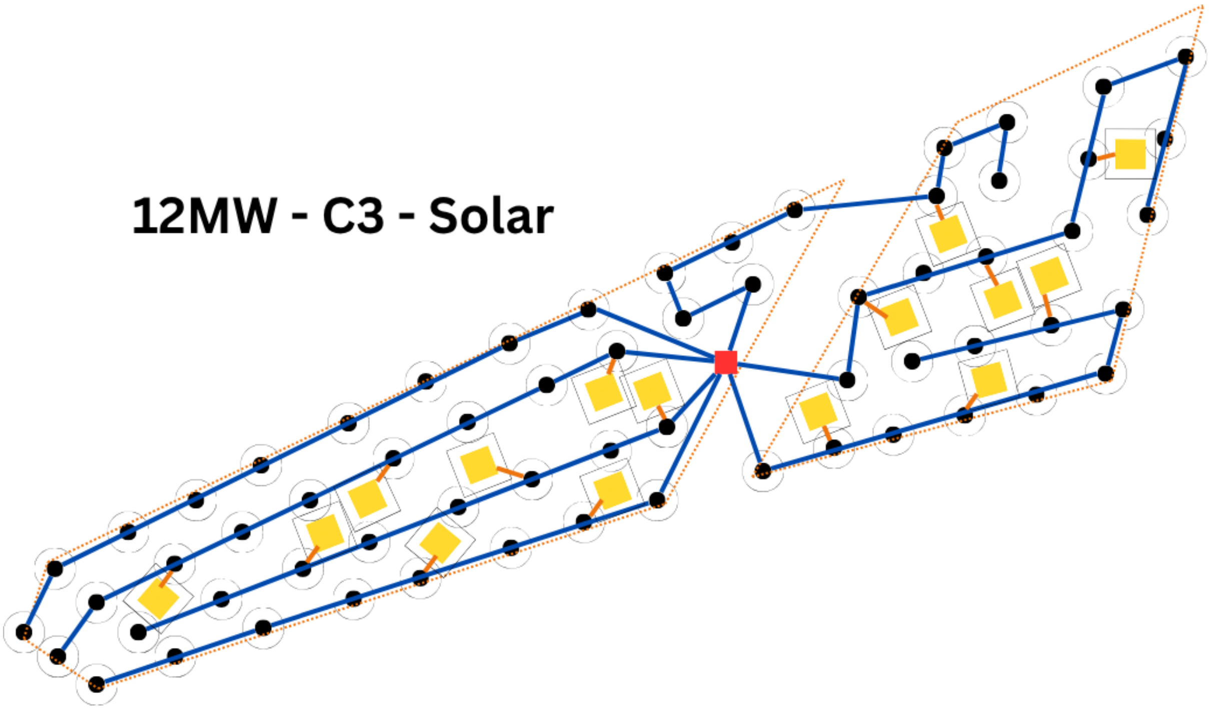

Figure 9: Cable Iteration 3 with 750MW of Solar Islands

Figure 9 shows a first design iteration where offshore solar islands were integrated directly into the wind turbine strings, with solar units placed at every 3rd turbine to ensure the total cable capacity up to that point can meet the added load from a 50MW solar island.

While this approach allows for incremental additions of solar generation, it results in a dispersed deployment pattern and introduces a high degree of variation in cable loading. This is a significant issue because intra-array cables are engineered and sized for the cumulative load of a set number of wind turbines.

This lack of uniformity has several negative consequences. It would significantly increase the complexity of the electrical design, as engineers would need to account for dynamic loads instead of predictable ones. This could necessitate oversizing entire cable strings to handle infrequent peaks—an inefficient and expensive solution—or developing complex control and curtailment systems. The approach would also lead to additional costs related to more extensive planning and modelling, specialized switchgear to manage new fault levels, and a more rigorous testing and certification process required to validate such a non-standard grid configuration.

To address these challenges, a revised iteration (shown in Figure 10) was developed that centralises the solar deployment into dedicated areas. This ensures that string capacity limits are respected while simplifying the cable layout and reducing overall system complexity.

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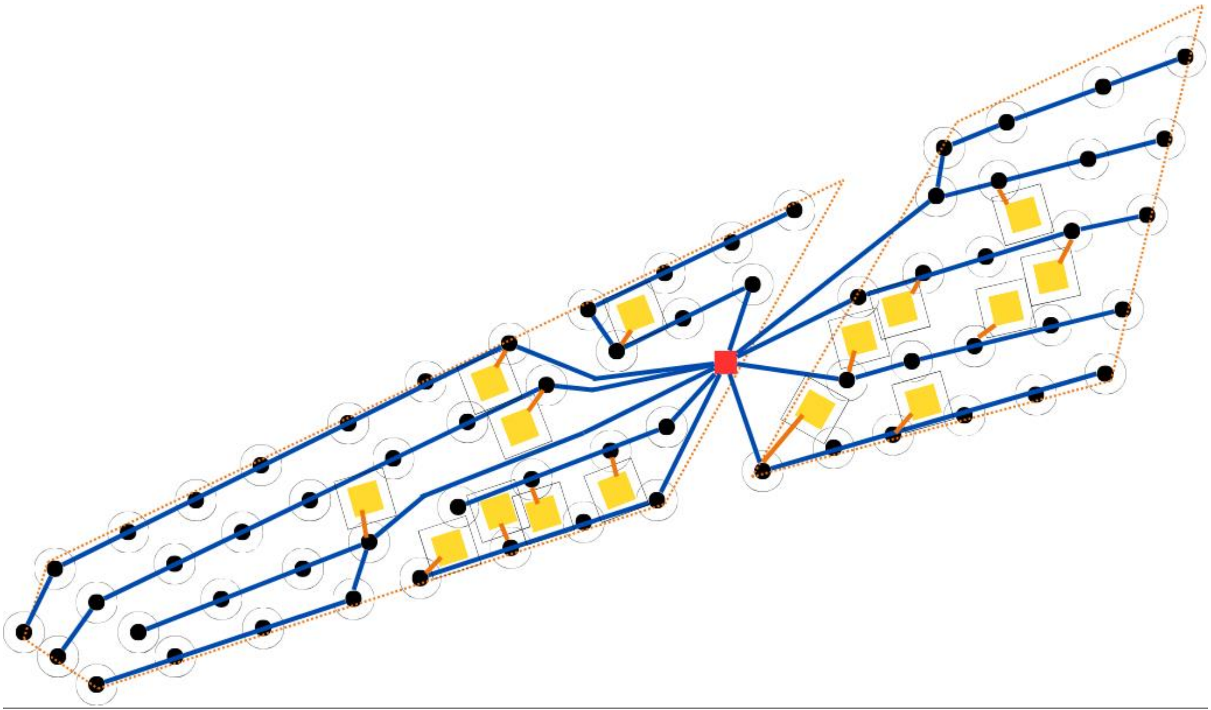

Figure 10: Final 12 MW hybrid layout integrating wind and centralised offshore solar, with optimised cabling to maintain string capacities below 150 MW and improve accessibility for operations and maintenance.

This final 12 MW hybrid layout is an advanced solution that resolves the cable loading issues of a fully dispersed model. While this configuration successfully manages electrical load by distributing the solar islands across more turbine strings (with a strict limit of two islands per cable), it introduces a clear trade-off. The primary drawbacks are the increased installation costs due to the greater number of strings and the added complexity of the substation design needed to handle the additional connections.

This strategy provides a key advantage: it allows for a significant amount of solar capacity to be added to the park without overloading any single string, keeping the total power on each cable well below the 150 MW operational limit. By placing the solar islands near the substation but connecting them to different strings, the design avoids the high electrical variability of the earlier dispersed model while also preventing the access challenges of a single, massive solar farm. This approach successfully integrates both technologies by leveraging the capacity of multiple cable routes in a controlled and balanced way.

To support operational efficiency and reduce system complexity, this centralised strategy simplifies the additional cable routing needed for implementing offshore solar but increases the number of inter-array cables. By clustering the solar islands around the substation, a large part of the wind farm does not include additional equipment, which, improves accessibility for operations and maintenance vessels. While the consolidated solar farm itself forms a dense area requiring its own specific maintenance strategy, the overall park accessibility is enhanced.

One of the main challenges in this 12 MW scenario is the relatively high number of turbines required to match the total solar capacity, which makes balancing cable loads more complex. Despite these constraints, the layout successfully integrates both technologies while maintaining redundancy and compliance with realistic cable capacity limits.

4. Technical Considerations for Upscaling

To reflect ongoing technological developments in offshore wind, a new base layout was developed using 15 MW wind turbines. This scenario explores how increased turbine capacity affects spatial design, exclusion zones, and electrical architecture. The figure below shows the adapted base layout using 15 MW turbines.

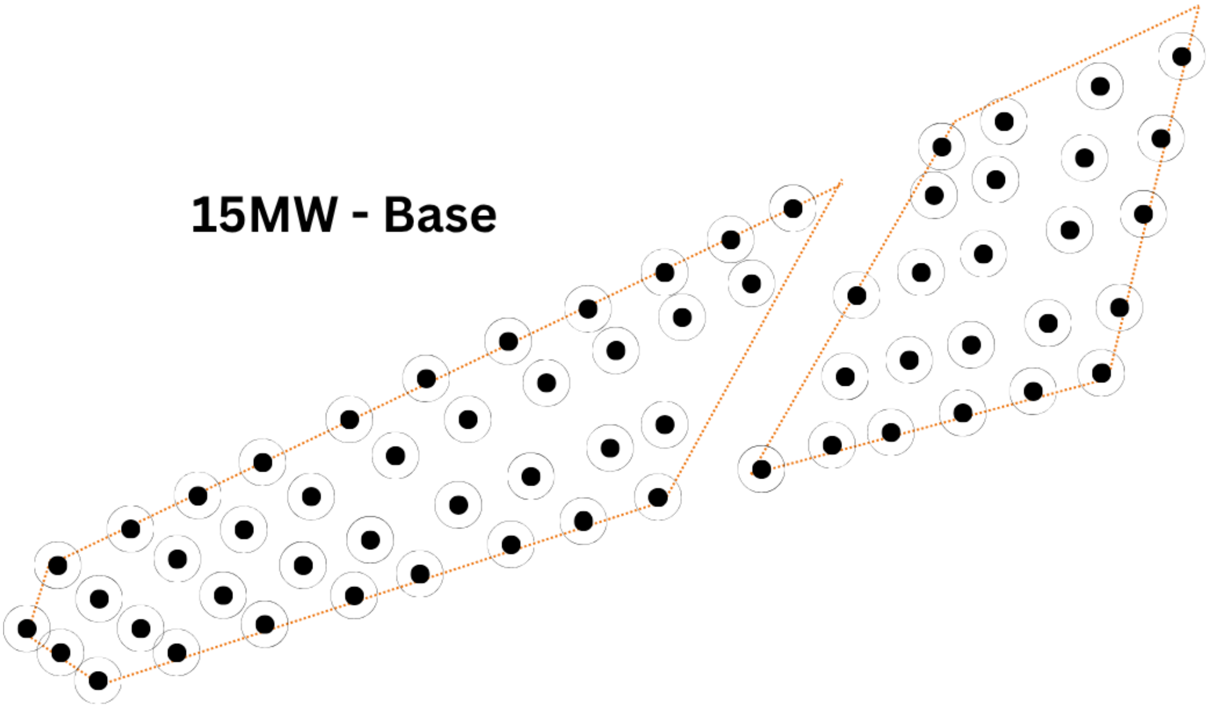

Figure 11: Base layout with increase capacity 15MW turbines

Compared to the original 12 MW configuration, the increased turbine size leads to an increased footprint of approximately 15 percent per turbine due to enlarged exclusion zones and required spacing. This change introduces new spatial challenges. As a result, the existing turbine placement is no longer feasible without adjustment, prompting the need to remove or reposition several turbines to ensure safe separation, maintain accessibility, reduce wake effects and allow room for future hybrid integration.

While the original configuration used 63 turbines at 12 MW each to reach a total installed capacity of 756 MW, the updated layout achieves a comparable capacity of 750 MW using only 50 turbines rated at 15 MW each.

The reduction in turbine count results from both the higher unit capacity and the need to expand spacing between turbines to account for enlarged exclusion zones. Turbines that conflicted with these revised safety and wake buffers were removed. Additionally, the removal of specific turbines was influenced by the goal of integrating offshore solar within the layout. Open areas that offered more flexibility for solar placement were prioritized, ensuring that both systems could coexist without compromising accessibility or maintenance routes.

A key constraint introduced by the shift to 15 MW turbines relates to intra-array cable sizing. With larger power output per turbine, fewer units can be connected within a single string before exceeding standard cable limits. In this design, a maximum of eight turbines per string was adopted to remain within a typical 150 MW threshold for 66 kV cable capacity. This constraint significantly influenced the new cable routing strategy, requiring shorter, parallel strings and avoiding overloading in radial layouts. These new sizing rules were applied consistently across all subsequent hybrid scenarios.

A first iteration of the 15 MW hybrid layout was developed by systematically removing turbines whose exclusion zones overlapped under the updated spacing requirements. This step was essential to reduce wake effects and to free up space for the integration of offshore solar platforms. Following the turbine adjustment, solar units were introduced in two main configurations. In certain areas, clusters of solar islands were grouped into dedicated strings, each feeding into the substation independently. In other zones, smaller branches of solar platforms were positioned between wind turbine strings, connecting laterally to the existing cable infrastructure while ensuring not to exceed 150MW per string. These configurations demonstrate the spatial adaptability of the TNW site when modular solar technologies are employed, and they provide valuable insights into how offshore solar can be integrated without compromising wind turbine access or layout efficiency.

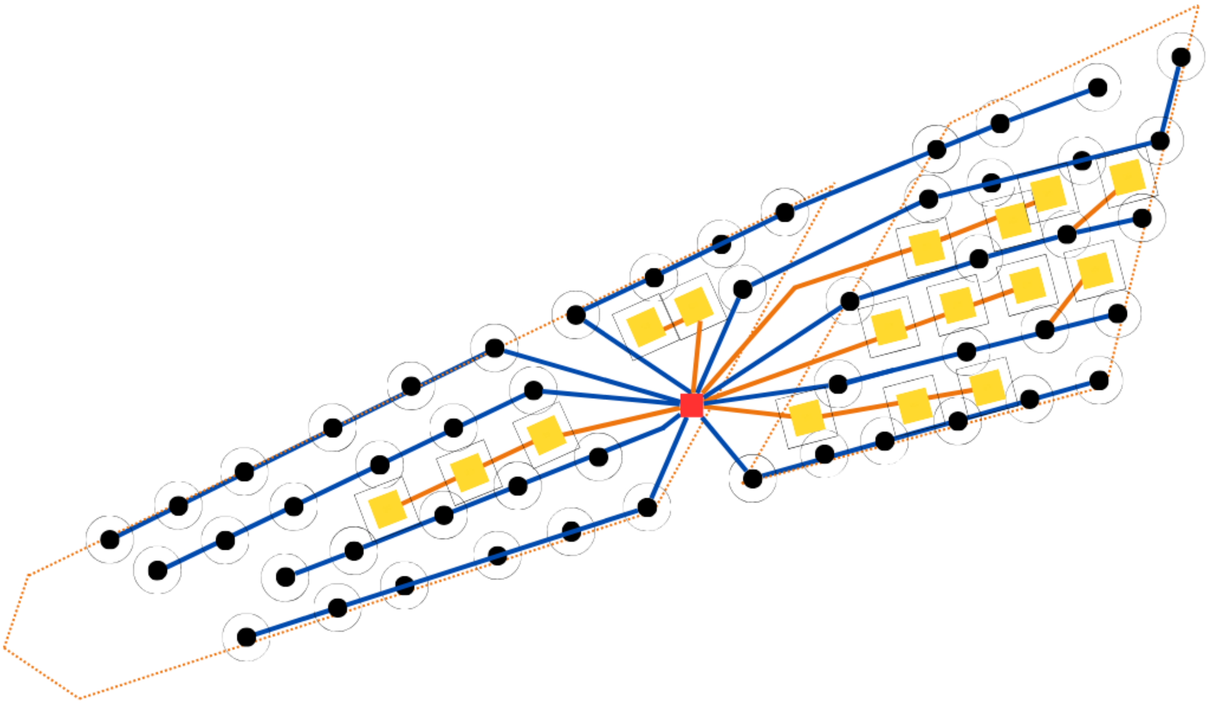

Figure 12: First iteration of the 15 MW hybrid layout showing wind turbine placement, intra-array cabling, and the integration of modular offshore solar units into both dedicated and interspersed configuration

While the first 15 MW hybrid layout successfully demonstrated the spatial feasibility of integrating solar alongside wind, it also introduced several challenges. In particular, the layout resulted in complex cable routing, overlapping exclusion zones, and a dense network of intra-array connections that would be difficult to implement in a real-world setting. To address these limitations, a second iteration was developed with a clearer spatial separation between wind and solar components. This revised layout prioritised the creation of a large, unobstructed zone for offshore solar deployment, while simplifying the cable architecture to reduce congestion and maintain system clarity.

The new base cable layout is shown in Figure 13, featuring 50 turbines arranged to preserve redundancy and remain within the 150 MW threshold for intra-array cable capacity. Figure 14 presents the corresponding hybrid version, in which 750 MW of offshore solar has been integrated into the layout.

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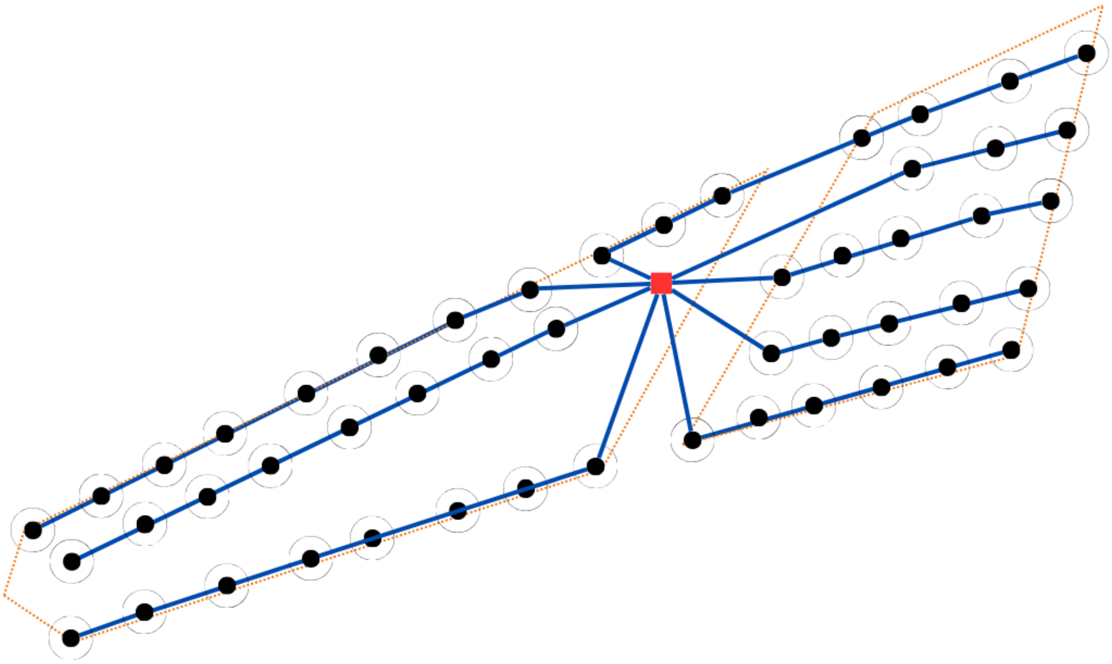

Figure 13: 15 MW base layout with 50 turbines and optimized intra-array cabling, maintaining system redundancy and adhering to 150 MW string capacity limits.

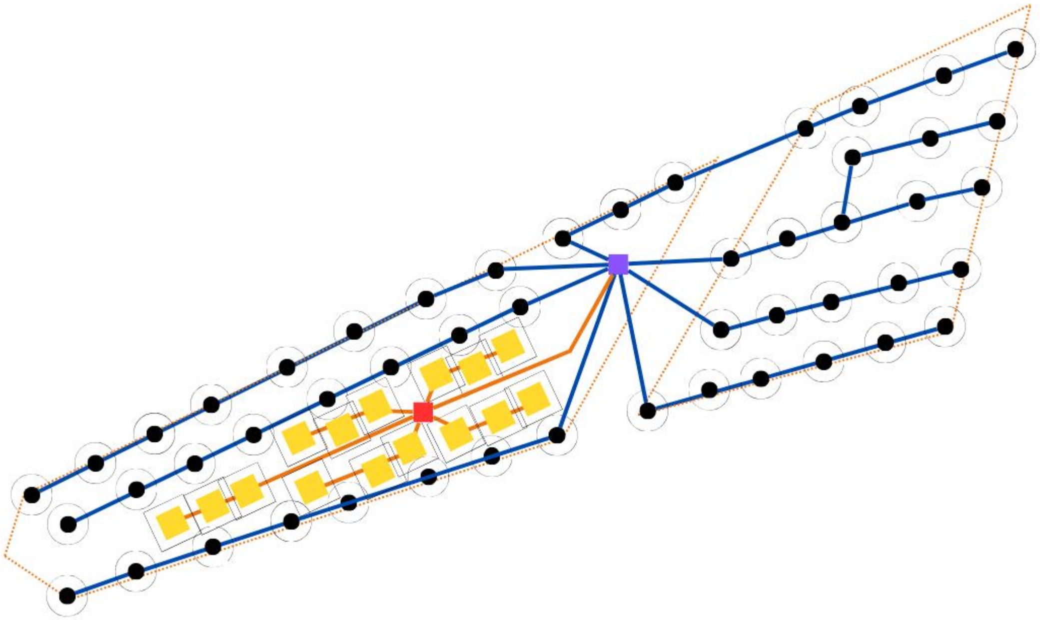

Figure 14: Hybrid layout with 50 × 15 MW wind turbines and 750 MW of offshore solar, featuring a dedicated solar substation and spatially optimized solar island placement.

To manage the solar capacity and enable efficient grid connection, a dedicated offshore substation could be introduced for the solar component. This separation of wind and solar collection systems allows for more efficient power export while preserving the potential for shared infrastructure elements, such as export cables and access vessels.

These scenarios demonstrate that, even under stricter cable limitations and with a reduced number of wind turbines, large-scale solar integration is still achievable. The layouts maintains accessibility,

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respects operational exclusion zones, and maximises the TNW site's potential as a spatially efficient, multi-source offshore energy park.

5. Wave Energy Integration

In addition to wind and offshore solar, wave energy represents a promising supplementary resource for multi-source offshore parks, particularly in locations like the Ten Noorden van de Waddeneilanden (TNW), where wave conditions are relatively strong and consistent. Studies of the North Sea indicate that the northern edge of TNW has some of the highest wave energy density within the designated wind farm area, making it the best possible location for wave energy converter (WEC) deployment.

The integration of wave energy into the layout was considered for both the 12 MW and 15 MW configurations. In both case, the northern perimeter of the site for wave installations, where wave direction and energy levels are optimal, was reserved for WECs. The goal was to achieve this without compromising access to wind turbines or exceeding spatial constraints related to cable capacity and maintenance corridors.

These layouts incorporate wind, offshore solar, and wave energy into a single configuration. This design features a combined generation capacity of 1,700 MW—comprising 600 MW of wind, 900 MW of offshore solar, and 200 MW of wave energy—exporting power through a shared 1,500 MW grid connection.

This specific energy mix is a deliberate strategy to maximize the asset's value and efficiency. The study on the TNW site found that a multi-source configuration increases the energy density by 22% and boosts the capacity factor relative to the export cable by 19% [2]. Crucially, this approach enhances grid reliability by dramatically reducing periods of low output; prolonged periods (over 24 hours) where production is below 20% of the export cable's capacity are cut by 86.5% [2]. The selection of a generation capacity higher than the grid connection, a practice known as "overplanting," ensures the export infrastructure is utilized to its full potential, increasing the plant's overall capacity factor. The roles of the chosen technologies are as follows:

- **Wind (600 MW)** serves as the proven foundation of the project, providing a reliable and bankable energy yield that underpins the financial case.
- **Offshore Solar (900 MW)** acts as the high-volume innovator, chosen to maximize annual energy production by capturing a complementary generation profile, particularly during summer months.
- **Wave Energy (200 MW)** is included as a pioneering component, positioning the project at the forefront of marine renewables and adding a third layer of energy complementarity to create a smoother, more consistent power output.

However, delivering the 600 MW of wind power with 12 MW turbines requires significantly more units (50 turbines) than in the 15 MW layout (40 turbines). This leads to increased spatial density and reduced flexibility for placing the additional energy sources. This added spatial constraint makes it increasingly difficult to integrate offshore solar directly into the wind turbine strings. Managing intra-array cable loads, maintaining access, and avoiding exclusion zone conflicts becomes operationally unfeasible as the system grows more complex. To address this, offshore solar units are deployed in dedicated strings, separated from wind infrastructure. Each solar string is limited to a maximum of 150 MW—equivalent to three 50 MW platforms—ensuring compatibility with standard 66 kV intra-array cables and simplifying grid integration.

The northern edge of the layouts is allocated to a continuous wave energy converter (WEC) array, where wave energy density is highest. In both versions, these WECs serve the dual purpose of power generation and acting as a wave attenuation barrier, providing shielding for solar units positioned further south. A central substation collects energy from all sources, with separate routing for wind, solar, and wave cables to prevent interference and ensure electrical separation.

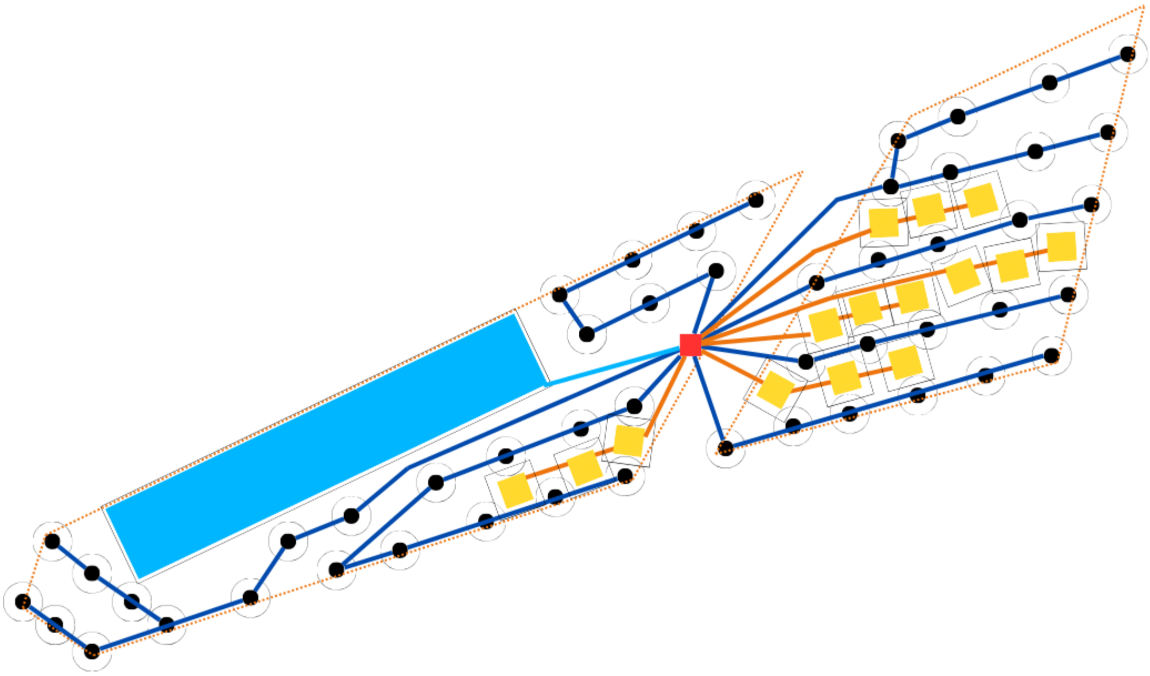

Figure 15: Final 12 MW hybrid layout with 600 MW wind, 900 MW offshore solar, and 200 MW wave energy. Solar is integrated through dedicated 150 MW strings, while wave energy converters occupy the high-productivity northern edge of the site.

This 12MW layout demonstrates that even under the tighter spatial constraints of a lower-capacity wind turbine configuration, a well-planned multi-source system remains feasible, provided that modular deployment and simplified cabling strategies are applied.

For the 15 MW layout below, the objective was to maintain a combined production capacity of approximately 1,500 MW, with 600 MW allocated to wind, 900 MW to offshore solar, and an additional 200 MW assigned to wave energy. To accommodate the wave component, wind deployment was slightly reduced, primarily in the western section of the site. This adjustment created sufficient space along the northern boundary for a continuous WEC array while maintaining access and minimizing interference with existing infrastructure. Additionally, the wave energy converters (WECs) function as a natural wave barrier for the offshore solar platforms positioned behind them, reducing wave impact and thereby supporting improved maintenance conditions and extended system longevity. The cabling layout was adjusted accordingly to route power from the wave farm to the central substation, using dedicated connections that avoid overlap with wind and solar strings.

The primary implication of integrating a large-scale wave farm is the introduction of spatial trade-offs. Allocating the northern perimeter to wave energy directly reduces the area available for wind turbines, necessitating a more compact wind farm layout. This highlights a key challenge in multi-source parks: balancing the capacity of each technology to maximize the site's overall energy yield without compromising the efficiency of any single component. The cabling layout was adjusted accordingly to

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route power from the wave farm to the central substation, using dedicated connections that avoid overlap with wind and solar strings.

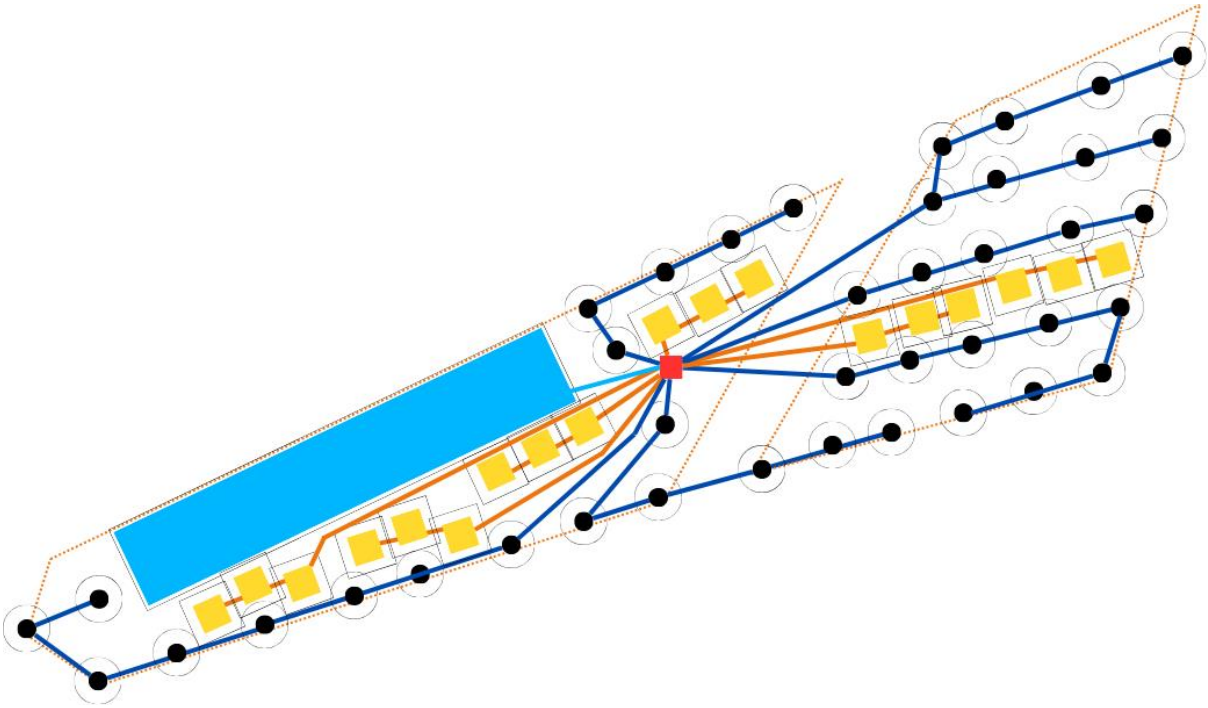

Figure 16: 15 MW hybrid layout with wind (600 MW), solar (900 MW), and wave (200 MW) energy integration. The northern section is reserved for high-productivity wave energy converters, with cabling routed to a shared substation.

These layouts illustrate the feasibility of accommodating three generation technologies within a single spatial envelope, while respecting cable limits, access routes, and exclusion zones. More importantly, it demonstrates the critical need for a holistic design philosophy from the project's inception.

6. Scenario Descriptions

The layouting exercise tested four distinct scenarios, each reflecting a different combination of wind turbine capacity, solar integration strategy, and technology mix. These scenarios were designed to explore how spatial constraints, cabling limitations, and energy density interact in multi-source offshore park planning. Together, they provide insight into the trade-offs and design flexibility available for future offshore deployments.

Scenario 1 represents the base case using 12 MW wind turbines with integrated offshore solar. While technically feasible, this configuration is spatially constrained due to the large number of turbines required to meet capacity targets. The high turbine density reduces the available space for solar deployment, and the complexity of routing solar cables between densely packed wind turbines presents additional design and operational challenges. This scenario demonstrates that lower-capacity wind

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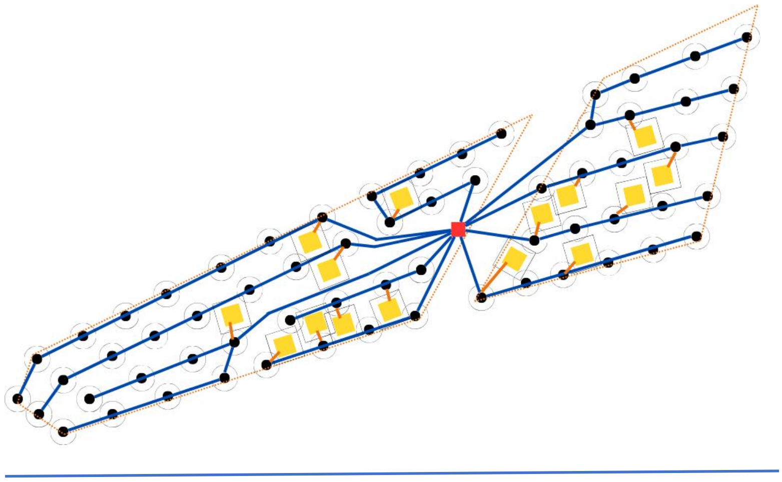
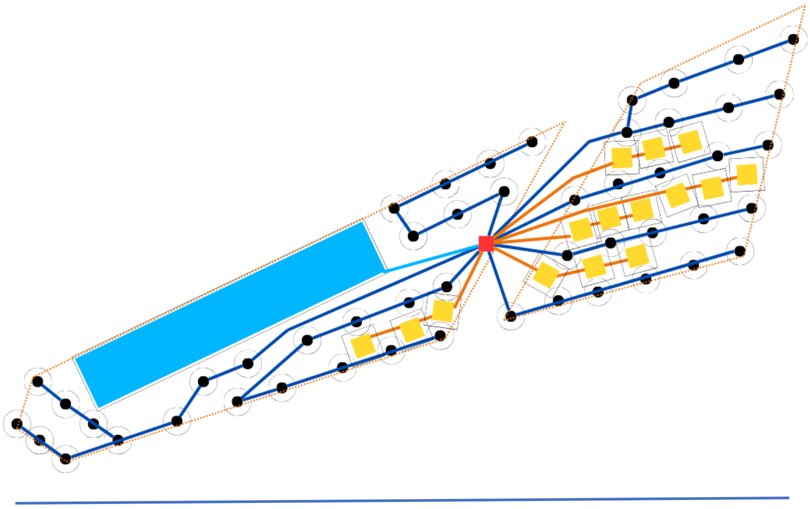
turbines make multi-source integration more difficult unless turbine counts are reduced or additional space is made available.



Scenario 2 builds on the first configuration by increasing the share of solar energy and reducing the number of wind turbines accordingly. By shifting from mixed wind-solar strings to dedicated solar strings, cable layouts are simplified, and space is freed up within the central part of the layout. This approach also enables more precise management of cable loading, ensuring that intra-array limits are not exceeded. Scenario 2 highlights the benefit of rebalancing energy contributions between sources and using modular solar groupings to overcome spatial constraints.



Scenario 3 introduces 15 MW wind turbines, enabling a more streamlined layout with fewer turbines needed to achieve the same capacity. This reduction in turbine count significantly eases spatial planning and allows offshore solar to be more efficiently incorporated between turbine strings or in open areas. The overall energy density of the park is higher, and access corridors are easier to maintain. Additional space in the western section of the site—left intentionally open—demonstrates how larger turbines provide more design flexibility for integrating other technologies or maintaining ecological buffers.

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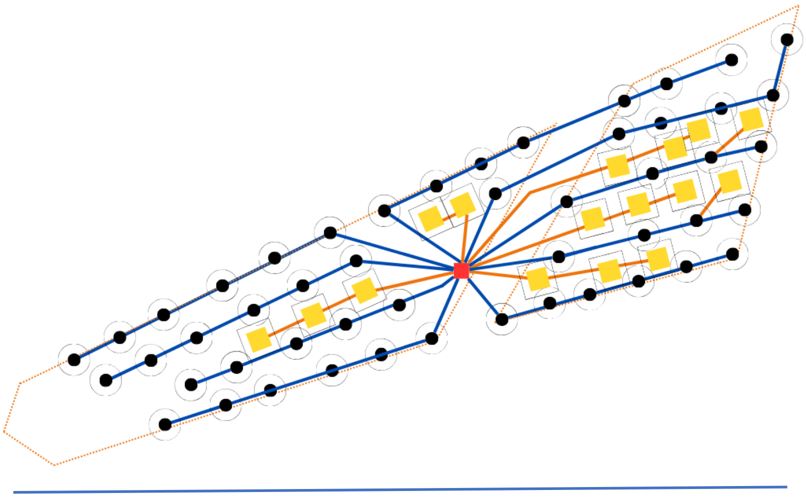
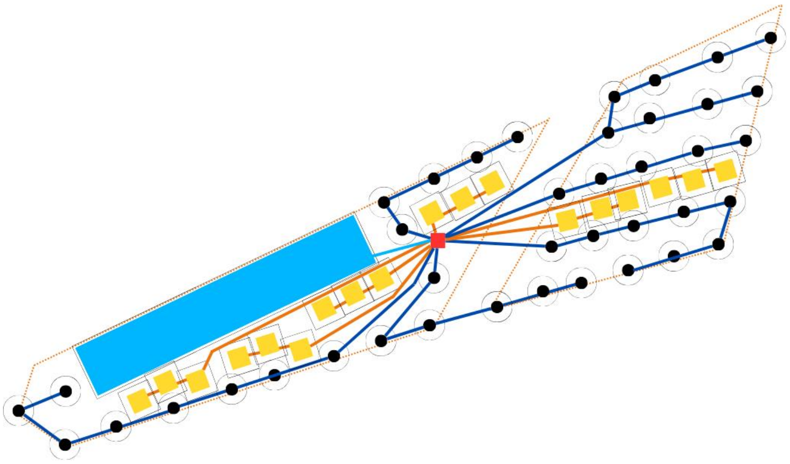


Scenario 4 represents the most integrated and flexible layout, combining 15 MW wind turbines with large-scale solar and a dedicated wave energy zone. The inclusion of three technologies enables a diverse and modular approach to layout design. Each technology occupies a clearly defined area, reducing complexity and allowing for tailored infrastructure. This scenario illustrates how a well-balanced hybrid system offers not only higher energy output but also greater freedom in design choices and system optimisation. The separation of sources also supports redundancy and simplifies maintenance planning.



Overall, the scenarios underscore the value of early design-phase flexibility and the benefits of combining multiple technologies within a single spatial envelope. While high-density wind-only layouts may appear efficient in isolation, the integrated scenarios show that multi-source systems can deliver superior energy profiles, infrastructure efficiency, and long-term adaptability.

7. Electrical Infrastructure

Components, Constraints, and Scenarios

The successful integration of wind, solar, and wave energy into a cohesive multi-source park is fundamentally dependent on a robust and intelligently designed electrical infrastructure. The layout scenarios explored in this deliverable are underpinned by a set of electrical design principles that balance current industry standards with the flexibility required for future upscaling. This section details the assessment of equipment placement, the rationale behind key system limitations, the specific component needs of each scenario, and the infrastructure required to manage complex power flows in a hybrid generation environment.

Equipment Placement and Integration Strategy

The placement of electrical equipment was assessed based on a range of factors including accessibility, cost, and system efficiency. Several integration strategies were considered for connecting the solar and wave components into the main wind farm array. The primary options evaluated include:

- Direct Turbine Integration: Connecting solar or wave arrays to the electrical system within a nearby wind turbine tower, leveraging existing infrastructure but adding complexity to the turbine's internal systems.
- In-line Integration: Using subsea T-connectors to link solar or wave strings directly into the 66 kV intra-array cables that connect the wind turbines. This approach is modular but requires careful load management.
- Direct Substation Connection: Routing the power from solar and wave farms via their own dedicated intra-array cables directly to the offshore substation, landing via an additional J-tube. This simplifies the wind turbine strings but increases the total amount of cabling and the number of connections at the substation.

The choice of strategy depends on the specific layout. For instance, the initial dispersed solar layout (Figure 9) would rely on in-line connections, which created challenges related to variable cable loading. In contrast, the more advanced layouts (Figures 10, 15, and 16) utilize dedicated strings for solar and wave energy, centralizing their connection points at the substation to simplify power flow management and respect capacity limits.

The 150 MW Intra-Array Cable Limit

A critical constraint shaping the electrical design in all scenarios is the capacity limit of approximately 150 MW per intra-array cable string. This is not a physical law but a widely accepted techno-economic benchmark for offshore wind farms using the industry-standard

66 kilovolt (kV) cables. Exceeding this limit introduces significant engineering and financial challenges, including:

- Thermal Limits: Higher power transmission generates more heat. Exceeding the cable's thermal rating can degrade the insulation and dramatically shorten its operational lifespan.
- Voltage Drop: Longer and more heavily loaded cables experience greater voltage drop, leading to power losses and potential equipment malfunctions if the voltage falls outside of operational tolerances.
- Component Sizing: All connected components, including switchgear, circuit breakers, and connectors, must be rated to handle the maximum potential power and fault currents. Standard 66 kV components are readily available and cost-effective up to the 150 MW threshold.

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- Dynamic Ampacity: The actual current-carrying capacity (ampacity) of a subsea cable is affected by factors like seabed temperature and burial depth. Pushing a cable to its absolute limit reduces the safety margin needed to account for these environmental variables.

This constraint directly influenced the layout designs. For example, the shift to 15 MW turbines meant that a maximum of eight turbines could be connected in a single string to remain below the 150 MW threshold, requiring shorter and more numerous strings compared to the 12 MW layouts.

Comparative Analysis of Electrical Components by Scenario

The four distinct layout scenarios not only differ in their spatial configuration but also in the quantity and complexity of the electrical equipment required. The choice of turbine capacity and the mix of generation technologies directly impact the number of transformers, inverters, and substations needed, which in turn has significant logistical and cost implications.

A high-level comparison of the primary electrical components for each scenario is outlined below.

Component	Scenario 1 (12 MW Wind + Solar)	Scenario 2 (12 MW Wind + Solar + Wave)	Scenario 3 (15 MW Wind + Solar)	Scenario 4 (15 MW Wind + Solar + Wave)
Wind Turbine Capacity	756 MW	600 MW	750 MW	600 MW
Solar Capacity	750 MW	900 MW	750 MW	900 MW
Wave Capacity	0 MW	200 MW	0 MW	200 MW
Total Installed Capacity	1,506 MW	1,700 MW	1,500 MW	1,700 MW
Turbine Transformers	63	50	50	40
Solar Inverter/Transformer Stations	15	18	15	18

Wave Converter/Transformer Stations	0	1	0	1
Main Offshore Substations	1	1	1-2	1-2
Total Strings to Substation	High	Very High	Medium	High

Table 1 : High level overview of electrical infrastructure needed per Scenario.

Key Component Differences and Logistical Implications

- Transformers: The number of turbine transformers—typically located in the nacelle or tower base of each turbine—is directly tied to the turbine count. Scenarios 3 and 4, which use fewer, higher-capacity 15 MW turbines, require 40-50 turbine transformers. In contrast, the 12 MW scenarios require a larger number of smaller transformers (50-63 units) to achieve similar wind capacities. While more numerous, the transformers for 12 MW turbines are logistically simpler to transport and install compared to the heavier units required for 15 MW turbines. Each 50 MW solar island and the 200 MW wave farm also requires its own dedicated step-up transformer to raise its output to the 66 kV intra-array grid voltage, adding to the total count.
- Inverters and Converters: This equipment is unique to solar and wave energy systems. Solar panels produce Direct Current (DC), which must be converted to Alternating Current (AC) by inverters before being transmitted. Similarly, the power from Wave Energy Converters (WECs) is often variable and requires conversion to be synchronized with the grid. Therefore, Scenarios 2 and 4, which include solar and wave energy, have the highest number of power conversion systems. These are typically large, containerized stations located on the floating solar islands or on a dedicated platform for the wave farm, adding weight and complexity to the floating structures.
- Dedicated Offshore Solar Substation: As the scale of solar integration increases, so does the complexity of the central offshore substation (OSS). In the 15 MW hybrid layout (Scenario 3), a key strategic option is the introduction of a dedicated substation for the solar component. This approach, shown in Figure 14, offers several logistical advantages:
    - Reduced Congestion: It separates the collection systems, preventing the primary wind OSS from becoming congested with a high number of incoming solar cable strings.
    - Simplified Power Management: It allows for more efficient power collection and management for the solar farm before the energy is combined with wind power for export to shore.
    - Enhanced Redundancy: A dual-substation system can provide greater operational redundancy.

- However, this strategy carries a significant trade-off, as it requires the costly fabrication and installation of a second offshore platform, adding a major logistical step to the project's construction phase. The total number of incoming cable strings dictates the size and complexity of the OSS switchgear, which protects and directs power flows. A higher number of strings, as seen in the multi-source scenarios, necessitates more circuit breakers and control systems, increasing the physical footprint and cost of the substation topside.

Future-Proofing and Upscaling Infrastructure

While the scenarios in this report are based on the established 66 kV standard, the offshore energy industry is actively developing solutions to accommodate larger, more powerful energy parks. One key development is the introduction of higher voltage intra-array cables, such as 132 kV. Shifting to 132 kV could increase the capacity of a single string to over 300 MW, nearly doubling the power transfer capability. This would allow for longer strings connecting more turbines, reducing the total number of cables needed and simplifying the layout of gigawatt-scale projects. This would also decrease the number of circuit breakers and other switchgear components required at the offshore substation, leading to significant cost savings.

Furthermore, advancements in subsea substation technology present an alternative to traditional topside platforms. Subsea transformers and switchgear can be placed on the seabed, reducing the need for large, costly, and maintenance-intensive structures. These technologies will be crucial for managing the complex power flows of future multi-source parks.

8. Energy Performance and System Benefits

The integration of solar and wave energy into offshore wind farms offers quantifiable benefits in terms of energy yield, output stability, and infrastructure efficiency. Drawing on the performance modelling from Hinne et al. (2024) [2], a hybrid wind-solar configuration at the TNW site demonstrated a 22 percent increase in energy density compared to a wind-only layout. This result highlights the spatial efficiency gained by utilizing the space between turbines for offshore solar deployment. Furthermore, the inclusion of a complementary energy source like solar contributed to a 13 percent improvement in output smoothness, as measured by a reduction in the coefficient of variation. These improvements were particularly pronounced during low-wind periods, with the hybrid layout experiencing 86.5 percent fewer hours with energy output below 20 percent capacity. This flattening of the production curve moves the hybrid system closer to a virtual baseload, reducing the need for external balancing or storage solutions.

The modeling also indicated a 19 percent increase in effective capacity factor when measured relative to cable capacity. By co-locating generation technologies and optimizing string layouts, the system made better use of the available electrical infrastructure, thereby improving the return on installed capacity per kilometer of cable. This efficiency gain becomes particularly valuable in scenarios where cable corridors are limited or export capacity is constrained. These results suggest that multi-source offshore parks not only increase total energy output, but also enable more reliable and predictable feed-in to the grid.

9. Implications for Global Upscaling

The findings of this layouting exercise carry important implications for future offshore energy deployment, both in the North Sea and globally. Multi-source parks represent a promising strategy to make more efficient use of limited marine space, particularly in regions with overlapping demands from fisheries, shipping, nature protection, and military activities. By consolidating energy production within a shared footprint, hybrid parks can ease spatial planning tensions and unlock new sites that might be unviable for single-source installations alone.

Economically, shared infrastructure across wind, solar, and wave systems—such as substations, export cables, and maintenance fleets—offers a pathway to reducing capital and operational costs. These synergies can accelerate return on investment, especially in areas where seabed works and permitting processes are major cost drivers. Moreover, the smoother, more consistent energy output of hybrid systems can contribute to improved project bankability and system-level resilience.

From a policy perspective, hybrid offshore parks align well with integrated energy planning goals in the EU Green Deal, the North Seas Energy Cooperation, and global climate frameworks. The TNW case illustrates how flexible design tools and modular technologies can be adapted to different resource conditions, making the approach scalable to other regions including the Baltic Sea, the U.S. East Coast, and parts of Southeast Asia.

10. Conclusions and Recommendations

This study has shown that multi-source offshore energy parks are a technically viable and strategically advantageous pathway for the future of marine renewable energy. Through the case of the Ten Noorden van de Waddeneilanden (TNW) site, the integration of wind, offshore solar, and wave energy within a single spatial footprint was demonstrated to deliver meaningful gains in energy density, production smoothness, and cable infrastructure efficiency. These benefits are achieved while respecting real-world constraints such as exclusion zones, cable capacity limits, and vessel accessibility.

The design scenarios developed in this exercise highlight the importance of flexible, modular planning approaches. Layouts must be adapted to reflect evolving turbine technologies, site-specific environmental conditions, and infrastructure constraints. In particular, attention must be paid to cable sizing thresholds, exclusion zone overlaps, and the practicalities of integrating solar and wave components without compromising wind turbine accessibility.

To support future development, it is recommended that spatial planning tools and regulatory frameworks explicitly account for hybrid configurations, rather than treating wind, solar, and wave as standalone sectors. Planning methodologies should incorporate multi-source optimisation from the outset, enabling co-location to be treated not as an exception, but as a default design approach.

The scenarios presented here offer a blueprint for how such integration can be approached. They demonstrate that, with proper spatial and electrical planning, multi-source offshore parks can contribute not only to decarbonisation goals but also to more efficient marine spatial use and more stable, bankable energy production profiles. As global offshore renewable deployment accelerates, hybrid configurations should be further investigated, supported, and scaled.

The practice of finalizing a wind farm layout and later "adding" other technologies often leads to sub-optimal results. This approach can create infrastructure conflicts, mismatched capacities, and missed opportunities for synergy. In contrast, an integrated planning process considers the interplay between all technologies from day one. This allows for the strategic placement of assets—like using a wave farm to protect a solar farm—and ensures that shared infrastructure, like the substation and export cables, is appropriately sized for the total combined output. This shift from a sequential to an integrated design approach is essential for unlocking the full technical and economic potential of future multi-source offshore energy parks.

11. References

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