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Techno-economic Assessment of Offshore Wind and Hybrid Wind-Wave Farms with Energy Storage Systems

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Abstract

Ocean renewables (such as offshore wind and wave) are abundant and essential energy resources for supporting future emission-free targets. However, their energy intermittency and high cost have hindered commercialization and wide-scale implementations of these ocean energy technologies. This paper focuses on both issues and aims to increase the dispatchability of ocean energy farm, by investigating the potential of a hybrid wind and wave energy platform with various energy storage systems (ESSs). In the paper, a novel method is proposed to assess the ESS for an offshore renewable energy farm to guarantee the energy dispatchability to the local demand. The effect of two farm configurations on the ESS capacity is analysed: one involves wind turbines only and the other one uses a hybrid configuration (with wind and wave generation subsystems). Lifecycle cost models of energy farms are developed and the economic feasibility of different energy storage systems are investigated. The sensitivity of energy farm configurations and the energy storage systems to the resource characteristics at multiple locations are also studied. The results indicate that the combined wind and wave energy farm significantly reduces the energy storage system capacity requirement and provides competitive lifecycle costs compared to the standalone wind energy farm, though the amount of these benefits vary on the local resource characteristics. In addition, it was concluded that the Lithium-ion battery option in a combined energy farm offers better overall performance over the other storage options considered.

Keywords: Wind energy, Wave energy, Hybrid wind and wave energy, Energy

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storage system, Techno-economic analysis.

1. Introduction

Offshore wind and wave renewable energy sources have great potential; hence they are likely to play a critical role in forming the energy supply landscape of the future in the countries with sea/ocean borders and considerable offshore energy availability. Compared to onshore wind farms (which are almost saturated), offshore wind farms can provide significant benefits in harvesting much more stable and stronger wind resources pushing the wind turbine (WTs) sizes to their limits [1]. In addition, offshore wind farms also minimize visual pollution and eliminate the noise impacts on the local community.

Globally, offshore wind energy has grown significantly over the past decade as the installed capacity has increased by 21% each year since 2013. In addition, it is predicted that about 370 GW offshore wind will be installed by the end of 2030 [2]. This shows an increase of 85% compared to a prediction of 2021 (200 GW by 2030 [3]). Furthermore, it is predicted that the share of offshore wind energy in global new wind capacity will rise from 23% in 2021 to 30% by 2031.

Wave energy is another ocean renewable resource having greater energy generation potential and higher predictability over wind energy [4, 5]. However, unlike WTs (which have technological maturity and displayed significant growth within the last two decades), wave energy converters (WECs) are not commercially viable yet though a range of devices has been proposed in the last century [4]. Therefore, there is an opportunity to support the development of WEC systems that can offer competitive solutions to complement the mature WT technologies.

Although WEC technologies are still immature in general, it is observed that the topology of the WEC systems is gradually converging over the 20 years into three main types [6]: Oscillating Water Column, Oscillating Bodies and Overtopping devices, which already demonstrated significant potential in commercialization via sea trials across the globe.

It is foreseen that two primary challenges are impeding the development of ocean renewables: high capital expenditures (CAPEX) and power intermittency. The former is due to lack of convergence of WEC designs to a commercial product and the technical challenges of deploying WTs in deep sea applications (which require floating structures and complex controllers). The latter issue, power intermittency, however, is connected to the nature of the ocean renewable energy resources – larger power potential presents large power variations in offshore wind and wave resources. This leads to significant challenges in the transmission of power effectively to the nearest substation (offshore and/or onshore) and the mitigation of the impacts of the intermittency on power grid operation and security. Although energy storage systems (ESS) have been considered to mitigate the energy variability that exists in the intermittent onshore wind energy sources, ESS options/types are highly limited and their costs are significantly higher in offshore applications.

Therefore, both the high-cost aspects and the intermittency issues can be addressed in this paper by the integration of offshore wind and wave energy resources under a building block that shares the high cost infrastructure and utilizes the phase difference in two intermittent resources (which also minimizes the need of ESS). Note that a number of benefits of the combined system have been reported in the literature, including enhanced energy production [7], cost reduction due to shared facilities [8–11] and energy variability reduction [12–15].

Previous studies on combined wind and wave systems mainly focus on the hydrodynamic design [16–18] or solely on the economic analysis/comparison [19–21], neglecting the energy variability and dispatchability to the grid. The exploitation of offshore renewables is anticipated on an enormous scale in the near future. This endeavour requires appropriate assessment of energy storage technologies that can be collocated with ocean energy farms. However, the technical and economic feasibility of ESS for offshore energy farms has not been systematically studied, and the requirement of suitable ESS sizing to form a more dispatchable renewable energy supply has not been investigated in the literature.

In addition, there is a lack of study on the comparison of different offshore renewable energy farm configurations (such as stand-alone wind and combined wind and wave energy farm with consideration of ESS) and their energy variability and dispatchability while assessing the necessity of ESS and its sizing. Furthermore, the influence of local resource specifications on the power generation and energy storage functionalities has not been thoroughly considered in the literature.

To fill the above-mentioned gaps, this paper analyses the capacity and classification of ESS for offshore wind and combined energy farms and compares them based on a systematic techno-economic assessment. The renewable energy farm's dispatchability to the power grid is also considered in the paper for meeting local demand. The main contributions of this paper are: 1) a novel method to estimate the required ESS capacity for offshore energy farms in light of energy dispatchability (firmness); 2) a high fidelity life-cycle cost model developed to study the technical applicability and economic feasibility of ESS options subject to energy farm configurations. Two distinct sea sites in the Southern and Northern hemispheres are selected and their potentials to deploy two types of offshore energy farms are discussed in order to investigate the sensitivity of the storage to the location specifications (resource characteristics). Therefore, this paper is aimed to provide a systematic guidance for industry, developers, spatial planners and policymakers at the pre-planning stage of ocean renewable energy farm deployments.

This paper is structured as follows: Section 2 analyses the wind and wave data statistics and introduces the methodology used. The applied economic cost model for offshore energy farms with different system configurations is described in Section 3. Section 4 investigates the main results. The techno-economic feasibility of EES options under distinct location characteristics are discussed in Section 5, followed by the conclusion.

2. Methodology

2.1. Offshore Locations and Wind and Wave Resources

For determining suitable sites for combined offshore wind and wave energy farms, several approaches have been proposed in previous studies, such as the wave system identification method and site selection matrix in [22] and the co-location feasibility index in [23]. In this paper, two offshore sites, one near Sydney (152.31°E, 34.00°S) in Australia and the other in the North Sea (8.03°E, 56.65°N) in Europe, are selected as the case studies. Note that these locations have been reported to be the optimal locations for developing combined wind and wave farms in their studied region [22, 24].

In terms of data sources, the case study in Sydney uses the wind-wave hindcast data (obtained by the WaveWatch III model) running on a series of nested grids with 7 km resolution in the Australian region [25]. The data used in the North Sea site is obtained from ERA5 [26], which is hourly data covering long historical wind and wave data from 1940 to the present day. The main parameters considered in this paper include the wind speed at 10 m height (U_{10m}), significant wave height (H_s) and wave peak period (T_p). Since wind generation power is proportional to the cube of the wind speed at hub height, the power in wind is significantly affected by wind speed variation (the impact of the height and the roughness of the blowing surface). Thus, the wind speed at hub height (U_{100m}) is calculated by:

$$U_{100} = U_{10} \cdot \left(\frac{z_{100}}{z_{10}} \right)^{\alpha}, \tag{1}$$

where α is the friction coefficient with a value of 0.1 under open water terrain [27].

Fig. 1a shows the wind speed histogram of two sites at 100 m height, indicating that both locations have good wind resources with the majority of wind speeds between 7 and 12 m/s (IEC Class II or above [28]) and the Sydney site has a slightly higher wind resource compared to the North Sea site. In terms of wave parameters, Fig. 1b&c show the wave statistics scatter map in the Sydney and North Sea sites. Significant discrepancies can be identified for the sea states in Sydney that are more concentrated around $H_s = 1.5$ m and $T_p = 8$ s, while for the North Sea the most frequently occurring sea state is around $H_s = 1$ m and $T_p = 6$ s with a wider distribution of H_s. According to the wave system identification in [22], the shorter wave peak period at the North Sea location suggests that the waves are mainly generated by wind with a minor fraction of swell waves. This may lead to a higher correlation and shorter lag time between wind and wave resources.

2.2. Method of Power Generation

The wind power generation is calculated by the power curve of a commercial WT (Gamesa G128-5MW [29]) that is given as a function of the wind speed at hub height as shown in Fig. 2 (top). The wave power generation is estimated

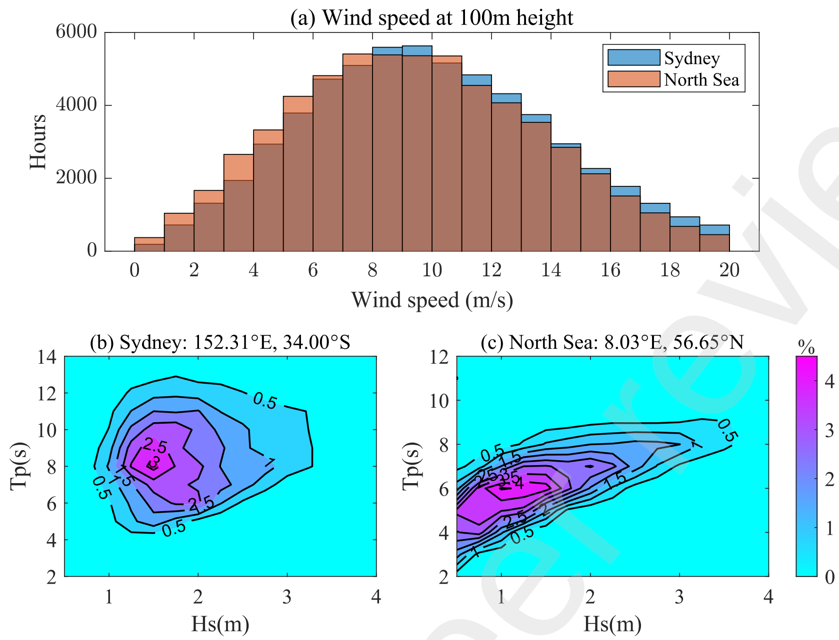

Figure 1: Wind and wave resources in Sydney and North locations from 2014 to 2020 [25, 26]: a) wind histogram; b) wave scatter plot in Sydney; c) wave scatter plot in North Sea.

by the power matrix (Fig. 2 bottom) of the WaveStar C6 600 kW WEC at given significant wave heights (H_s) and peak wave periods (T_p). WaveStar C6 WEC was chosen as it has been commercially and experimentally tested and recognised as a relatively mature technology (TRL 7) as reported in [30–32]. To avoid intensive simulations, the power curve and power matrix of the WT and WEC are assumed to be consistent for different deployment sites. In addition, this paper assumes that the wind and wave resources from all directions can be captured as the WEC buoy is axisymmetric and the WT has an ideal yaw system, although it is acknowledged that the direction of wind and wave may affect the power performance of both technologies.

2.3. Hybrid System Configuration

In this work, a DC-linked offshore wind and wave conversion system is selected to perform the techno-economic analysis. Fig. 3 shows a diagram of the hybrid offshore wind and wave conversion system used in the techno-economic analysis. The middle schematic presents the configuration of offshore hybrid offshore devices comprising a wind turbine coupled with 4 WECs surrounding the wind turbine in a axisymmetric layout. The block diagram around the schematic shows the conversion systems of the wind and WECs (in the red-dashed block), the collocated energy storage systems (such as the offshore option A and onshore option B), the DC-DC converter with high-voltage DC transmission line

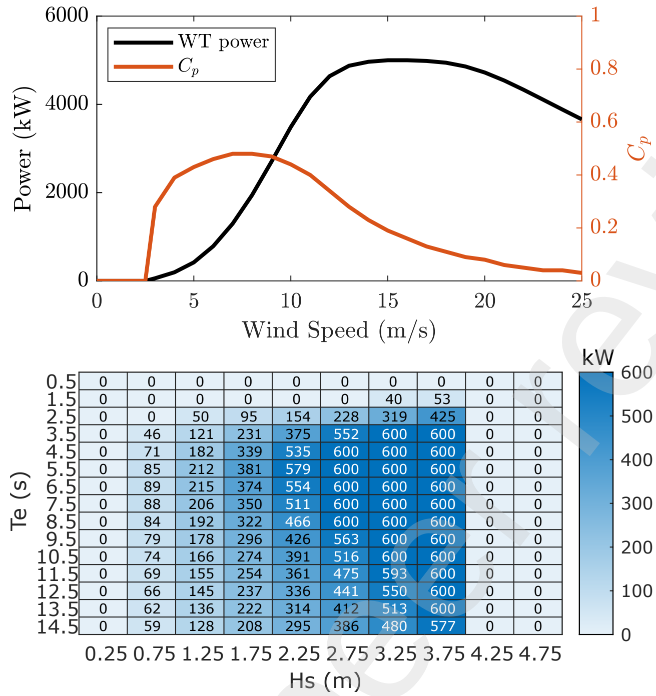

Figure 2: Power curve of Gamesa G128 5 MW wind turbine (top) and power matrix of WaveStar C6 600 kW WEC (bottom)

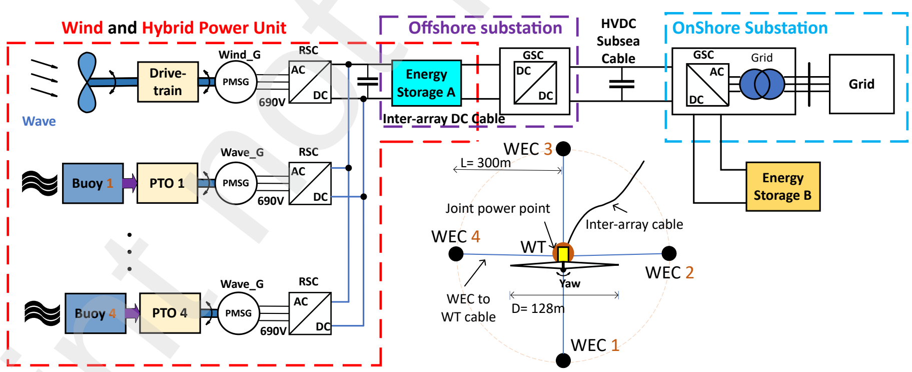

Figure 3: A diagram of the hybrid offshore wind and wave conversion system

on offshore substation (in the purple-dashed block) and the onshore substation (in the blue-dashed block).

Note that the DC system in a hybrid power unit presents a number of benefits. These include facilitating the integration with various DC converters running at various system frequencies from multiple generator units. Note that a direct drive (no gearbox) brushless permanent generator is considered in the offshore wind turbine system since it is the preferred generator technology as it offers a highly reliable system that is desirable in a harsh operating environment. In addition, DC conversion is preferable to be able to integrate multiple WECs that will operate under different conditions. High voltage DC sub-sea cables are also considered since they are suitable for long distance transmission (typically above 50 km, such as in the Sydney location).

It is also noted that there are two potential energy storage options: Energy Storage A and Energy Storage B (in Fig. 3). The option of Energy Storage A can be deployed distributively on each hybrid/WT-alone platform, or it can be a large unit centralized on an offshore substation. On the other hand, the Energy Storage B option performs as a normal onshore energy storage station. The technical and economic comparisons of these two storage options are investigated in Section 5. The four WEC devices are evenly distributed around a WT with a distance of 300 m to minimise the interactions between WEC devices. Note also that such a building block can be duplicated and distributed at a farm scale.

2.4. Managing Power Dispatchability Using Energy Storage Systems

It is known that energy storage systems have been widely applied to reduce the variability and intermittency of non-dispatchable renewables generation. In this paper, the methodology of managing the variability and intermittency of offshore renewables using a suitable size of energy storage system is proposed as shown in Fig. 4. This effective algorithm firstly generates the daily demand profile and generation profile by utilizing the real demand data as well as the wind and wave data. These profiles are integrated to obtain the energy dispatch profiles and then compared with generation time series data to calculate the energy difference (deficit and surplus). Finally, the energy deficit and surplus are used to size the ESS capacity by the accumulated state of charge (SOC) method.

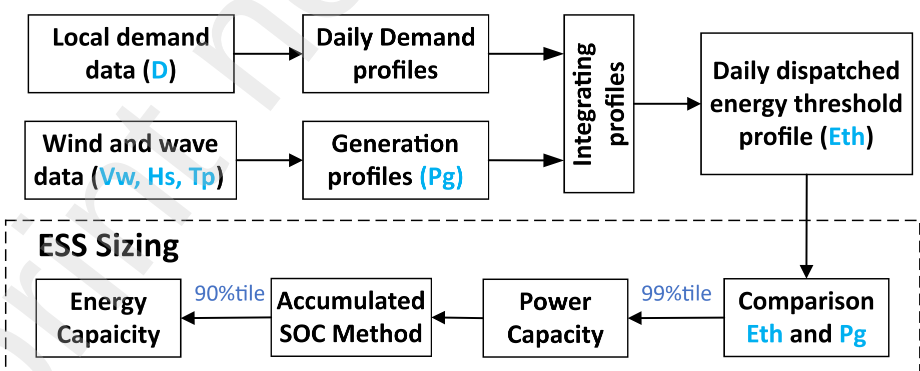

Figure 4: Method of dispatching energy with statistical sized ESS

The demand information is obtained from the Australian Energy Market Operator (AEMO) [33] and from the European Network of Transmission System

Operators for Electricity [34]. The normalized daily demand profile (DP^i, a vector of 1 × 24) at day i can be defined by:

$$DP^i = \frac{(D^i - \overline{D^i})}{\overline{D^i}} \tag{2}$$

where D^i is the hourly demand data at day i and $\overline{D^i}$ is the mean value of demand data at day i. The dispatch energy threshold E^i_{th} at day i is determined based on the mean value of the generation profile ($\overline{P^i_g}$) at day i and the normalized demand profile at the same day, according to

$$E^i_{th} = \overline{P^i_g} \times DP^i. \tag{3}$$

The power capacity can be estimated by the energy deficit and surplus that is the energy difference between the power generation time series ($\boldsymbol{P_g}$) and the energy dispatch threshold time series ($\boldsymbol{E_{th}}$) in a year, given by:

$$\boldsymbol{\Delta P_g} = \boldsymbol{P_g} - \boldsymbol{E_{th}}, \tag{4}$$

where $\boldsymbol{E_{th}} = \left[E^1_{th},\ ...,\ E^{365}_{th}\right]^\top$ and $\boldsymbol{P_g} = \left[P^1_g,\ ...,\ P^{365}_g\right]^\top$. For best practice, seven years generation data (from 2014 to 2020) in the Sydney location is used to estimate power capacity. The charging/discharging rated powers (P_c and P_d) of the ESS are assumed to be equal and estimated to be the average of the 99th percentile of $\boldsymbol{\Delta P_g}$ of each year to cover most of power charging and discharging event.

The corresponding ESS energy capacity is determined by the distribution of the accumulated SOC series which is defined by:

$$S_t = \begin{cases} \min(\Delta P_g, P_c) & \text{if } \Delta P_t > 0 \\ \max(\Delta P_g, P_d) & \text{otherwise,} \end{cases} \tag{5}$$

and

$$A_t = \begin{cases} S_0 & \text{if } t = 0 \\ A_{t-1} + S_t & \text{otherwise,} \end{cases} \tag{6}$$

where S_t and A_t are charging or discharging power series and accumulated SOC series, respectively. Note that, as the initial values of S_0 present a significant impact on the accumulated SOC data, the first step is to determine its initial values which are given by $S^y_o = -\text{mean}(A^y_t)$ to balance the offset of the SOC data series at each year y. Then the ESS energy capacity is estimated by taking the average of the 90th percentile of A^y_t at each year between 2014 to 2020.

3. Economic Model

From a financial point of view, the different renewable energy systems (RES) can be compared through an approximation of their life cycle costs (LCC) and energy generation over their lifetime. The most commonly applied metric for a techno-economic assessment of energy generation plants is the Levelized Cost of Energy/Electricity (LCOE) which displays the net present value of the studied system by applying a discounting method on the costs and outputs of the RES. Different calculation methods of LCOE have been presented and compared in [35]. In this paper, the LCOE is defined by [21]:

$$\text{LCOE} = \frac{\sum_{t=0}^{n} C_t/(1+r_{\text{discount}})^t}{\sum_{t=0}^{n} E_{\text{tot}}/(1+r_{\text{discount}})^t}, \tag{7}$$

where C_t and E_{tot} are the annual total cost and annual total energy production, respectively, and the variables n and r_{discount} are the lifetime of the RES (which is taken as 25 years in this paper) and the discount rate reflecting the nominal inflation; the latter is taken as the average value of r_{discount} used in case studies in [36] and set to 7.6%. The annual energy production (E_{tot}) is estimated by averaging the 7 year generation data (calculated as in Section 2.2), given by:

$$E_{\text{tot}} = \frac{\alpha\eta}{7}\left[\sum_{t=2014}^{2020} E_t\right], \tag{8}$$

where E_t is the energy generation at year t; α and η are the energy production availability (percentage of time for normal generation of energy farm), depending on the time window for maintenance operations [19], and the energy conversion system efficiency, depending on the total energy loss of the RES.

The annual total costs C_t are divided into capital expenditures (CAPEX), annual operational expenditures (OPEX) and decommissioning expenditures (DCPEX), covering the total life cycle costs of each subsystem of the studied RES, and they are given by:

$$C_t = \text{CAPEX} + \text{OPEX} + \text{DCPEX}. \tag{9}$$

Note that CAPEX represents the initial investment costs before the RES is fully operational. The investment costs include the costs of: the development and consenting of the farm ($C_{\text{D\&C}}$), the building and purchasing costs (C_{Build}), the installation and commissioning (C_{Install}) and the power connection and balance of plant ($C_{\text{Connection}}$) for the offshore energy farm, as given by:

$$\text{CAPEX} = C_{\text{D\&C}} + C_{\text{Build}} + C_{\text{Install}} + C_{\text{Connection}}. \tag{10}$$

The OPEX includes the operation and maintenance ($C_{\text{O\&M}}$), insurance ($C_{\text{Insurance}}$) and administrative (C_{Admin}) costs, given by:

$$\text{OPEX} = C_{\text{O\&M}} + C_{\text{Insurance}} + C_{\text{Admin}}. \tag{11}$$

To categorise the costs of the different subsystems occurring at different project periods, the life cycle costs (LCC) of the entire project are structured as shown in Fig.5. Overall, the LCC can be grouped into three subsystem costs: the generation system (GENC), energy storage system (ESSC) and supporting

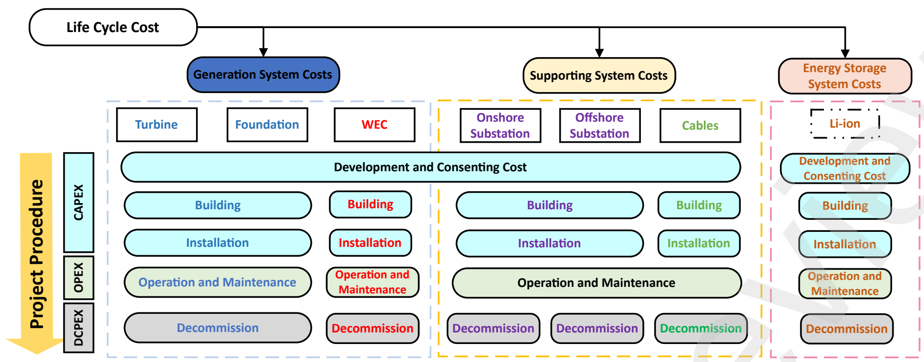

Figure 5: A diagram of the lifecycle cost model is categorized: 1) by different project periods: CAPEX in cyan, OPEX in green, and DCPEX in grey; 2) by different subsystems of the RES: the generation systems (such as wind turbine in blue and WEC in red), the supporting system (such as the offshore substation in purple and the inter-array and connection cables in green) and the energy storage system in orange.

system costs (SSC). The GENC covers the costs of all the generation systems in the offshore energy farm, such as the WT, offshore foundations and/or WEC systems; the ESSC comprises all the costs related to the ESS; the SSC includes the costs of power connection, such as onshore substation, offshore substation and cabling cost. In terms of the cost at different project development stages, the cost modules of CAPEX, OPEX and DCPEX are highlighted in cyan, green and grey respectively.

It is necessary to define key assumptions that were made in order to be able to financially assess and compare the different cases. As was reported in [20, 37–39], the costs of RES systems are project- and location-dependent. It is assumed that a company that has experience and knowledge in offshore projects will develop and install the hybrid system with the same approach and procedure in both locations [39]. The detailed analysis of three subsystems is described in the following subsections. All costs obtained from literature are converted to € and summarised in Table 1.

3.1. Generating Systems Costs

The cost characteristics for the WT generation system are taken from a technical report based on a 1 GW wind farm with 100 units of 10 MW in a location 60 km offshore in 30 m depth, which was planned to be operational in 2022 [38, 40]. This technical report includes a more detailed breakdown of all CAPEX and OPEX costs; all costs are normalized with installed capacity (per MW), which is applied to the case study of this research.

For approximating the costs of the WEC units, an estimation of a generic, utility-scale floating wave energy farm with a 160 MW capacity is selected; its characteristics are summarised in [41].This paper gathers more recent estimations of costs for the wave energy sector while keeping in mind influence factors such as learning curves and economy of scale of future projects [41].

When considering a hybrid system that shares infrastructure and is co-located, cost advantages can be justified. Especially, sharing significant investment costs such as development and consenting and connection costs (described in more detail in Section 3.2) leads to a decrease of 12% in total capital costs of the generation system [21]. Also $C_{\mathrm{O\&M}}$ of the total generation system can be decreased by 12% as personnel and service vessels can be shared [19, 21]. The hybrid system also increases the availability (α) and total energy generation of the WT units surrounded by WECs as it increases the accessibility to the WT for O&M tasks; an offshore wind farm shows $\alpha = 80\%$, a combined farm reaches α of 90% for the wind turbines, while the α of WEC generation system is 95% and stays equal in both RES cases [19]. In our analysis, η is assumed to be 0.9 for both WT and WEC generation systems.

3.2. Supporting System Costs

These RES-wide costs include the $C_{\mathrm{D\&C}}$, offshore and onshore substation and the inter-array and export transmission cable costs (as depicted in Fig. 5). Such costs depend on the installed capacity of the generation system, the inter-array cable connection length (km_{ia} in Table. 1) and the distance to shore, respectively. In this paper, all generating subsystems are assumed to be mature and at utility scale. Therefore, for the supporting system, utility scale costing parameters can be applied which are taken from the technical report of a 1 GW offshore wind farm [38, 40]. The values for the supporting system CAPEX and OPEX are summarised in Table 1.

3.3. Energy Storage System Costs

Recent publications have focused on extensively comparing and reviewing possible ESS technologies, both technically and economically [42, 43]. Parameters characterising the technical aspects (e.g. power and energy capacity, density and lifetime) and the financial assessment (e.g. capital cost and LCOE) are represented using broad ranges of values as they are highly dependent on the maturity level of the ESS technologies selected for specific projects and their required capacity for the application [43]. A number of novel offshore - co-located or hybrid - storage systems have been introduced [44] but due to their low maturity level no extensive economic analysis is available, yet. Furthermore, the ESS does not influence the other RES costs (costs of generating and supporting system); both offshore and onshore storage solutions are considered as the generation farm is of utility scale. Although it is acknowledged that offshore ESS would increase the CAPEX and OPEX due to installation and operational costs compared to the similar onshore counterparts, this aspect has not been included in the financial assessment as limited data is currently available due to the absence of such an application. For ESS systems that have a lower lifetime than the defined project lifetime, the replacement costs are solely based on the CAPEX calculated with the energy capacity. Note that, unlike the energy storage unit, the power conversion unit in ESS usually does not have to be replaced. Li-Ion is chosen for the initial case study to compare the systems in the two selected locations, as Li-ion ESS is widely applied and has reached a high level of technological maturity. However, the applicability and economic feasibility of other ESS options is discussed in Section 5.

Table 1: Financial input parameters of subsystems for the offshore RES

System	Subsystem	Parameter	Value	Unit	Ref
GEN	WT	CAPEX	1789	k€/MW	[38, 40]
		OPEX	63.8	k€/MW/year	
		DCPEX	139.2	k€/MW	
	WEC	CAPEX	3100.0	k€/MW	[41]
		OPEX	124.0	k€/MW/year	
		DCPEX	-	N/A	Incl. in CAPEX
ESS (Li-Ion)		CAPEX	372.5 357.1	k€/MW k€/MWh	[42–48]
		OPEX	9.6	k€/MW/year	
		DCPEX	-	N/A	Incl. in CAPEX
SS		CAPEX	398.5 6.8 203.0	€/MW k€/MW/km k€/km_{ia}	[38, 40]
		OPEX	24.4	k€/MW/year	
		DCPEX	75.4 2.7	k€/MW k€/MW/km	

4. Results

4.1. Requirement of Energy Storage System Capacity

Fig. 6 shows the portion of the time series of the power generation from wind (blue line) and wave (purple line), the energy dispatch threshold (green line) and the demand information (orange dashed line). It can be seen that the energy dispatch threshold profile follows the daily demand profile indicating that the commitment of the offshore energy farm to supply energy to the grid corresponds to the local demand. The difference between generation and the dispatch threshold is the requirement for storage, which is used to size the power and energy capacity of ESS. The black circles in Fig. 6 highlight the advantages of a combined wind and wave farm during no/low wind periods, as the dispatch threshold in those periods can be partially or even fully met by the wave energy generation instead of completely met by, thus mitigating the storage capacity.

Regarding the power capacity of the ESS, Fig. 7 shows the hourly charging and discharging statistics. By taking the 99 percentile values into account, the power ratings of ESS for a stand-alone wind farm and a combined energy farm in the Sydney location are 0.6 per unit (p.u.) and 0.48 p.u. of the total

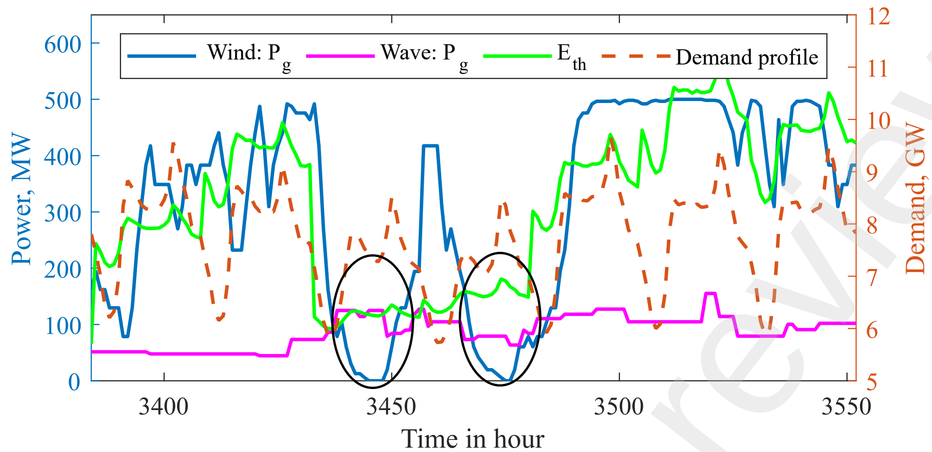

Figure 6: Portion of time series (one week) of generation, dispatch threshold and demand profiles in the Sydney location

farm installed capacity (corresponding to 300 MW and 240 MW, respectively). In addition, the ESS power capacity of the wind farm and combined farm for the North Sea location are 0.64 p.u. and 0.54 p.u. (320 MW and 270 MW, respectively).

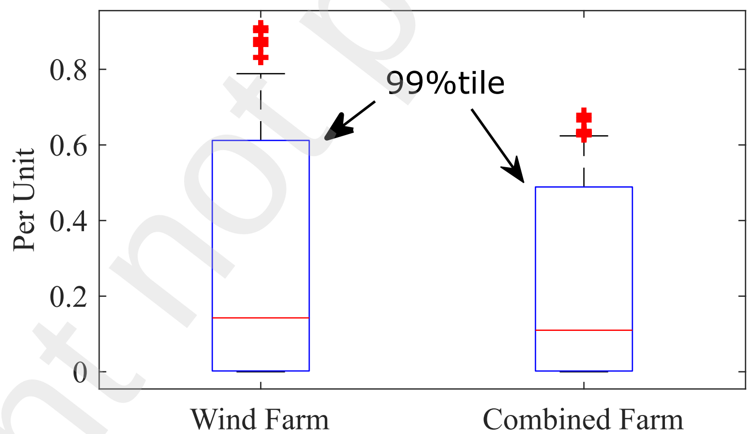

Figure 7: Statistical power capacity for ESS

Based on the accumulated SOC method (see Eq. (5) and (6)), the ESS energy capacity can be estimated by averaging the yearly capacity A_t^y over 2014 to 2020. Overall, the energy capacity of ESS for a standalone wind energy farm and a combined wind and wave (WW) farm in the Sydney location are 1320 MWh and 864 MWh (3.6 h and 4.4 h of storage duration). These values in the North Sea location are 1280 MWh and 1053 MWh (4 h and 3.9 h of storage duration, respectively).

4.2. Site Characteristics

Table. 2 summarizes the geographic information such as distance to the shoreline (D_s) and water depth (D_e), the correspondence (where C_r and τ are the cross-correlation coefficient and lag time between wind and wave power) and power densities (P_{wind} and P_{wave}) of the wind and wave resources in two different locations. Note that site A (Sydney) is a far-shore location with a 90 km transmission distance and deeper water of about 100 m, while site B (North Sea) is a near-shore location having an 8 km distance to the shore and shallow water characteristics (with 35 m water depth).

Table 2: Resource and economic assessment of three system configurations in two locations

Site	D_s/D_e. km/m	C_r/τ -/h	P_{wind}, P_{wave} kW/m^2, kW/m	Config.	ESS MW/MWh	Gen. GWh/yr	LCOE €/MWh
A	90/100	0.60/5	1.02, 21.6	WT only	-	26.0	93.6
				WT+ESS	300/1320	26.0	132.0
				WW+ESS	240/864	**38.6**	110.4
B	8/35	0.81/1	0.87, 13.3	WT only	-	24.4	84.7
				WT+ESS	320/1280	24.4	125.1
				WW+ESS	270/1053	**33.6**	118.0

The adjacent distance to the shore is the primary driver that influences the transmission cable length, hence defining voltage level. This leads to higher supporting system costs. The DC transmission cable is selected for both locations as the DC-linked hybrid system is used in this paper, as shown in Fig. 3.

The water depth plays an important role in selecting offshore wind foundation types. Floating WT platforms can be deployed in sea sites with a water depth of more than 100 m, while bottom-fixed WT foundations are more economically feasible to install in a shallow water area with depths of less than 50 m [39]. Therefore, in this paper, the floating platform and the bottom-fixed monopile foundation are used in the Sydney and North Sea location, respectively. The estimated costs of the two platform types are obtained from [39]. In the same reference, the monopile and the floating structure present a relatively comparable CAPEX value since the former has a higher cost of manufacturing, while the latter has a higher mooring cost. It should be noted that in a more detailed cost structure for both foundation types the costs significantly depend on the soil characteristics of the selected locations; however, this is out of the scope of this paper.

It can be concluded that, in general, for offshore energy farms with the same installed capacity (500 MW), the combined energy farm has lower requirements on both power and energy capacity of the ESS compared to the stand-alone wind energy farm (see in Table.2). However, the benefits vary in the two distinct locations. The combined energy farm in Site A reduces the power capacity by 20% (from 300 MW to 240 MW) and the energy capacity by 35% (from 1320 MWh to 864 MWh). On the other hand, in Site B power capacity can be reduced by 15.6% (from 320 MW to 270 MW) and energy capacity can be reduced by 17.7%

(from 1053 MWh to 1280 MWh). Note that Site A has better performance in reducing both the ESS power capacity (20% versus 15.6%) and energy capacity (35% versus 17.5%) which is a result of a lower correspondence between wind and wave power. As reported in [22], the lower correlation (C_r) and longer lag time (τ) are two preferable factors indicating better power smoothing (lower energy variability) as wind and wave resources complement each other. Therefore, smaller energy deficit and energy curtailment from energy farms lead to a smaller required size of ESS.

4.3. Economic Analysis

The LCOEs of three energy farm configurations in the two locations are compared in Table. 2. Although abundant wind and wave energy can be captured in Site A, the LCOEs of both the standalone WT farm and the hybrid WT with ESS farm (93.6 €/MWh and 132.0 €/MWh) are higher than those of Site B with values of 84.7 €/MWh and 125.1 €/MWh respectively, mainly due to the costly far-shore transmission. In addition, as a result of the smaller storage capacity and higher availability of resources in Site A, the LCOE of a combined energy farm with a Li-ion battery (as an ESS) has a considerably lower value of 110.4 €/MWh. The LCOE values of the wind-only farm with different turbine sizes, locations and future costing trends are studied in [37, 40].

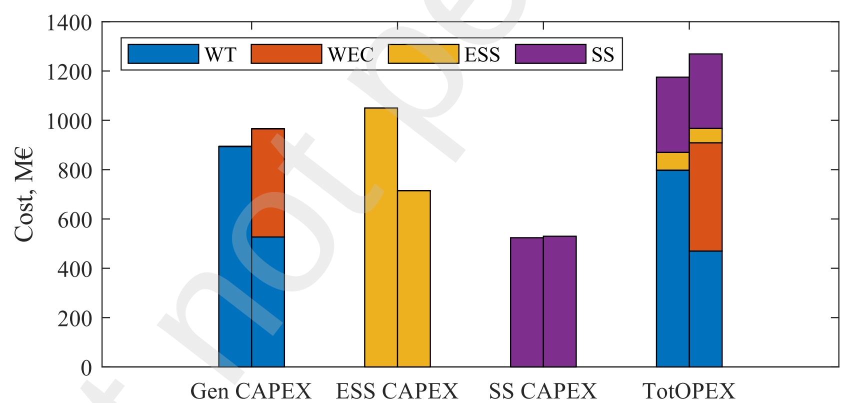

Figure 8: Breakdown of undiscounted costs of 500 MW offshore energy farms in the Sydney location, under wind only (left groups) and WW system (right groups) configurations

As illustrated in Fig.8, the total investment costs of the generation system in the combined energy farm at the Sydney location show a slight increase of 8% compared to the wind-only farm due to the higher CAPEX of WECs. Note that the WT CAPEX in the combined energy farm significantly decreases due to fewer generation units being required to reach the same capacity (500 MW) of the energy farm and the shared infrastructure and installation costs.

In terms of ESS CAPEX, the combined energy farm significantly reduces the ESS CAPEX by 32% compared to the stand-alone wind energy farm, highlighting the potential of combined wind and wave energies and their feasibility in future utility-scale projects. On the contrary, the SS CAPEX is slightly higher in the combined farm due to the additional cost of inter-array cabling between WECs and WT (as shown in Fig.3). Note that the majority of overarching costs stay comparable due to coordinated efforts such as substations costs and DC system costs which are based on the total installed capacity of the generation system of the energy farm. Although the combined farm decreases the O&M costs of the WTs significantly (being only 67 units and sharing O&M costs with WEC units), the total OPEX increases due to the higher costs of the WEC units. This slight increase in the above-mentioned costs is less significant when compared to the decrease of ESS CAPEX in the combined offshore farm. Overall, the combined energy farm not only has merits in reducing ESS capacity requirement while maintaining energy dispatchability to local demand but also presents higher economic feasibility for those locations having good potential for hybrid exploration.

Furthermore, the breakdown costs of the same offshore energy farm in the North sea are shown in the appendix (Fig A.1). Due to the short transmission distance and shallow water, the SS CAPEX is much lower than that of the Sydney location. However, the cost saving of ESS between wind-only and combined energy farms is lower than that of the Sydney location (17% versus 32%), resulting from different synergies between wind and wave resources, which is consistent with previous analysis.

5. Discussion on Energy Storage Applications

Although energy variability reduction in the combined wind and wave energy farm has been approved by the previous studies, large-scale energy storage systems located nearshore will be needed to reduce the intermittency, variability and uncertainties to the power network. Large-scale storage is also necessary as the power system inertia is reduced due to decommissioning conventional generators and an increased portion of the intermittent renewable energy resources.

Therefore, ESS options need to be analyzed and compared to be able to identify the most suitable types for the proposed combined energy conversion system. In [44], various marine ESSs are reviewed, and the following mature and commercially available ESSs are considered in this study including flywheel energy storage (FES), compressed air energy storage (CAES), pumped hydro storage (PHS), battery electrical storage (BES) options such as lithium-ion (Li-ion), vanadium redox flow batteries (VRFB), lead-acid batteries and sodium-sulfur (NaS) batteries.

As shown in Fig. 3, both offshore (option A) and onshore (option B) ESS are considered to be integrated with offshore energy farms. However, due to the unique challenges of the marine environment, it is expected that the applicability of ESS in offshore platforms will be significantly different from the onshore types. Particularly in large-scale applications, the complexity of the installation and construction process and the operation and maintenance tasks will be much higher than for small systems. In addition, the environmental impact in the offshore location needs to be carefully studied both due to the difficulties in access and the sensitivity of the surrounding environment, as it can all lead to higher costs.

To evaluate the above listed ESS for offshore energy farms, some key factors that need to be evaluated include the volumetric or gravimetric power and energy densities, the level of storage duration, their technical maturity, efficiency and economic feasibility. The priorities of these factors can also vary due to the specific characteristics of a site and the power network features. For example, in a given application, the storage duration may be considered first, followed by the technical maturity, the complexity of system (installation and operation), power/energy density and efficiency.

5.1. Comparisons of Storage Types

Table. 3 shows the key technical and economic parameters of different ESS types. Note that the values of the estimated parameters in the table were summarized in [42–48] and they are dependent on specific applications. Therefore, this table can be used to determine the suitability of a given ESS. For example, FES can store kinetic energy and it has the highest gravimetric power density at higher efficiency, up to 95% [42, 45]). However, FES may not be considered as an option in an application if the energy storage duration level requirement is higher. In addition, the low volumetric and gravimetric energy density may not be suitable in an application that has limited space available to integrate, such as in offshore platforms with floating foundations.

Table 3: Technical and economic parameters of main ESS types [42–48].

	ESS Types	Volumetric Power Density, kW/m^3	Volumetric Energy Density, kWh/m^3	Gravimetric Power Density, W/kg	Gravimetric Energy Density, Wh/kg	Suitable Storage Duration	Maturity	Efficiency %	UCP, UCE €/kW, €/kWh	O/M €/kw-yr	Life Years Avg.
Mech.	FES	1000-2000	20-80	400-1500	5-100	secs-mins	precommercial	90-95	2765/11059	19	20
	CAES	0.04-10	0.4-20	2.2-24	10-30	hours-months	commercial	42-54	1602/101	21	25
	PHS	0.5-1.5	0.5-2	0.4-1.5	0.5-2	hours-months	mature	70-80	2533/158	3	25
Elec.	Lead-acid	10-400	25-90	75-300	30-50	mins-days	mature	70-90	442 / 419	48	5
	VRFB	2.5-33	10-33	80-150	30-50	hours-months	precommercial	75-85	432/715	67	20
	Li-ion	56-800	94-500	150-200	75-200	secs-hours	commercial	75-95	373/357	10	12.5
	NaS	140-180	150-300	90-230	150-240	secs-hours	commercial	80-90	432/762	77	15

On the other hand, CAES can store both mechanical energy for a short storage duration (via gas accumulators in wave energy converter [49]) and electrical energy for hours of storage duration (such as the first utility-scale of CAES in Germany [50]). Since it is more economical in a large-scale energy storage application and has relatively low volumetric and gravimetric density and low efficiency (42-54%) [42], CAES deployment may not be suitable for offshore platforms and can be an option for onshore storage.

Within the last decade, PHS has received attention due to its technical maturity (similarities to conventional hydroelectric power generation). Although the technology is very competitive compared to the other ESSs, it requires a significant initial investment and entirely relies on the nearby landscape, its structure and most critically the availability of water resources to be utilized for energy generation. Although several offshore PHSs have been reported in

[44], their technical maturity and cost estimation have not been demonstrated for wider applications.

Unlike their counterparts, however, utility-scale batteries have been widely used in numerous applications for arbitrage, firming, frequency control ancillary services (FCAS) and black-start. This paper considers four mature battery technologies including lead-acid, vanadium redox flow, Li-ion and NaS batteries, which are widely used [42, 44].

Among battery types, lead-acid batteries have the lowest cost and a higher energy density compared to mechanical ESSs (CAES and PHS), which may be deployed in offshore and onshore applications. However, they have a very short lifetime (about 5 years) which will lead to a significantly high replacement cost, and which is not desirable in the harsh ocean environment.

Similarly, VRFB is also a relatively mature technology with the longest lifetime among the battery options. Due to the unique working principle of VRFB, it is suitable for long time storage (mins to hours) and its power and energy capacities are easily scalable by increasing the number of electrodes and the number of cells, the tank size and concentration of the electrolyte solution. However, this energy storage is not considered as a solution for the offshore platform due to its higher maintenance cost, sensitivity to ambient temperature and low energy density, hence requiring a large space. However, it can be a good candidate for onshore applications.

The lithium-ion battery is one of the most advanced storage technologies having the best overall performance compared to other batteries in terms of energy efficiency, technical maturity and power and energy density. Therefore, such batteries can be deployed in the combined wind/wave energy systems on- and off-shore. Although they have a relatively short operation duration and higher cost, their high reliability and lower maintenance cost override the limitations.

Similarly, NaS batteries are considered one of the most promising BES technologies due to their high power density, negligible self-discharging rate and longer lifetime relative to the Li-ion batteries. However, the higher cost and high-temperature requirement for their operation are the two main barriers for offshore applications.

Note that hydrogen energy storage (HES) technology has not been considered as an ESS in the above classification. This is due to the fact that the technology is not mature enough. Although HES technology has the potential to integrate with large offshore wind farms, its profitability has to be demonstrated under all scenarios due to high investment costs [51]. Moreover, it is expected that HES can be feasible if the existing rate of the carbon tax is adjusted in the future [52].

5.2. Economic Feasibility of Storage Types

The technical and economic feasibility of different ESS types are summarized in Table. 4, where 'N/A' denotes non-applicability due to technical infeasibility. In terms of their economic aspects, the LCOEs of the wind-only energy farm (with ESS) and the combined energy farm (with ESS) are compared by using various ESS types in the two locations (Site A and B). In general, the combined energy farm with ESS shows lower LCOE than the wind-only farm with ESS in both locations regardless of the chosen ESS type. In addition, Site A has better synergies for a combined energy farm as more significant cost savings can be made compared to Site B. These are consistent with the discussion in section 4.3. Furthermore, it is concluded that due to the modularized design and mature system components, the Li-ion battery can be placed in both on- and off-shore locations. Differently, the CAES mechanical storage only being located at the onshore position shows competitive LCOE values compared to other ESS types in both locations and system configurations. For example, in the Sydney location (site A), the lowest LCOE of 109.8 €/MWh can be found in a combined energy farm by selecting the conventional large-scale CAES onshore, which is closely followed by the Li-Ion battery with the value of 110.4 €/MWh. Note that, unlike the Li-ion battery, the CAES does not offer technical flexibility (like modularized and mature system components) to deploy on an offshore platform. Although some small-scale CAES are being developed and could be available for offshore applications, such technologies are more expensive than traditional large-scale CAES, and their costs are currently hard to predict due to low maturity [44]. Furthermore, the impact of the energy efficiency on the ESS capacity and on the total energy generated is not quantitatively considered in the financial assessment. It depends on the specific design (such as scales and implementations) of the chosen ESS and on its application.

Table 4: Techno-economic comparison of ESS in a combined energy farm.

ESS Types		Mechanical Storage			Battery Storage			
Position	Feasibility	FES	CAES	PHS	Li-ion	VRFB	Lead-acid	NaS
Offshore	Tech.	×	×	×	✓	×	✓	×
	Econ.	N/A	N/A	N/A	✓	N/A	×	N/A
Onshore	Tech	×	✓	✓ or ×	✓	✓	✓	✓
	Econ.	N/A	✓	✓	✓	✓	×	×
Location	Config.	LCOE (€/MWh)						
Site A	WT+ESS:	N/A	**126.6**	140.8	**132.0**	166.7	180.7	**176.8**
	WW+ESS:	N/A	**109.8**	119.3	**110.4**	131.5	139.1	**137.5**
Site B	WT+ESS:	N/A	**121.5**	137.3	**125.1**	162.0	176.1	**172.6**
	WW+ESS:	N/A	**115.6**	128.1	**118.0**	146.7	157.6	**155.1**

CAES is a more cost-effective solution for large-scale energy storage applications compared to Li-ion batteries due to its low energy capital cost and long lifetime. Lead-acid and NaS batteries are the most expensive technologies to date for both energy farm configurations and locations because of their short lifetime and high O&M costs. It is worth noting that PHS has economic and technical potential to be integrated with large-scale energy farms for long-duration energy storage when a suitable nearshore location is available.

In summary, currently, no ESS technology offers an acceptable LCOE value (e.g. lower than their onshore counterparts) to justify the high cost of offshore installation and operation. In this paper, costing values have been obtained from publicly available data, which did not include offshore-specific information. However, in future studies, an in-depth analysis of the cost advantages of the combined energy farm with an offshore storage system will be studied to analyze the approach used in this paper.

6. Conclusion

This paper has studied the ESS requirements in offshore wind and combined wind and wave energy farms by applying a novel statistical method, which considered the reduction of the energy variability of RES while meeting an energy dispatchability to the local energy demand. The high fidelity cost model of both offshore RES configurations is developed to investigate the economic synergies among the combined energy farms. In addition, different ESS types are comprehensively discussed and assessed in terms of their technical and economic feasibility in offshore RESs. The influence of location-specific characteristics on the techno-financial assessment of the RES configurations and ESS sizing is analysed.

The results indicate that, compared to the stand-alone wind energy farm, the combined wind and wave energy farm can significantly reduce the energy storage capacity to meet the energy dispatch commitment to the local demand, hence decreasing the LCOE. However, the economic benefits of a combined energy system vary with the location characteristics including sea sites with low correlation and long lag time between wind and wave, hence they have a lower LCOE and vice versa. Regarding ESS technologies, CAES and Lithium-ion batteries have a better overall performance in terms of applicability and techno-economic feasibility. However, other energy storage technologies such as NaS batteries or HES are also found promising.

Note that interaction between WT and WEC and the direction of the wind is assumed negligible when assessing the energy generated by the RES. In addition, due to the immature WEC technology (insufficient experience) and large uncertainties in offshore storage applications, the LCC model of the WEC and ESS sub-systems does not provide accurate values for the financial metric. Future work will investigate the DC-linked hybrid system proposed in this paper and will design the optimal control scheme for integration with the battery storage system in terms of power smoothing. In addition, the revenue model of the combined energy farm with ESS will be investigated, and a detailed economic analysis will be conducted by taking the energy efficiency and usage of the storage system into consideration.

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Appendix A. Figures

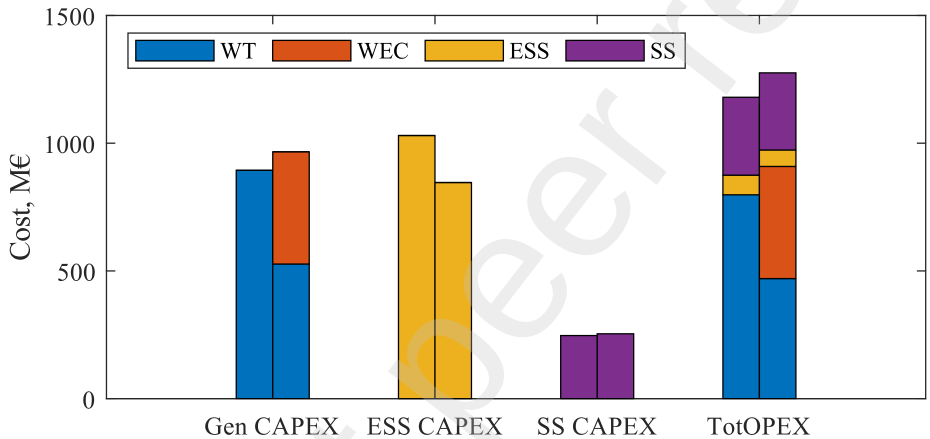

Figure A.1: Breakdown of undiscounted costs of 500 MW offshore energy farms in the North Sea location, under wind alone (left groups) and combined system (right groups) configurations