Site selection and conceptual design of an offshore floating modular energy island in the United Kingdom

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Abstract. This study investigates the optimal site location and conceptual design of an offshore Floating Modular Energy Island (FMEI) for the United Kingdom, with the aim of supporting the nation's target of achieving net-zero carbon emissions by 2050. The study evaluates the integration of multiple renewable energy sources, including floating offshore wind turbines, floating photovoltaic solar panels and wave energy converters, to form a scalable and modular energy island. The framework used three criteria groups: technical (wind power density, wave energy potential, solar irradiance), economic (shore distance, water depth, shipping lanes, cables/pipelines), and environmental (buffer zones around marine protected areas). Using the Analytic Hierarchy Process, weights of 44.3% for technical, 38.7% for economic, and 16.9% for environmental factors were applied, identifying five promising UK sites for FMEI deployment. Site 3 emerged as the optimal location, offering strong renewable resources and favourable proximity to shore. A conceptual design proposed a layout featuring an octagonal platform, comprising eight 10 MW floating wind turbines on WindFloat T-unit platforms, floating solar platforms and wave energy systems, totalling an estimated annual energy output of 494,170 MWh. The study concludes that FMEIs can significantly contribute to the UK's renewable energy production.

1. Introduction

In recent years, the climate emergency has been widely discussed, with organisations cooperating on a global scale to reduce and minimise the effects of climate change caused by human activities. To address the global call to action, the United Kingdom (UK) Government set an aim for the country to reach a net-zero economy by 2050 and has provided the energy sector with a 100% zero-carbon emission target to achieve by 2035 [1]. The UK Government has leveraged £24bn in private investments for clean energy projects [2]. Although the benefits and necessity of clean, renewable energy are evident, the implementation of onshore renewable energy convertors within the UK still faces many challenges. Besides regulatory policies, the most prominent challenges for renewable energy systems are the inconsistencies of renewable sources in providing a stable supply for the energy grid. Offshore energy sources offer greater potential than onshore locations based on their unlimited exposure and conditions. Generally, investments are in single-purpose infrastructure, such as large-scale wind farms. However, the adaptation of

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an integrated "ecosystem" of offshore facilities can contribute to a more sustainable, safe and reliable energy production [3].

The use of combined offshore energy sources for power generation, storage and conversion using floating modules is becoming an increasingly discussed topic, particularly for those that can serve as offshore multi-use floating platforms with the capacity to be modular and expandable. A recent study provided an in-depth discussion on modularity, floatation and multi-purpose platforms with integrated renewable energy sources [4]. The connection of offshore modular units and their use for energy storage, distribution and generation introduces the topic of floating modular energy islands (FMEIs). In a recent study [5], it was found that FMEIs can offer increased capital gains through shared floating, mooring and storage infrastructure in addition to the greater energy potentials from offshore locations. While various concepts and planned projects exist globally, the UK has only a few, with the Swansea Port Development Project, also known as the Blue Eden Project, being the most prominent [6]. Contributing to the conceptualisation of energy islands in the UK, this study aims to examine and propose a site location and a conceptual design for deploying an energy-efficient floating modular energy island within the United Kingdom's Exclusive Economic Zone.

2. Site Selection for a FMEI in the UK

2.1. Methodology

This section outlines the methodology used to identify a suitable site location for a FMEI, based on various criteria. The study focused on the UK Exclusive Economic Zone (EEZ) and potential sites within this region were considered. The FMEI is aiming to integrate wind, solar and wave energy systems and thus the first step is to identify the most suitable location based on available energy resources, i.e., wind power, solar irradiance and wave power density, as their synergy strongly influences the viability of the FMEI. Alongside the assessment of the energy resources, proximity to protected areas and existing infrastructure are considered. Additionally, economic criteria such as distance from shore, water depths and high-density shipping routes as well as environmental criteria are assessed. Given the considerable distance from shore, social acceptance was not considered in this study, as the examined site locations lie beyond visual range and are unlikely to interfere with typical coastal community activities such as fishing or recreation.

The use of open-source geographical information systems (GIS) [7] to provide spatial datasets combined with multi-criteria decision making (MCDM) is a common approach taken in literature for various selection criteria and has been applied in similar past studies [8]. The use of GIS can provide a visualisation of the resources, while allowing buffers and data restrictions to provide a graphical view of suitable locations that is easily interpretable. Analytic Hierarchy Process (AHP) are among the most preferred MCDM methods, as it offers straightforward running processes, whilst being highly applicable to GIS analyses [9] and has therefore been applied in this study. The AHP process structures complex problems into a hierarchy of goals, criteria, sub-criteria and alternatives. It uses pairwise comparisons developed by Saaty [10] to assess the relative importance of each element on a scale from 1 to 9, enabling the calculation of priority weights. A consistency ratio (CR) is then applied to ensure the logical coherence of these judgments. To calculate the CR, the pairwise comparison matrix is first multiplied by the priority vector to obtain the weighted sum vector. Each element of this vector is then divided by the corresponding element of the priority vector to yield the consistency vector. The average of the consistency vector provides an estimate of the maximum eigenvalue λ_{max}. Using this value, the

Consistency Index (CI) is calculated as: $CI = \frac{\lambda max - \eta}{\eta - 1}$, where η is the number of criteria. The Consistency Ratio is then determined by: $CR = \frac{CI}{RI}$, where RI is the Random Index, a tabulated value dependent on the size of the matrix.

2.2. Constraints

The constraints considered in this study are presented in Table 1 and explained hereafter. While mean wind speeds can be used as a measure of the wind resources, the mean wind power density gives a more accurate indication of the available wind resource [11]. The wind power density in the examined UK region range from 440.48 to 1731.78 W/m^2, and thus values below 1000 W/m^2 are excluded as a reasonable threshold. With respect to solar energy resources, Global Horizontal Irradiance (GHI) values within the UK area of focus, range from 780.17 to 1162.95 kWh/m^2/year [12]. To refine the analysis, a buffer threshold of 850 kWh/m^2/year was applied. Water depth is a key factor in selecting suitable floating foundations, as increased depths significantly raise investment costs [5]. As a result, a water depth range, starting from 65 m and extending up to 500 m, has been used as a constraint in the site selection process. Locations with wave energy ≤10 kW/m should be avoided due to reduced energy potential and increased constraints [13]. The FMEI must avoid existing infrastructure, such as undersea cables and pipelines and it should not obstruct major shipping routes. Conversely, proximity to existing offshore energy infrastructure can be advantageous due to established grid connections. Buffer distances of 750 m for infrastructure avoidance and 3 km for beneficial proximity have been adopted [5]. The maximum allowable distance from a port is set at 100 km [5]. Accurate data on general buffer zones around marine protected areas in the UK is limited. Kurniawati et al. [5] applied a 2 km buffer zone for energy island site selection near Crete, which has been adopted for this study. The exclusion criteria for the selected UK region are summarised and visualised in Figure 1 through a series of GIS maps, illustrating key constraints related to wind power density (Figure 1a), solar energy (Figure 1b), water depth (Figure 1c), proximity to pipelines and power cables (Figure 1d), wave energy desnity (Figure 1e) and shipping routes (Figure 1f).

Table 1: Summary of criteria, constrains and weights

Main Criteria	Sub-criteria	Data source	Constraints	Main Priority Weight	Sub-criteria Weight
Technical	Wind power density	Global wind atlas [11]	>1000W/m^2	0.443	0.707
	Global solar irradiance	Global solar atlas [12]	>850 kWh/m^2/year		0.070
	Wave power density	ABPmer [13]	> 10 kW/m		0.223
Economic	Water depths	EMODnet [16]	between 65 m and 500 m	0.387	0.336
	Distance to shore		< 100 km		0.461
	Distance to shipping routes		< 3 km		0.126
	Distance to undersea cables/pipes		> 750 m		0.077
Environmental	Distance to protected zones	EMODnet [16]	> 2 km	0.169	1.000

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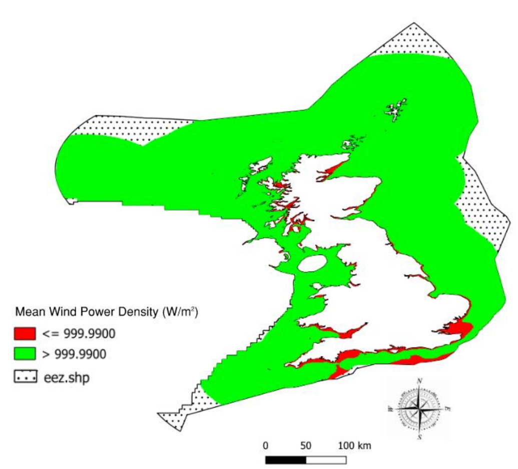
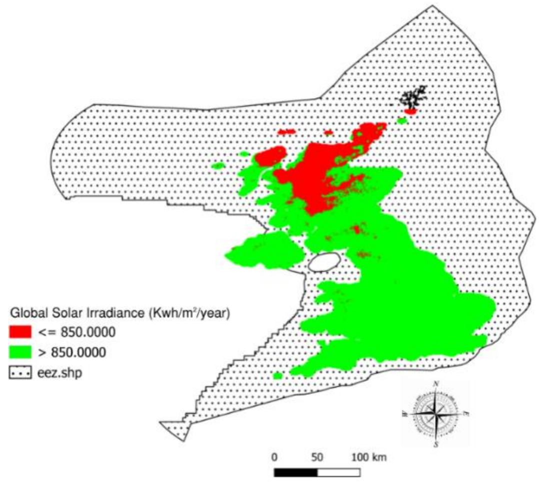
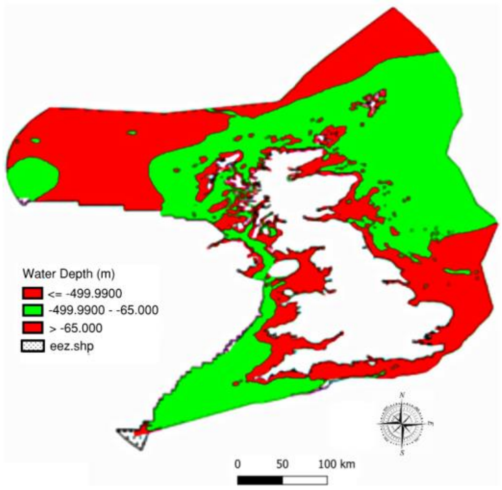


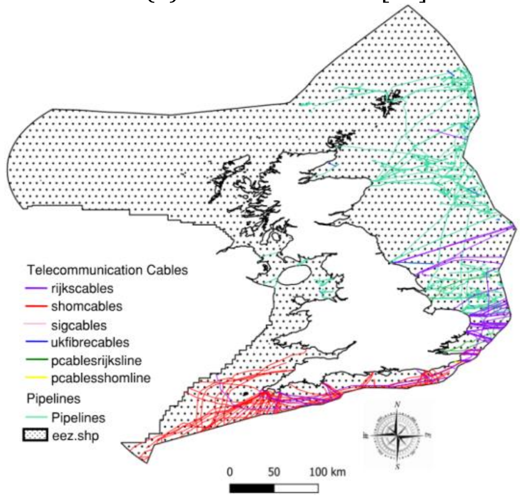
(a) Wind power [11]



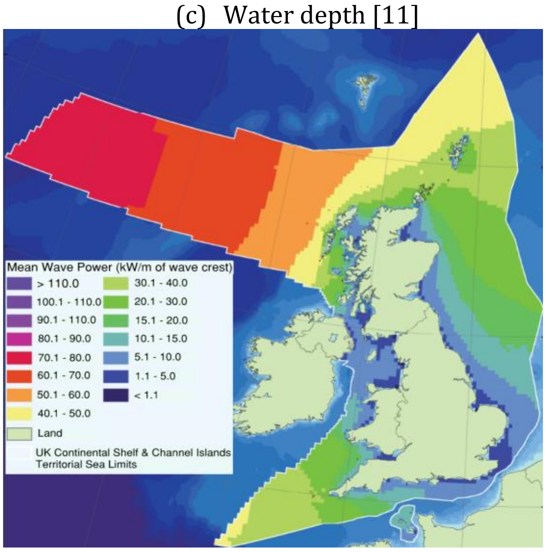
(b) Solar irradiance [12]



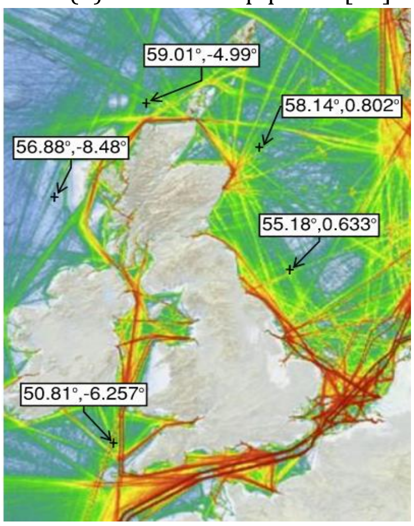
(c) Water depth [11]



(d) Cables and pipeline [16]



(e) Wave power density [15]



(f) Shipping routes [16]

Figure 1: Exclusion criteria in study area.

2.3. Criteria and weights

Pairwise comparisons using the AHP were employed to determine the priority weights for the main technical, environmental and economic criteria. The technical criteria encompass wind, wave and solar energy, with wind technology standing out as the leading offshore renewable technology, due to its high technical readiness and adaptability to varying conditions. As such, wind power density at offshore locations plays a crucial role in enhancing the technical viability of FMEIs. In contrast, although wave energy has a global potential of 29,500 TWh, it remains underdeveloped, economically unviable and less reliable. Offshore solar, being a relatively new energy source, offers limited potential for FMEIs, largely due to moderate GHI levels. The environmental criteria in the AHP assess the ecological impact of offshore energy islands, particularly on marine biodiversity. Protecting species and habitats within marine protected areas is vital for maintaining marine ecosystem health, which in turn supports essential ecosystem services crucial for both human and environmental well-being. Economic considerations were assessed through a combination of spatial and qualitative analyses. Maintenance costs were inferred based on distance from shore, with greater distances expected to increase operational and service vessel costs. Water depth was included due to its direct impact on installation complexity, mooring system design, and associated capital costs. Logistical challenges were considered by evaluating proximity to existing subsea infrastructure and the presence of nearby energy networks, which influence construction and maintenance efficiency. Although engineering feasibility typically dictates project viability, economic factors can be equally critical in certain contexts [14].

The sub-criteria weights were obtained by pairwise comparing each sub-criterion's importance within its main criterion, deriving the principal eigenvector from the comparison matrix, and normalising it to sum to one. For the pairwise comparisons, the technical and economic criteria are considered equally important, with the economic criteria being moderately more important than the environmental criteria. Technical criteria are deemed moderately more important than environmental criteria, as they directly influence engineering feasibility and typically hold the highest priority in offshore infrastructure projects. With regards to the technical sub-criteria, wind is considered the most dominant energy source, with a significant priority weight of 8 compared to solar and a relatively high weight of 4 compared to wave energy. With regards to economic sub-criteria, distance to shore is the most influential criterion, rated 5 times more important than distance to cables, 2 times more than water depth and 3 times more than distance to shipping routes. Water depth also ranks relatively high, rated 4 times more important than both distance to cables and shipping routes. In contrast, distance to cables and distance to shipping routes are considered the least important, with values below 1 when compared to the other criteria. While environmental considerations are crucial, they generally carry slightly less weight compared to technical factors, as indicated by various studies [17, 18].

2.4. Selected site candidates

After normalising and reconstructing the pairwise comparisons for the technical, economic and environmental criteria, the Saaty values [10] were calculated. The weights of the primary criteria are shown in Table 1. Weighted pairwise comparisons yielded a relative weight of 44.3% for technical criteria, 38.7% for economic factors, and 16.9% for environmental considerations. In line with prior research on floating wind farms in the Canary Islands [18], metocean data proved to be the most critical site selection factor, reaffirming the importance of both energy potential and infrastructural viability in offshore energy design. The evaluated sub-criteria weightings are also included in Table 1. The matrix satisfied a consistency ratio of less than 10% in all cases, indicating that the consistency index requirement has been met throughout the analysis. Based on this analysis, Figure 2 displays the five selected site candidates (S1 to S5) for a FMEI in the UK. These sites were chosen for their favourable technical, economic and environmental conditions, highlighting their potential to support the successful implementation of floating energy islands in alignment with the renewable energy sector's strategic goals.

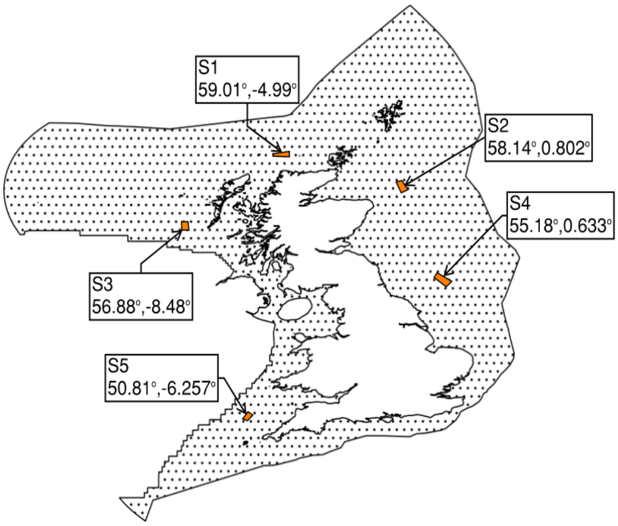


Figure 2: Site candidates for FMEI concept.

Table 2: Energy potential assessment for candidate sites

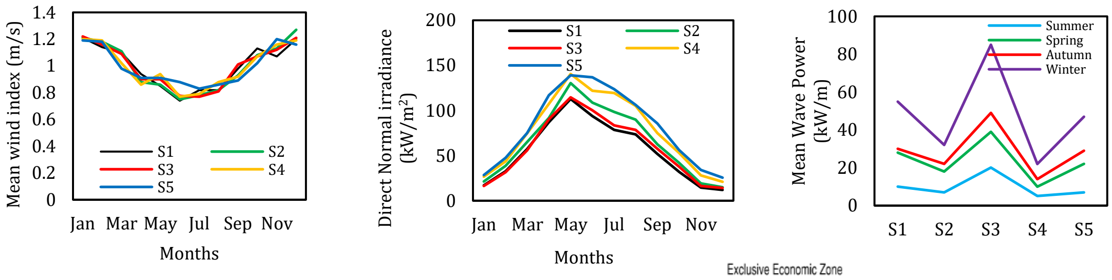
Site Reference	Annual mean wind power density (W/m^2) [11]	Total annual GHI ($kWh/m^2/year$) [12]	Annual mean wave energy (kW/m) [15]
S1	1582	845.5	30
S2	1389	907.1	20
S3	1530	896.4	47
S4	1294	1010.9	13
S5	1164	1113.2	26

3. Discussion of the results

3.1. Energy potential assessment

Data from the Global Wind Atlas [11] were used to identify the offshore wind energy data. The climate data are initially provided on a grid with an approximate spacing of 30 km and are employed as input to force the Weather Research and Forecasting mesoscale model, which operates at a finer spatial resolution of 3 km. A generalization process is subsequently applied to the data, yielding a set of generalised wind climates that match the spatial resolution of the mesoscale model output. Analysis of the mean annual wind power densities at 150 m height are tabulated in Table 2. As shown, all site candidates exhibit wind power densities exceeding 1000 W/m^2, highlighting strong offshore wind potential. This aligns with the recommendation set by [20], which considers any site with wind power density above 800 W/m^2 to be excellent for offshore wind energy generation. Figure 3a presents a graphical representation of the monthly wind index at 100 m height for the selected sites. This normalised measure of wind speed highlights that wind resources are at their lowest during the summer months. Figure 3b graphically shows the monthly power production for the five candidate sites. Data from the Global Solar Atlas [12] were used to identify solar irradiance of the selected site candidates and the corresponding GHI is shown in Table 2. While the UK has limited solar resources due to its climate, the southern coast (closer to S5) offers the highest potential, exceeding 1100 kWh/m^2. With regards to wave energy resource, the UK holds about 35% of Europe's wave energy resource [20], with an estimated total potential of 230 TWh/year-70 TWh/year in deep waters and 40–50

TWh/year considered exploitable. The mean wave energy is presented in Table 2, whereas Figure 3c shows seasonal mean wave power [15], showing the seasonal and annual energy potentials for each site.



(a) mean wind index (b) direct normal irradiance (c) mean wave power

Figure 3: Wind, solar and wave characteristics for FMEI site candidates.

3.2. Optimal site location

The integration of wind, wave and solar energy into a FMEI concept presents a resilient and synergistic renewable energy solution. Collectively, these resources form a robust generation profile, particularly advantageous for modular platforms where shared infrastructure can significantly reduce capital expenditure and improve operational efficiency. Candidate sites demonstrating high wind and wave power densities, strong solar irradiance, moderate shore distances (<100 km) and favourable water depths (<65 m), while avoiding congested maritime corridors, emerged as the most viable for optimising energy yield and minimising logistical and regulatory barriers. Based on GIS overlays and weighted criteria, Site 3 was identified as the most favourable location for FMEI development. It offers an optimal blend of high wind resource availability, considerable wave energy potential and strong solar irradiance, all within acceptable proximity to shore and with minimal interference from maritime or environmentally protected zones. This balance not only maximises renewable output but also enhances the economic and operational feasibility of the FMEI concept. The projected total annual energy generation for Site S3 would be 494,170 MWh, with the assumptions analysed in the following section. This reflects the site's favourable conditions and underscores its strong potential as a high-yield, multi-source renewable energy hub.

3.3. Proposal for conceptual design of a FMEI

This section presents a conceptual design of FMEI in the UK. The proposed layout is shown in Figure 4. The FMEI will consist of an array of 8 outer periphery floating offshore wind turbines (FOWT) with the centre platform being a floating, modularly constructed, very-large floating structure of octagonal geometry. The "central hub" will be manufactured from precast Ultra-High Durable Concrete and can be assembled in a dock or port before being towed to the site. The central platform will provide sufficient area to facilitate green hydrogen production facilities, staff quarters, transmission systems and scope for future expansions or needs.

The hub will be flanked by 8 floating offshore wind turbines, each rated at 10 MW. Key design considerations for the wind component include turbine model selection, rotor diameter and inter-turbine spacing. The concept proposes the use of the Vestas V164-10.0 MW turbine, mounted on the WindFloat T-unit semi-submersible platform, an evolution of the system deployed in the Kincardine project in Scotland [21]. Optimal turbine spacing lies in the range of 10–15 times the rotor diameter to minimise aerodynamic losses [22]. Applying a 10D configuration for the V164-10.0 results in a recommended spacing of 1.64 km between turbines. The WindFloat T-unit platform, developed by Principle Power [23], features a tubular semi-submersible design with water entrapment plates, ensuring enhanced hydrodynamic stability and operational efficiency. The 8 FOWTs will be moored using shared suction caisson anchor systems, which reduce geotechnical complexity and overall installation costs. Assuming a net capacity factor of 40%, the estimated annual energy generation from wind at this energy island is 280,320 MWh.

Adjacent to each turbine, floating solar platforms will host approximately 50,000 photovoltaic modules apiece, connected flexibly via hinged joints and supported by semi-submersible structures. A commercial 300W Sunmodule system can be used for each photovoltaic unit [24]. The supporting structures are to be interconnected to the central hub via hinged connections and then flexibly connected to neighbouring. The required area that the solar arrays are to provide is 0.085km^2 (0.0838km^2 of PV units and 0.00167km^2 of open space). Evaluation of the annual global horizontal irradiance showed the annual energy potential to be 75,118 MWh for an area of 0.0838km^2 for 50000 PV panels. Conservatively considering an onshore PV capacity of 10.4% for Arbroath in Scotland [29], with eight solar platforms in an array, the total solar energy contribution would amount to 62496MWh annually.

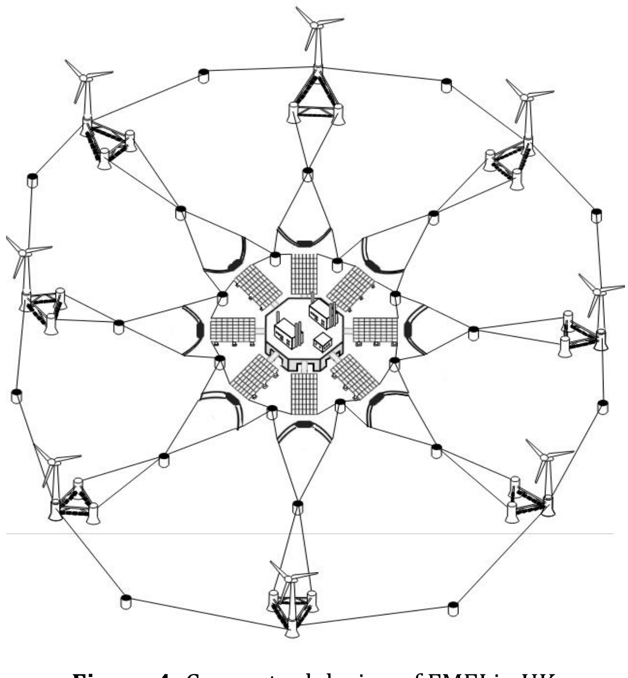


Figure 4: Conceptual design of FMEI in UK.

Complementing these systems, wave energy is harvested through a dual-technology approach: WaveDragon devices, placed around the solar arrays [25] and mWave Bombora units integrated within the turbine platforms [26]. This layout optimises spatial use while enabling multiline mooring and interconnectivity between modules for streamlined energy transmission and maintenance access. Considering a net capacity factor of 16% and the rated capacity of the 12 MW used in a location with a higher wave climate than 24kW/m, the estimated annual energy produced is 134,554 MWh for one island comprising of eight WaveDragon devices. The annual energy production for one mWave device can be estimated as 2100 MWh. With eight devices integrated into the wind turbines, and assuming a net capacity factors of 16% for wave energy, the estimated annual energy produced will be 16,800 MWh for one island. Therefore, based on the capacity factors and site-specific conditions, the total projected annual energy generation at Site 3 is approximately 494,170 MWh, with wind contributing 56.7%, wave 30.6% and solar 12.64%, confirming its strong suitability for a fully integrated floating multi-energy island (FMEI).

4. Conclusions

This study conceptualises a Floating Modular Energy Island (FMEI) for the UK, aiming to integrate offshore wind, solar, and wave energy to support the 2050 net-zero emissions target. It builds on recent research highlighting the potential of FMEIs for enhancing offshore renewable integration, spatial efficiency, and energy security [27], [28]. Site selection considered technical (wind, solar, wave), economic (proximity to shore, depth, infrastructure), and environmental (marine protection zones) factors. Weighted via the Analytic Hierarchy Process, these criteria were assigned 44.3%, 38.7%, and 16.9% importance, respectively. Five UK sites were shortlisted, with Site 3 emerging as the most suitable due to its strong resource availability and minimal conflicts. The proposed system comprises floating wind turbines, photovoltaic platforms, and wave energy converters, forming a modular and scalable layout. The layout features a central concrete platform, eight 10 MW WindFloat turbines (spaced 1.64 km), and shared suction caisson anchors, along with floating solar and wave energy systems. The total estimated annual energy output at Site 3 is 494,170 MWh. Future research should focus on energy storage integration to enhance supply reliability and grid stability.

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