Grid value of co-located offshore renewable energy

Erik Jonasson, Irina Temiz

Abstract—**Co-locating renewable energy sources such as wave power, solar photovoltaic and wind power, forming a hybrid power plant, may reduce the overall variability, increase the utilization of the transmission system, and reduce the needed physical area. An important topic to address regarding the formation of hybrid power plants is which energy sources to co-locate, and to what proportions these energy sources should be included in the hybrid power plant. In this study, offshore hybrid power plants are analyzed in the North Sea region. By minimizing the plant variability the proportions of each energy source are found, forming the plant with minimal need for energy storage for constant power output operation. The added grid value of such plants is analyzed in terms of electrical infrastructure utilization and power production ramping. It is found that in conditions suitable for the wave energy converter used in the study, a plant configuration of 23% wave power, 22% wind power and 55% solar minimizes the need for energy storage. It is shown that the inclusion of wave power in a hybrid power plant lowers ramping of power generation, increases the capacity factor and provides an overall higher grid value compared to stand-alone installations.**

Index Terms—**Co-locating Renewable Energy, Hybrid Power Plant, Complementarity**

I. Introduction

THE main power grid integration challenge of Renewable Energy Sources (RES) such as wind, solar and wave energy is the intermittency and variability of the generated power, arising from the variable meteorological prime movers. As the penetration level of renewable energy is increasing in the system the increased variability of power generation needs to be addressed. As a consequence, the market for ancillary services such as frequency regulation has grown quickly [1] and efforts are being made in for example demand flexibility, local energy communities, and energy storage [2], [3]. Another topic that addresses this issue is decreasing the variability of the renewable energy production itself. One way of achieving this could be by co-locating multiple energy sources in the same place to form a Hybrid Power Plant (HPP). An HPP consist of multiple energy sources sharing one point of common coupling, as defined in [4]. Co-locating multiple energy sources poses the possibility to lower the overall variability, increasing the utilization of the transmission cable at the same time as lowering the ocean- or land use, and has therefore received increasing interest in both industry and academia [5]. One crucial element in the design of HPPs is which energy sources, and to what proportions these energy sources, should be included in the plant. Studies have been made on co-locating hydro, wind, photovoltaic (PV), wave, etc but the far most common is the co-locating of wind and PV [6]. The decision criteria of proportions of the energy converters is often derived from economic or reliability metrics, or a combination [7].

This article will analyze a HPP comprising wind, Offshore Floating PV (OFPV), and wave power for the North Sea region. The power profiles of wind and PV at the same location have previously been shown to be anti-correlated and therefore introduce the possibility of lowering the variability of the combined power profile [8]. Investigating the North Sea is of interest due to the rapid deployment of primarily wind power installations [9] and the high electrical load in the surrounding areas, which could cause a cluttering effect in the future. The inclusion of wave power in the HPP is based on the possibility of delay effects of wind speeds and wind-generated waves [10]. The proportions of each energy resource type will be determined based on what plant configuration minimizes the Need For Energy Storage (NFES), in other words, the plant that most closely resembles constant output power as discussed in [11]. The combined plant power profile will be analyzed to address the added grid value of co-locating energy sources offshore.

Grid value is a term used for describing services and characteristics that are of benefit to the electrical grid. In [12] grid value is construed as the provision of defined grid services, avoided system costs, measurable and contributions to desired grid qualities such as low carbon intensity. Grid value have also been investigated in terms of anti-correlation of generation profiles [13]. A recent review stressed the importance of identifying the value added in terms of integrated renewable energy portfolios to improve system reliability and resilience [14]. Although grid value is a loosely defined term, it is useful when addressing characteristics that benefit the power system but is not necessarily associated with monetary revenue streams or that are easily measurable. In the scope of this work, grid value is defined as the added value derived from the ability to deliver a reliable, stable supply of energy

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and the efficient usage of the electrical transmission system. This is evaluated in terms of NFES, utilization of the electrical transmission, and ramp rates of the aggregated power profile of the HPP.

A. Aim of the study

This study aims to investigate the potential and feasibility of co-locating wave, OFPV and wind power in the North Sea region. Furthermore, the grid value of such a HPP will be discussed. The contribution of the work is twofold:

- Determine the proportions of each energy source in a HPP composed of wave, OFPV and wind power that minimizes need for energy storage to facilitate constant power output
- Analyze the added grid value of such a HPP

II. Method and Data

A. Reanalysis data

The data used in this study originate from the reanalysis dataset ERA5, in which modeled data based on physical relationships and observations are combined to create a consistent dataset of various meteorological variables. The dataset is freely accessible at [15]. Hourly instantaneous wind speeds at 100 meters above sea level, global horizontal irradiance and air temperature of a spatial resolution 0.25°×0.25°(approximately 25 km×18 km for the North Sea) for the years of 2017-2021 are used to generate OFPV and wind power output. The spatial resolution of wave parameters in ERA5 is 0.5°x0.5°. Significant wave height and wave energy period for the same time period are used to generate wave power output, and the data is interpolated to match the spatial resolution of that of OFPV and wind.

B. Energy converter modelling

In order to model the output power profiles of the energy converters and the HPP the meteorological data is used together with the specifications of the energy converters. The Wave Energy Converter (WEC) concept used in this study is the point-absorber type developed by CorPower Ocean [16]. A power matrix relating significant wave height, H_s, and wave energy period, T_e, to output power, provided by CorPower, is used to generate the output power profile. The matrix can not be published due to confidentiality.

The Wind Turbine (WT) output power is modeled with wind speeds at hub height as input. Wind speeds at hub height were derived from the reanalysis data of wind speeds at 100 meters above sea level using (1)

$$V_{hh} = V_{ref} \left(\frac{Z_{hh}}{Z_{ref}} \right)^{\alpha} \tag{1}$$

where V_{hh}, V_{ref} is the wind speed at hub height and reference level, Z_{hh}, Z_{ref} is the hub height and reference height, and α is the power law exponent. The value of 0.11 is used for the power law exponent which is suitable over ocean conditions [17]. An 8 MW offshore reference turbine from NREL with cut-in, rated and cut-out wind speeds of 4 m/s, 12 m/s and 25 m/s [18] is used to generate the output power. The power curve of the reference turbine is shown in Fig. 1.

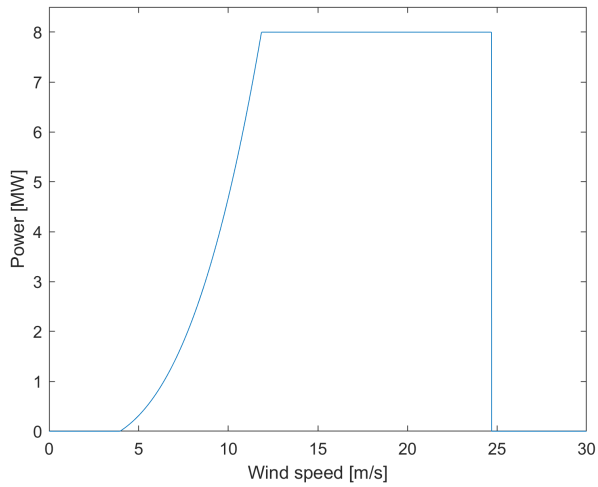

Fig. 1. Wind turbine power curve based on the NREL 8 MW Offshore reference turbine [18]

OFPV is based on the same technology as regular land-based PV but is instead placed on water bodies either on rigid structures or on moored floating pontoons [19]. It is assumed that the panels are oriented parallel to the sea surface and that tilting effects induced by waves are negligible. The output power can therefore be estimated using (2)

$$P_{PV} = \eta_{PV} \cdot A \cdot G \tag{2}$$

where η_{PV} is the PV temperature dependant efficiency, A is the panel area and G is the global horizontal irradiance. In this study specifications from the PV panel JAM72S30-535 have been used, with the efficiency of 20.7 % at standard testing conditions and a panel area of 2.6 m^2.

C. Aggregated power

The co-located energy sources form an HPP sharing one point of common coupling. The power production is aggregated and transmitted to the grid, as per the current definition of an HPP by IEA [4]. By defining fractions of installed power of each energy source as $x_{WT}, x_{OFPV}, x_{WEC}$ the combined power output P_{HPP} can be calculated as in (3);

$$P_{HPP} = x_{WT} P_{WT} + x_{OFPV} P_{OFPV} + x_{WEC} P_{WEC} \tag{3}$$

where P indicates power and x is the fraction of each subscripted energy source. By normalizing the rated power of the HPP to 1 per unit (pu) the possible combinations may be restricted by $x_{WT} + x_{OFPV} + x_{WEC} = 1$. To determine the appropriate fraction of each type of renewable energy generation in the HPP the NFES is minimized. NFES is defined as the sum of the differences between actual energy output and mean energy output divided by the total energy output and is calculated as in (4) [11].

$$NFES = \frac{\sum |\bar{P} - P_i| \Delta t}{\sum P_i \Delta t} \tag{4}$$

By finding the combination that minimizes NFES, the aggregated power time series is calculated as in (3). The aggregated power output is the one that most closely resembles constant output power with the least need for additional energy storage.

D. Grid value metrics

The added grid value of the co-located energy sources is evaluated in terms of NFES, utilization of the electrical transmission and ramp rates of the aggregated power profile. The utilization of the electrical transmission system is calculated as in (5)

$$U = \frac{1}{n}\sum_{t=1}^{n}\begin{cases}1 & P > P_c^r \\ \frac{P(t)}{P_c^r}, & P \leq P_c^r\end{cases} \tag{5}$$

where U is the average utilization, $P(t)$ power output at time instance t, and P_c^r the rated power of the transmission cable. If the power output is greater than the cable rating the generated energy may be curtailed. The total curtailment losses are calculated as in (6)

$$C = \sum_{t=1}^{n}\begin{cases}(P - P_c^r)\Delta t & P > P_c^r \\ 0 & P \leq P_c^r\end{cases} \tag{6}$$

where Δt is the time resolution and C the total curtailment losses. It is assumed that the cable can be used up until the rated power and any excess must be curtailed. The final metric of grid value is ramp rates. The ramp rate is the difference in power output during a certain time interval, calculated as in (7). High ramp rates may pose problems in the power system when large fluctuations must be handled [20].

$$RR(t) = \frac{|P(t-1) - P(t)|}{\Delta t} \tag{7}$$

III. Results and discussion

A. Plant configuration

The fractions of wind, OFPV, and wave power forming the HPP and the reduction of NFES of the formed plant are shown in Fig. 2. In the north region of the studied area a production mix of approximately 15% wind power, 55% OFPV and 30% wave power minimize NFES. In the central region, the mix constitutes roughly 50% OFPV and 25% wind and wave power. In the southeast region close to shore, the fraction of wave power is zero or close to zero. This is expected because the WEC used in this study is unsuitable for this region's shallow water depths and low energetic wave climate. The decrease of NFES is similar in the entire region as shown in Fig. 2d). Fig. 3 shows the plant configuration for all locations arranged so that the wave power share is increasing. For increasing levels of wave power, penetrations levels of wind power are decreased, whereas the levels of OFPV are only slightly decreased. The lower fractions of wave power in the southeast region of the North Sea are consistent with the temporal correlation shown in Fig. 4. The wave- and wind power production estimates are positively correlated in the region, which indicates less possibility to reduce variability by co-locating. As

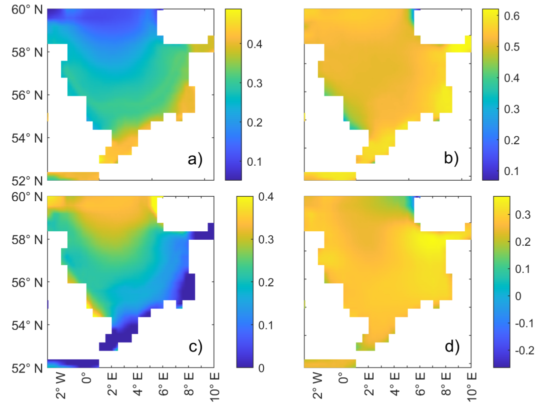

Fig. 2. Weight of a) wind, b) OFPV, c) wave power, and d) decrease of NFES.

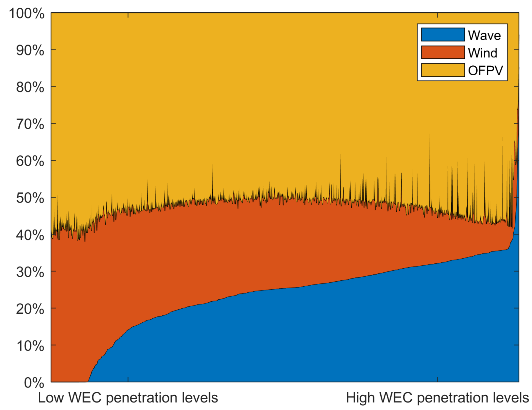

Fig. 3. Plant configuration arranged by increasing wave power penetration.

the wave energy resources are lower in this region of the North Sea [21], lower penetrations levels of wave power are also expected due to the definition of metric NFES. The complementarity index of all three combined sources based on [22] and [23] is shown in Fig. 4d). According to the authors of [22], the interpretation of the complementarity index is that there is a weak similarity between the sources for the entire region. For

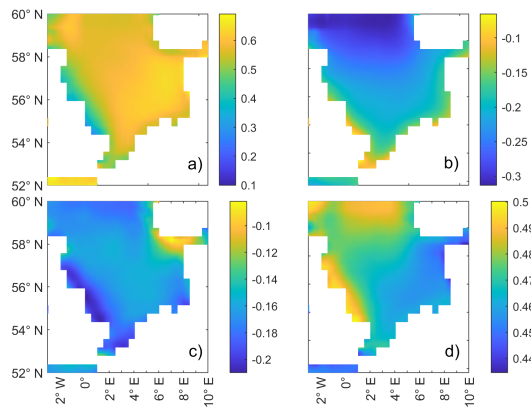

Fig. 4. Correlation of a) wave-wind, b) wave-solar, c) wind-solar, and d) complementarity index of all three sources.

the remainder of the paper, HPP refers to the optimal combination of energy sources as in Fig. 2.

B. Grid value

Fig. 5 shows ramp rates for a stand-alone Wind Power Plant (WiPP), Offshore Floating PV Plant (OFPVPP), Wave Power Plant (WaPP), and for the combined HPP, averaged over the entire North Sea region. The WaPP has the least occasions of ramp events, followed by the combined HPP. The high ramp rates of WiPP are due to events with wind speeds varying around the rated wind speed. In a real scenario, the turbines would not cycle between maximum and zero power output in these instances but this is a direct effect of power curve modeling. In Fig. 6 occurrences

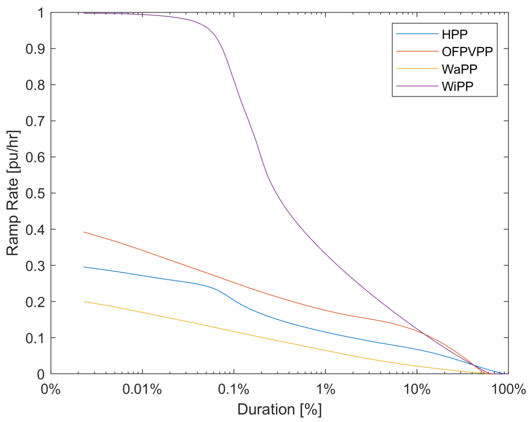

Fig. 5. Ramp rates duration

of significant ramp rate events are shown for the studied region. Areas with low values indicate a lower occurrence frequency of significant ramp rates. As can be seen in Fig. 6d) the areas where wave power is not included in the energy mix, along the coastline in the southeast region, the frequency of significant ramp rate events is higher, indicating that inclusion of wave power in a combined HPP reduces the ramping of generated power.

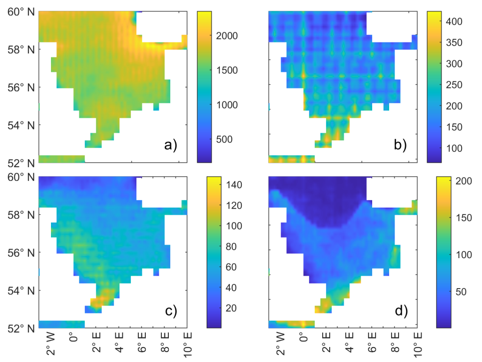

Fig. 6. Occurrences of ramp rates exceeding 0.2 pu/hr for a) WiPP, b) OFPVPP, c) WaPP and d) combined HPP.

Apart from reducing variability, co-locating energy sources also pose the possibility to increase the utilization of transmission cables and the collection point transformer. To further increase utilization it is possible to curtail the output power in instances of power levels over a certain threshold. As can be seen in Fig. 7 the cable rating (power capacity) can be kept at 0.7 pu while keeping the curtailment losses below 5% considering the top 90%-quantile, whereas, for the average location in the North Sea, a cable rating of 0.7 pu will lead to less than 3% curtailment losses for the formed HPP. Cable utilization increases with lower cable ratings. There is a small difference between

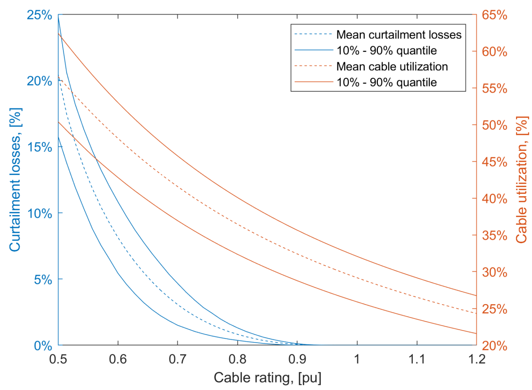

Fig. 7. Curtailment losses and cable utilization with varying cable rating for an HPP

the 90% och 10% quantile, in other words, the possibility of curtailing and increasing cable utilization is relatively constant in the studied region. However, it can be noted that in areas with low levels of wave power penetration reducing the cable rating will lead to higher curtailment losses.

C. Feasable locations

As seen in Fig. 2d) the decrease of NFES is relatively uniform in the studied region. However, as indicated in Fig. 4d), the complementarity potential is moderate in its entirety with a slightly larger potential for the U.K. coastline and in the northern area. The energetic complementarity benefit of co-locating wind, OFPV and wave power are in other words similar for the region, apart from the areas where wave power is not included in the mix. From a power variability point

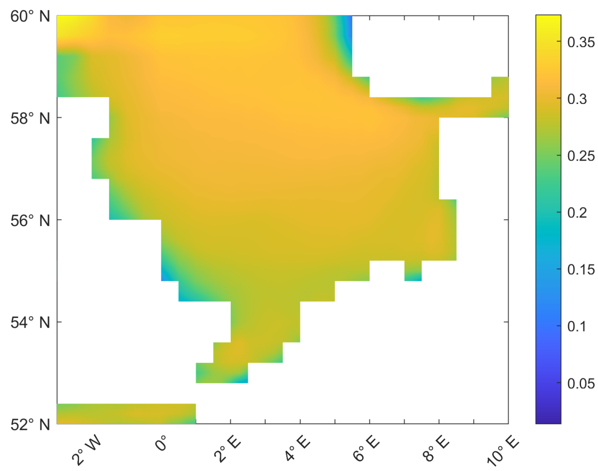

Fig. 8. Capacity factor of the HPP

of view, an HPP comprising wind power and OFPV is ideal for the southeast region, whereas the combination of wind, OFPV and wave power is beneficial in the rest of the region. As can be seen in Fig. 8, the capacity factor of such plants is similar in the whole region, with slightly lower capacity factors along the coasts. As shown in Fig. 9 the North Sea is in its entirety relatively shallow with water depths rarely deeper than 100m. Offshore WTs are normally bottom-fixed at depths lesser than 70m, and of moored floating structures at deeper sea levels [24]. The mooring systems for OFPV is an unresolved issue but can be assumed to be mostly a matter of higher cost at higher depths [19].

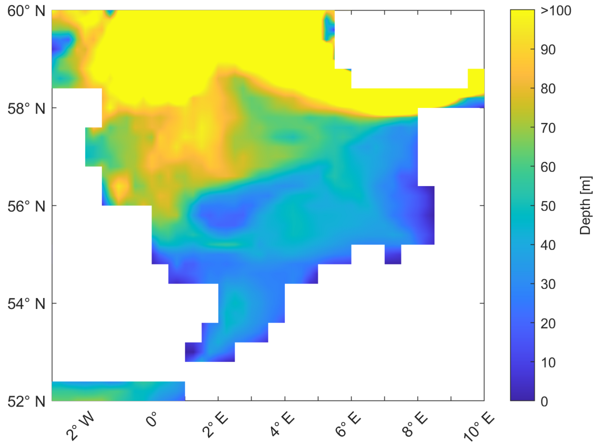

Fig. 9. Depth levels of the North Sea [15]

D. *Paired energy resources*

As it is not obvious that the combined operation of wind, OFPV and wave power provide further benefits than a combination of two of the considered energy sources, the following section will briefly discuss the cases of combined wave-OFPV, wave-wind, wind-OFPV compared to the combination of all three sources considering the variability, in terms of NFES, and energy generation, in terms of capacity factor.

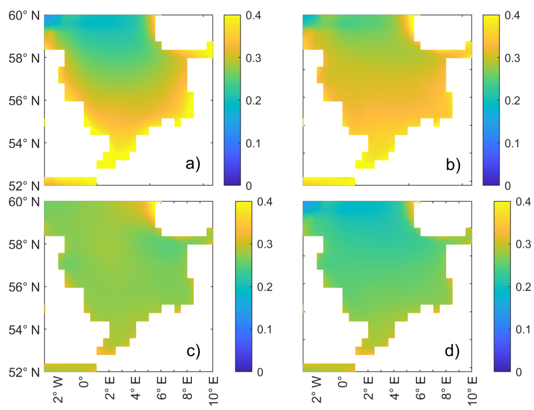

Fig. 10. NFES of combined a) wave-OFPV, b) wave-wind, c) wind-OFPV and d) wave-wind-OFPV.

In Fig. 10 NFES is shown for all paired combinations. The combinations wave-OFPV and wave-wind exhibit similar variability, and as for the combinations of only two sources the combination of wind-OFPV shows the biggest variability benefit. However, as expected, the combination of all three sources shows the smallest level of NFES. In Fig. 11 the capacity factor of all

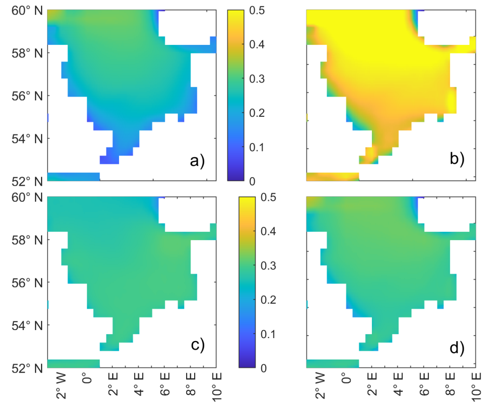

Fig. 11. Capacity factor of combined a) wave-OFPV, b) wave-wind, c) wind-OFPV and d) wave-wind-OFPV.

combinations is shown. A distinctive difference between the combinations is that the combination wave-wind shows a larger capacity factor than all other combinations, which have a similar capacity factor. As stand-alone installations, wind followed by wave power has the highest capacity factor, why it is natural that the combined operation of these energy sources has the highest energy production.

IV. Conclusions

In this article the grid value and configuration of co-located wind, OFPV and wave power have been investigated. It is found that for the areas where wave power is not included in the mix, 60% OFPV and 40% wind power minimizes NFES. When wave power is included in the mix, approximately 23% wave power, 22% wind power and 55% OFPV comprise the plant configuration that minimizes NFES, meaning that the inclusion of wave power displaces wind power to a larger extent than OFPV. A HPP is shown to be favorable in terms of energy storage need, and ramp rates of hourly power production, and a small amount of energy can be curtailed to increase the utilization of the transmission cable.

With regards to the ocean depths and the plant configuration, it is argued that in the south-east region of the North Sea co-locating wind power and OFPV is promising. Off the east coast of the U.K. and the northern region of the North Sea, co-locating wind, OFPV and wave power could be highly beneficial in terms of grid value. However, as this area of the North Sea is deeper, suitable technologies such as floating WTs and WECs suitable for deep waters would need to be utilized.

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