Wind and wave resource complementarity at a Dutch offshore site

By TNO
Iratxe Gonzalez-Aparicio
Max Houwing
Anthony Vitulli

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1 Acknowledgements

TNO would like to thank Dutch Energy from Water Association (EWA) for the fruitful discussions and interaction during the consultation phase of this study.

TNO acknowledge the effort made by Dutch WEC (Wave Energy Convertor) technology developers, including KNSwing, Slow Mill, Dutch Wave Power, Weco, and WaveHexapod, for giving insights on different wave technologies and for providing a suitable average power matrix representative for their technologies. Other Dutch WEC technology developers, including Symphony Wave Power and Ocean Grazer, were not involved in building the power matrix.

The power matrix can be seen as a virtual WEC and is not likely to be representative for the current state of technology; it is worthwhile to mention the importance of coming to a consensus (5 out of 7) as very valuable information for the assignment commissioned by TKI Offshore Energy and RVO and for the future steps towards the deployment of the technology.

Should other readers aim to do further analysis on this topic or use other wave power matrices, the data used for this study is publicly available for their own studies.

2 Introduction

Offshore Renewable energy can be harnessed by a variety of technologies such as offshore wind, floating solar, wave and tidal. In the Netherlands, currently, the deployment of offshore wind energy is at the core of the energy transition and is set to be the dominant source of renewable power for the foreseeable future. However, with so much offshore wind energy from the Dutch North Sea, the variable supply profile brings significant challenges to an onshore electric grid and energy off-takers traditionally based on conventional power sources. Combining the generation, for example, between wind, solar and/ or wave, therefore, is theoretically interesting if the supply can be smoothened and increase the baseload generation to a more constant profile (i.e. when the resources are complimentary to each other).

Looking at the wind and wave complementarity, the generation profiles of wave energy differ from the generation profile of offshore wind. The combination of sources could provide a more constant combined generation profile, increasing the baseload production. There can also be a negative impact due to curtailment in periods where the combined production exceeds the nominal capacity of the grid connection.

In 2021, the RVO granted TNO an assignment to deliver a report on the analysis of the combination of offshore wind energy and floating solar energy. The assignment was created in collaboration with TKI Offshore Energy, and the final report was delivered in March 2022. The conclusion of that study was that the correlation between wind and solar power is negative annually; that is, when wind power increases, solar power decreases and vice versa. This effect can more closely approximate baseload generation.

This new assignment investigates the combination of wind and wave energy. Focussed on the wave energy potential and how the wave energy can contribute to producing a more constant power by combining with the wind energy.

The concise assignment consists of four activities following the Request For Quotation (RFQ):

- Activity 1: Choose one suitable location in the Netherlands EEZ of the North Sea for the determination of the generation profiles for wave energy in combination with neighbouring wind energy.
- Activity 2: Investigate which available wave data for the location is suitable and reliable with a sufficient degree of detail.
- Activity 3: Determine which methodology is suitable for identifying the wave energy potential using the chosen wave data.
- Activity 4: Describe the (combined) generation profiles for offshore wind and wave energy for the chosen location. The analysis should cover both wind and swell waves.

Choices have been made in close consultation with leading partners in the wave technology sector.

Chapter 2, the introduction, includes the context of the assignment. Chapter 3 presents the main assumptions and considerations. Activity 1 and 2 are described in Chapter 4, and the dataset analysis and complementarity of wind speed and wave are included in Chapter 5. Chapter 6 summarises the methodology applied to analyse the combination of the wind and wave power profiles. The results are presented in chapter 7. Chapter 8 shows the conclusions and recommendations of the assignment.

3 Critical Considerations

General considerations

This study focuses on the resource complementarity of wind and wave energy and how wave energy can produce a more constant power by combining it with wind energy. This is a technical exercise where the economic business case is not included.

There are many aspects not considered in this assignment, such as cost trends, spatial plus environmental requirements, infrastructure needs and the business case (by combining both sources). Therefore, it is not possible to draw any conclusions regarding the deployment of the combination of these two-generation technologies based solely on this study.

TNO did not have a preference in this study for the selection of specific wave energy technology to combine with wind farms. When calculating the conversion of the wave resource into power through a power matrix, consultation has been made with the Dutch wave energy developers, represented and coordinated through EWA.

The averaged power matrix has been built and reached consensus by Dutch WEC (wave energy converter) technology developers, including Slow Mill, Weco, WaveHexapod, Dutch Wave Power and KNSwing. Other Dutch WEC technology developers include Symphony Wave Power and Ocean Grazer, not being involved in the averaged power matrix.

TNO was provided with information from an averaged power matrix based on their technologies, internal data and measurements (see annexes for additional information). TNO has evaluated and applied the power matrix to convert the wave resource into wave power and calculate the combined power generation profile.

Activity 1 Considerations: Choose one suitable location in the Netherlands EEZ of the North Sea for the determination of the generation profiles for wave energy in combination with neighbouring wind energy.

- The study aims to establish the correlation where electricity is generated from both wind and wave energy in the same area. Therefore;
    - The location selected must be close to a wind farm.
    - The locations restricted for offshore wind are out of the scope.
    - It is, of course, possible to have wind and wave energy projects take place in separate areas and not combined, not being the goal of this study.
    - The location selected is considered to have favourable conditions to produce wave energy based on the wave resource potential over the Dutch North Sea, in consultation with the wave energy community and also considering their studies [1].
    - The location was unanimously agreed upon.

Activity 2 Considerations: Investigate which available wave data for the location is suitable and reliable with a sufficient degree of detail.

- TNO focuses on the available resources (wind and wave) and not on conversion technology for the purpose of the second activity. With the resource, swell and wind waves are taken into account in order to study the complementarity between the variability of the two sources.
- An overview of the data sources, quality and wave potential was shared with the Dutch wave energy developers. The overview includes model-based and measured sources. The selection, model-based, was considered and agreed upon as the most suitable and reliable wave data for the location selected, with a sufficient degree of detail. However, it should be noted that there is a distinct lack of accurate and high-resolution wind wave and swell wave in comparison with potential measured data at the location selection, being the most suitable choice.
- The correlation of the resources is focused on the height and period of different waves; it is not technology-specific. There are no assumptions made for the conversion to power.

Activity 3 Considerations: Determine which methodology is suitable for identifying the wave energy potential using the chosen wave data.

- The research focuses on the fluctuations and variability of both wind and waves; therefore, a time series analysis has been performed with the highest time frequency possible, being hourly based. The correlation of the two is the subject of study, not the total energy that can eventually be converted. Therefore, the analyses are done on normalised time series.
- The approach applied to convert wave resource potential into normalised wave power has been provided by various Dutch WEC (Wave Energy Converter) technology developers for use in this TNO study. The technology developers have provided statements with a short description of the technology and a short overview of the method of acquiring the underlying data, attached in the annexes.

  According to the Dutch WEC developers involved in building the power matrix, the use of the averaged WECs represents the state of the art of their Dutch WEC technology. The database and power matrix provided are built based both on model and real testing. It ranges from designed and modelled WECs and lab-tested WECs to sea-trailed WECs. The aim is to present the "best practice" WEC, which is also suitable for the location selected. Note also that there are other scientific methods proposed for the comparison of WECs and not all the WEC developers in the Netherlands have been involved in building the power matrix.
- The data provided by the wave developers represents an averaged power matrix. It can be seen as a virtual WEC but is not likely to be representative of the current state of technology. Each technology behaves differently for different sea wave states. Therefore, using one specific technology with its specific power matrix more suitable for a wave state could likely produce more power than using the given averaged power matrix. For example, looking at the sweet spot for wind/wave, where the wave can be more beneficial for wind. In this study, the average was used, but using a specific power matrix could perform better or worse for this project.

Activity 4: Describe the (combined) generation profiles for offshore wind energy and wave energy for the chosen location. The analysis should cover both wave and swell effects.

- The analysis of the combination of the wind and wave profile is focused on the combination of wind and wave generation to provide a more constant power with less variability, evaluating the potential increase of baseload for the wind and for peak shaving. The infrastructure required for the combination of both technologies is out of the scope. Therefore, indicators such as curtailment, export cable capacity or cable pooling are not included in the analysis.
- The analysis is based on an hourly time series, representing a climatic year and evaluating the cumulative wind wave power on the hourly variability. It is, therefore, not enough to look at annual cumulative power or to extract annual capacity factors based on hourly power duration curves.

This report must be published in its entirety, including the considerations for the study, and not split.

4 Location and dataset selected

4.1 Site selected

This activity shows the overview of potential locations for wave energy within the Dutch Exclusive Economic Zone (EEZ), followed by an explanation of the process for selecting the location used in the analysis.

In order to select a suitable location for the combined generation of wave energy with neighbouring wind energy, a list of locations and their potential, as found in the literature, was created. This is shown in Table 1, highlighting the location, its position in the Dutch EEZ and the nearest wind farm, as well as the average wave energy potential and literature source. Furthermore, the numbered locations and KNMI stations mentioned in this table are shown graphically in Figure 1.

Table 1: Overview of considered locations for analysis, with the closest wind farm, average wave potential and literature reference listed.

Location	**Position in Dutch EEZ**	**Closest wind farm**	**Wave potential [kW/m]**	**Source**
L9 platform (53.61384°, 4.96089°)	*North*	Gemini ~80 km	15.22	[2]
(51.95°, 3.00°), *point 3*	*South*	Borssele	8.92	[1]
(52.00°, 3.28°), *point 4*	*South*	Borssele	8.92	[1]
(53.61°, 4.96°), *point 7*	*North*	Gemini 81 km	16.07	[1]
Above 54° N, between 4°E and 6°E	*North*	Doordewind ~50 km	~15	[3]
KNMI stations - K13 (53.22°, 3.22°)	*North-West*	IJmuiden Ver	~10.5	Based on the map by [3]
KNMI stations – LEG (51.92°, 3.67°)	*South*	Borssele	~7	Based on the map by [3]
KNMI stations - EUROPLATFORM (52.0°, 3.27°)	*South*	Borssele	8.92	[1] – Point 4
Location for wave in an OWF - 54.25°, 5.55°	*North*	Doordewind	15.5	Based on the map by [3]

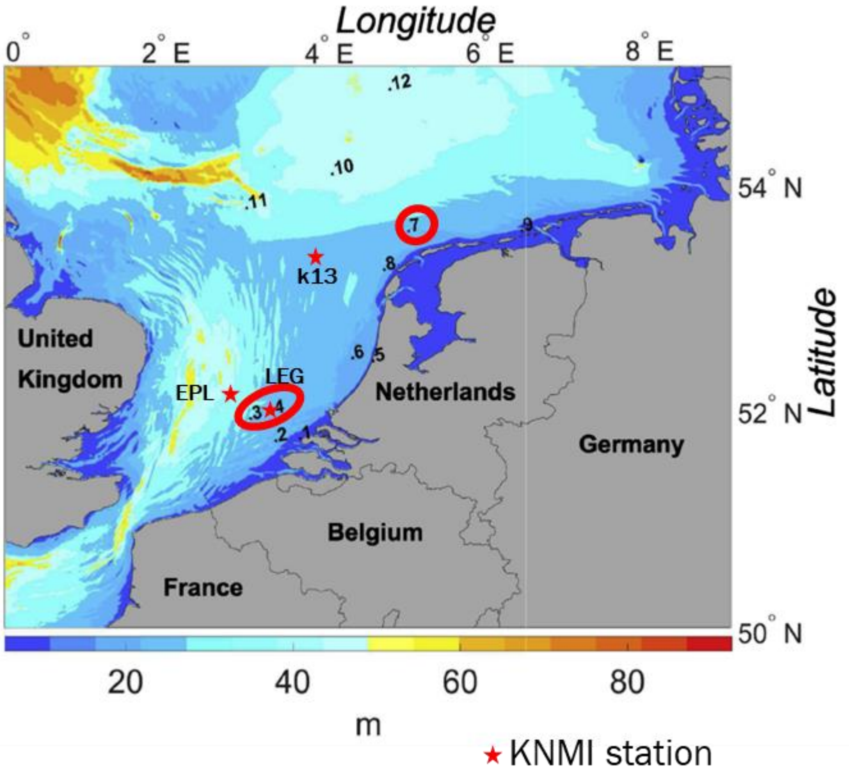


Figure 1: Overview of numbered locations and KNMI measurement stations mentioned in Table 1. Adapted from [1].

The selection of the location has been made on the overview and in consultation with the Dutch Wave Energy technology developers.

It was noted in [1] that "Higher resource magnitude is expected at upper parts of the North Sea", meaning the northern wind farms in the zone would be more suitable for combining offshore wind and wave energy generation.

The closest existing wind farm in this search area is Gemini, and the closest upcoming wind farm is Doordewind, as indicated in Figure 2.

Therefore, the location is selected, 54.25, 5.55, inside the Doordewind wind farm because of the highest wave potential (~15 kW/m) within all the considered offshore wind farms, assuming a favourable location for wave energy.

Figure 2: Location of the upcoming Doordewind offshore wind farm in the Dutch EEZ. Adapted from [9].

4.2 Data sources

This activity focuses on investigating publicly available, suitable, and reliable wave data for the location selected that has a sufficient degree of detail.

In order to evaluate the resource complementarity and generation profiles of wind and wave energy, robust data is needed, with high temporal and spatial resolution, covering a timespan of at least 20 years to cover climate variability. The dataset needs to be close to the location selected and have wind and wave variables suitable for the analysis of this study. With these preferences in mind, an overview of the available data was created, as presented in Table 2

Table 2: Overview of the considered data sources for the wind and wave resource, with the type of (wind and wave) data indicated, as well as the location, period spatial and temporal resolution, and availability.

Proposal	Database	Type	Wind data	Wave data	Location	Period	Spatial Resolution	Temporal resolution	Availability	Source
1	Danish Hydrological Institute (DHI)	Validated models: - Wave: MIKE 21 hydrodynamic model - Wind: CFSR corrected (NOAA & DHI)	Wind and direction modelled at 10 – 300m	Sign. Wave height, peak and mean wave period, direction and swell.	Longitude: 2.0°E – 6.2°E Latitude: 52°N – 54.7°N	1979-2019	~ 2km	1h	Public	TNO services
2 – possibility to consider, location not the best	KNMI (Dutch met-office)	Measurements	Wind speed and direction at met mast (~60 m height?)	Period (10 min average), Amplitude (10 min average)	- Platform K13 - Lichteiland Goeree - Europlatform	2016 – 2022	NA	10 min	Public	vanderZant et al. 2022
3 – model only, no database	Wave-data TUDelft	SWAN: third-generation wave model that estimates wave conditions in open oceans and coastal regions	No	wave period [s] and H is the wave height [m].	-	-	-	-	-	vanderZant et al. 2022
4 – would need to match to different source for wave	DOWA Dutch Offshore wind atlas	Validated models	Wind speed and direction at 10 – 600m	-	Longitude: 1.3°E – 8.2°E Latitude: 50.2°N – 54.7°N	2008 - 2017	2.5 km	1h	Public	TNO
5	North Sea Wave database (NSWD)	Validated model	No	-	-	-	-	-	-	Lavidas and Blok 2021

Another potential source of data is measured data from KNMI. This dataset contains both wind and wave measurements and has a very high temporal resolution (10 mins). However, this dataset is limited to measurement locations in the Dutch EEZ, all of which are on the west side of the area, not in the north. The dataset from DHI is publicly available and offers both wind and wave (modelled) data, covering a large timespan (1979-2019), with a fine spatial resolution (sub-2 km) and sufficient temporal resolution. On top of this, this dataset also covers the location chosen in Chapter 4. Therefore, it was decided to select the dataset from DHI for this analysis.

Table 3 presents the available parameters for both wind and wave data considered for the analysis. For the correlations, the wind speed data at 160 m hub height was considered, as it is the closest approximation to the envisioned hub heights of future offshore wind turbines [4]. The wave data selected were the mean significant heights and periods of the different types of waves; that is, the wind-sea spectrum, the swell wave spectrum and the combination of both, the full significant spectrum [5].

Table 3 Description of Data and Parameters for Wind and Wave Resource

Resource	Wind	Wave
Location	54.25 N, 5.55 E	
Data Period	01-01-2000 to 12-31-2019	
Reference	DHI – CFSR corrected	MIKE 21 Spectral Wave Model
Parameters	Wind Speed (120 m and 160 m height)	Sign. Wave Height (Hm0) [m], Peak Wave Direction, Peak Wave Period (Tp) [s], Mean Wave Period (T01) [s], Zero-crossing Wave Period (T02) [s], Mean Wave Direction (MWD), Directional Standard Deviation (DSD)
Heights (m)/Spectrum	The above parameters for heights from 10 to 300m	The above parameters for Full, Wind-Sea, and Swell Spectrum waves

4.3 Period

The complementarity of the wind and wave resources (Chapter 4) has been analysed for the period of 20 years available (2000-2019). The analysis of the combined power profiles (Chapter 7) has been carried out, selecting the most recent year available, 2019. It can be seen that the selected timespan contains several years with significant biases from the average wind and wave resources. As a follow-up of this study, it would be interesting to further analyse the impact of the negative and positive deviations of the weather on power production. This analysis is outside of the scope of this study and has been added as a recommendation for the wave energy community to start the study.

Table 4: Overview of the available years for analysis, the average wave and wind resource availability for these years, as well as the deviation from the overall average.

Year	Year #	Average Wave height [m]	Deviation from average	Average Wind speed [m/s]	Deviation from average
2000	1	1.74	6.0%	10.96	3.3%
2001	2	1.56	-4.7%	10.23	-3.5%
2002	3	1.56	-5.1%	10.57	-0.4%
2003	4	1.44	-12.5%	9.80	-7.6%
2004	5	1.67	1.5%	10.45	-1.6%
2005	6	1.71	4.2%	10.85	2.3%
2006	7	1.59	-3.3%	10.55	-0.6%
2007	8	1.78	8.7%	11.03	4.0%
2008	9	1.77	8.1%	11.23	5.9%
2009	10	1.52	-7.2%	10.43	-1.7%
2010	11	1.50	-8.5%	9.92	-6.5%
2011	12	1.72	4.6%	10.63	0.2%
2012	13	1.67	1.9%	10.62	0.1%
2013	14	1.64	0.2%	10.50	-1.1%
2014	15	1.61	-2.1%	10.64	0.3%
2015	16	1.75	6.9%	10.89	2.6%
2016	17	1.59	-2.9%	9.90	-6.7%
2017	18	1.73	5.3%	10.42	-1.8%
2018	19	1.61	-2.1%	10.33	-2.7%
2019	20	1.66	1.1%	10.57	-0.4%
Average	**-**	**1.64**		**10.61**	

5 Wind and wave resource complementarity

The complementarity between wind and wave is determined in this analysis by calculating the **correlation**, or degree of similarity/ independence, between wind and wave at the site selected. The correlation between them should be negative or closer to 0, which can indicate opposite trends over time and hence provide more stable potential over that same timeframe.

An additional metric calculated is the **delay** in occurrence or cross-correlation between wind and different types of waves. It reflects the level of correlation but the more likely durational offset between them. When there is a time delay between the wind speed and waves, it could translate into wind power peak shaving or flattening the variability of the wind in combination with the waves.

5.1 Approach and assumptions

Different statistical correlation methods exist, mainly the Pearson, Kendall and Spearman correlation coefficients, with the Pearson Correlation being the most robust and has been used in previous studies to measure the complementarity of wind and wave resource time series [2]. It is defined as the ratio between the covariance of the two time series, compared to the product of the standard deviations of each, as defined here below:

$$r(X,Y) = \frac{covariance(X,Y)}{stddev(X)*stddev(y)} \qquad (1)$$

In equation 1, X and Y are the wind and wave parameter time series of choice for comparison. Namely, this can be the wind speed at the hub height of a wind farm and the significant height of the wave time series. The latter can also be distinguished from wind-generated waves (wind-sea waves) and swell waves, which are both part of the wave spectrum that occur at different frequencies (significant waves)

The delay in occurrence or cross-correlation between the two resource time series reflects not only the level of correlation but the more likely durational offset between them. Winds generate local waves and could have higher correlations and shorter delays compared to swell waves, which are longer in cycles and occur from winds far from the location under consideration. As conducted by other studies investigating the relations between wind and wave resources [6] [7] [8], and is described here below as:

$$CC(t) = \frac{1}{N}\sum_{k=1}^{N-t}\frac{[(x(k)-u_x)*(y(k+t)-u_y)]}{\sigma_x*\sigma_y} \qquad (2)$$

Where u_x, u_y, and σ_x, σ_y, are the mean and standard deviations of the wind and wave time series, respectively. Note that the variable t is the imposed time lag that is applied to one of the signals, shifting it forward and assessing the correlation with such an applied offset.

5.2 Correlation analysis

Wind time series with an hourly resolution were compared considering different spectrums of the wave regime's significant heights and periods, namely distinguishing between waves driven by local winds (wind-sea) and swell waves. Equations (1) and (2) were implemented to understand the level of correlation and time lag between the data sets. Furthermore, joint frequency distributions were assessed to show the level of scatter and variability of the different data sets.

Firstly, the Pearson correlation coefficient was assessed between the wind speed at 160m above sea level and the different significant height data of the various wave spectra over the 20-year available period considering hourly timestamps. This is presented in Table 5 below.

It can be seen that the wind-sea waves are highly correlated with wind speed, while the swell spectrum is less correlated, with a correlation coefficient of 0.32. The full spectrum (significant waves) is closer to the wind-sea coefficient results and encompasses the combined effects of both spectra. Overall, it is shown that for this location, the correlation is positive, showing different ranges of complementarity.

Table 5 Pearson Correlation Coefficients between Wind and Different Wave Spectra Time-series

Parameters (20 years period)	**Pearson Correlation Coeff. - Hourly**
Wind speed (160 m) - Significant Wave H_0	0.84
Wind speed (160 m) - Wind-Sea Wave H_0	0.93
Wind speed (160 m) - Swell Wave H_0	0.32

Seasonal, diurnal, and yearly variations in the correlations between wind speed and significant wave height are computed and presented in Figure 3 to Figure 5 below. The hourly data was grouped either by month, hour, or year, respectively. The largest variation can be seen on the monthly (seasonal) cycle, ranging from under 0.2 in January to approximately 0.4 in July for swell waves, while wind-sea spectrum correlations are fairly constant throughout at above 0.9. Very little variation can be seen during the diurnal cycle for all three spectrums compared to the wind speed at 160m height. Similar to yearly correlations, the results show the variation from year to year, but they are in line with the overall values presented in Table 5 above.

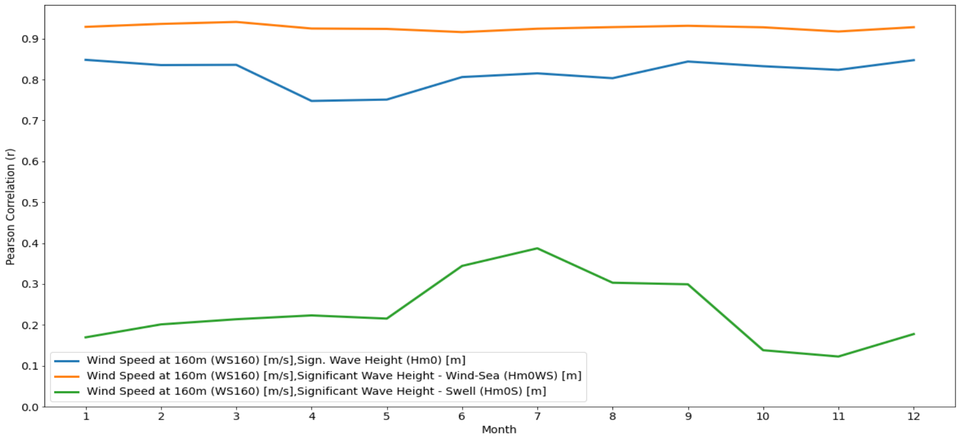


Figure 3 Monthly Variation of Pearson Coefficient between Wind and Wave Spectra

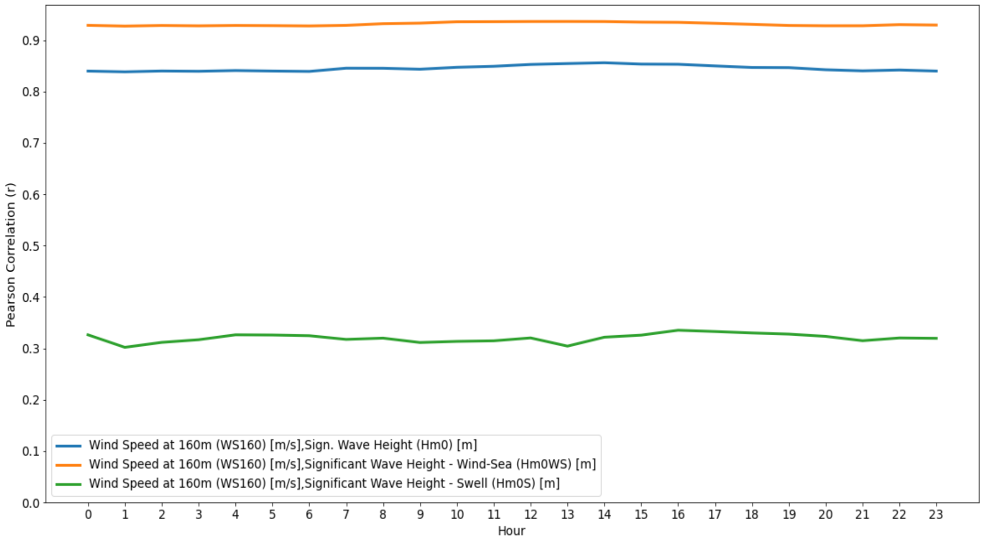


Figure 4 Hourly Variation of Pearson Coefficient Between Wind and Wave Spectra

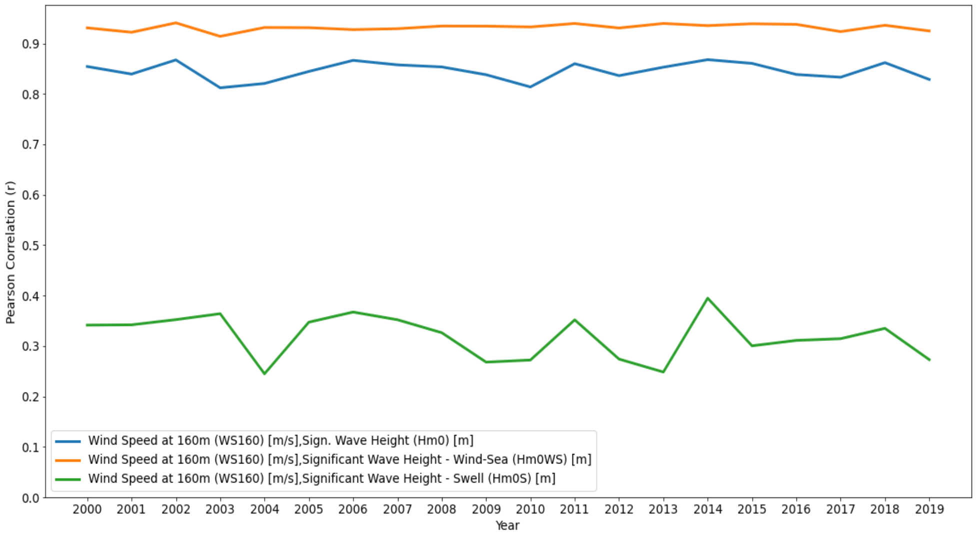


Figure 5 Yearly Variation of Pearson Coefficient Between Wind and Wave Spectra

The cross-correlation (time lag) between the two sources was also calculated and is presented in Figure 6. The smallest delay is observed for the wind-sea spectra, with the highest correlation occurring at a 1 hour delay, while the largest delay of 12 hours is observed for the swell spectra. Considering the full spectra, it results in a delay of approximately 3 hours. This would suggest that considering the swell wave data would result in a more consistent generation when the wind has blown through the region.

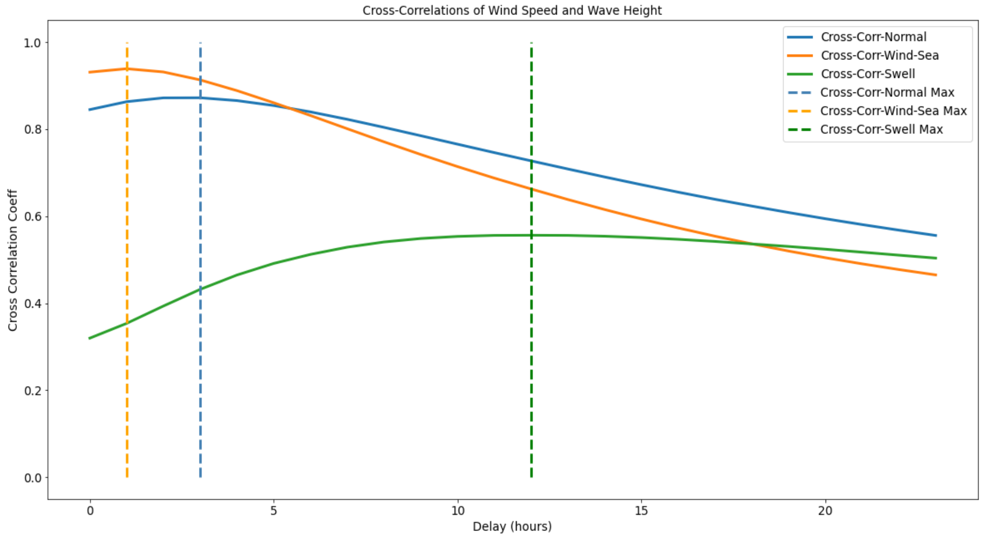


Figure 6 Average Delay between Wind and Various Wave Spectra. The Yellow vertical line indicates a 1 hour delay (wind sea waves), the blue line 3 hour delay (significant full spectrum) and the green line 12 hour delay (swell waves)

The temporal analysis is assessed on seasonal and yearly cycles. Figure 7 and Figure 8 show the maximum delay that was calculated when grouping the hourly data into common months and years. As regards annual variability, delays with swell waves decrease in the summer months down to 10 hours and achieve 13 hour delay in the winter months, whereas wind-sea delays are constantly at a 1 hour delay throughout the year. Over the years, the variation in delays vary more for swell waves, between 10 to over 16 hours, and are static for wind-sea spectrum waves.

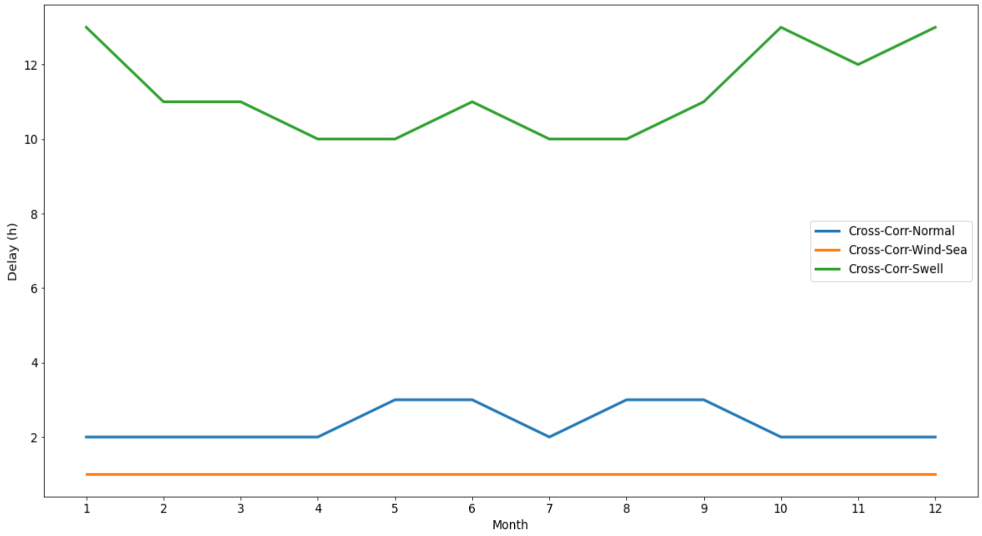


Figure 7 Seasonal Variation in Delay between Wind and Wave Spectra

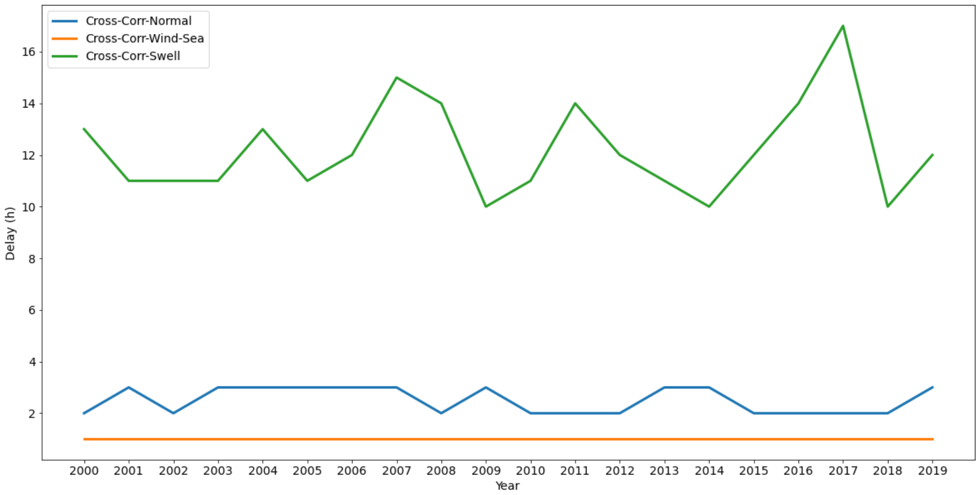


Figure 8 Yearly Variation in Delay between Wind and Wave Spectra

Figure 9 below shows an example of the wind and wave time series spanning the first 10 days of the year 2000. Notice how the wind speed occurs first in the timeline, followed closely by the wind-sea spectrum and then the swell spectrum. Observed peaks in the swell wave's significant height occur when the wind speed is reduced.

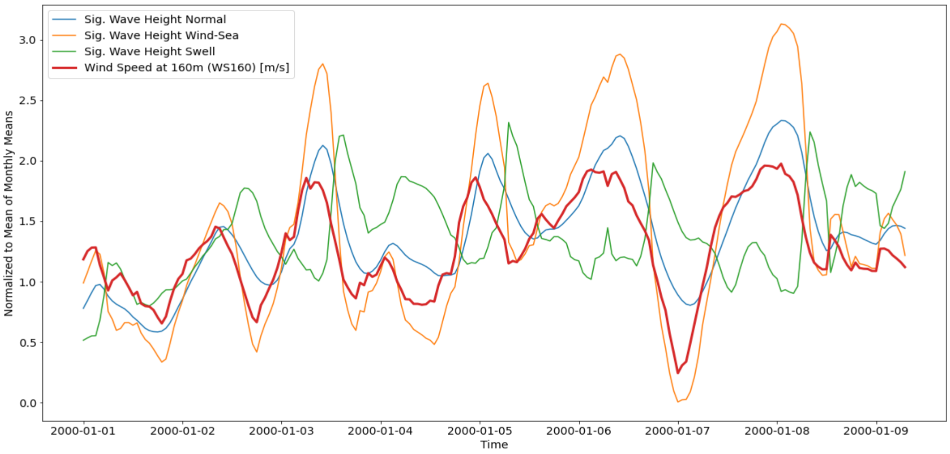


Figure 9 Wind and wave time-series spanning the first 10 days of the year 2000

The joint frequency distribution of wave period and significant height with wind speed are presented in Figure 10. These two-dimensional plots show the probability of two events occurring together (in this case, the wind speed with the wave period or wave height of the different spectra considered). The darker the colour in blue represents a larger density of points that occur for a certain wind speed and wave variable. It is also possible to observe the shape and scatter of such a combined distribution.

The wind speed was scaled down to 150 m hub height by considering the annualised shear exponent between 120 m and 160 m heights obtained from the data and was estimated to be an average of 0.074. This was done to best reflect speeds at the hub height of the wind turbine selected (see Chapter 7).

Between wind speed and swell wave spectra, the wave period is predominantly distributed between 2 and 10 seconds, occurring at lower wind speed regimes, with the same observation for significant height. Between wind and wind-sea wave spectra, there is less scatter and more linearity for both wave period and wave height. Looking exclusively at the resource potential, the longer periods and more scattered distribution of the waves with respect to the wind variability may reduce the combined generation by smoothening the wind peaks and off-peaks

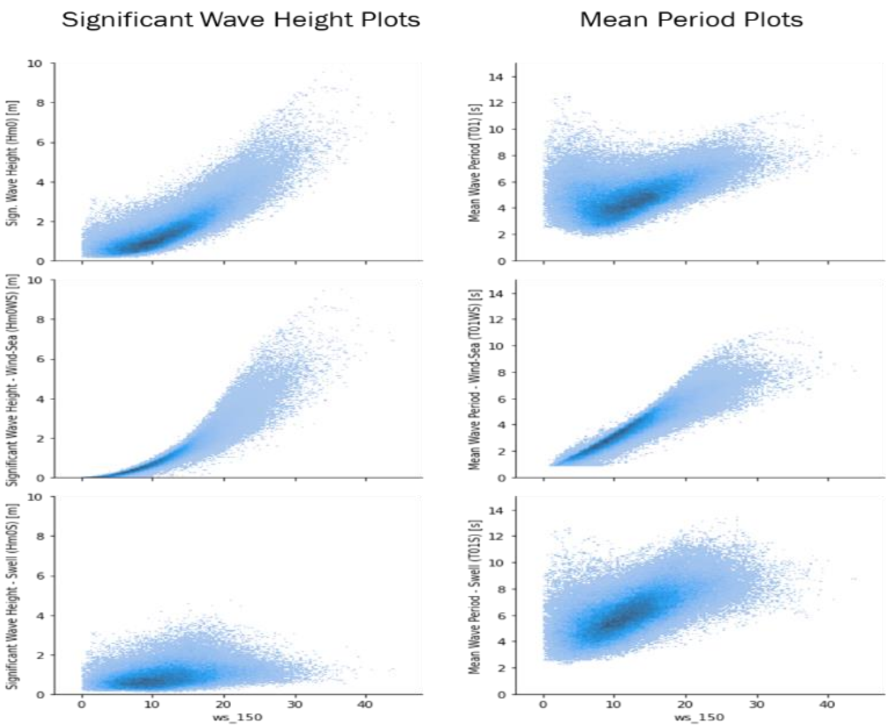


Figure 10 Joint Frequency Distribution of Wave Spectra Height, Period with Wind Speed at 150 m hub height

5.3 Key takeaways

An assessment of the wind and wave complementarity was conducted for a specific location in the North Sea with the following key messages:

- The Wind-Sea spectrum is heavily correlated to the wind speed, while the swell spectrum is less correlated. A high positive correlation is less desirable for baseload behaviour and may lead to curtailment/ exceeding current export cable capacity.
- The normal (full) spectrum is closer to the Wind-Sea coefficient results, encompassing the combined effects of both spectra. Overall, it is shown that for this location, the correlation is positive.
- Cross correlations between wind and wave time series result in the shortest delay of 1 hour for the wind-sea type of waves, while the largest delay of 12 hours is observed for the swell waves. The full spectra, that is, the significant waves, reach their maximum correlation at approximately 3 hour delay.
- The swell waves are characterised by longer periods and larger time lag with respect to the wind speed, as shown in the lower correlation and cross-correlation

with the wind. In areas of the sea where the swell waves are long due to long fetch winds, the power produced by the swell waves would contain more energy and, thus, more power. It should be noted that due to the shallow water depths in the Dutch North Sea, the swell waves are not as powerful as other areas in the North Sea.

- This would suggest that the swell waves would result in more constant generation when the wind has already blown through the region.

6 Approach for determining the wave energy potential

To translate the wave resource data to the available wave energy, a conversion step was needed that related wave heights and periods to the available power through a 3D power matrix.

The power matrix used to create these power time series was built by partners of the wave energy sector, including KNSwing, Slow Mill, Weco, WaveHexapod and Dutch Wave Power (see annexe 10 for the description of each technology and information received for this assignment).

The use of the averaged WECs represents the state of the art of Dutch WEC technology. It ranges from designed and modelled WECs, lab-tested WECs to sea trialled WECs. The aim is to present the 'best practice' WEC, which is also suitable for this location. Note also that there are other scientific methods proposed for the comparison of WECs. The aim is to present the 'best practice' WEC, which is also suitable for this location. Note also that there are other scientific methods proposed for comparison of WECs.

The power matrix relates the wave height (Hm0) and wave period (T02/Tp/Te) to the produced (normalised) power of the WEC(s). Thereby, a normalised power time series can be created to be used in the analysis described in Chapter 7. This power time series was created for the different waves: wind-sea waves, swell waves and the full spectra, the significant waves.

7 Combined generation profiles for offshore wind and wave energy

7.1 Approach and assumptions

In addition to the wave power time series generated, a normalised power time series for the wind energy generation was created in order to be able to analyse the combined generation profiles.

This wind power time series was created by using:

1. The wind speed at 120m and 160 m height at the location selected (close to Doordewind) to interpolate using the power law profile to the 150m, representing the hub height of the turbine selected and,
2. The power curve of a 15 MW NREL reference turbine to convert the available wind into the available power (Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine (nrel.gov)). The 15 MW wind turbine was selected as representative for 2030 and beyond, for the wind farms will be built in the newly designated areas. The 15 MW is chosen as currently these prototypes are under development. Although 18 MW will be the turbine expected to be more realistic for the time frame beyond 2030, there is no impact on this study of an assumption between the 15 MW and 18 MW.

The time series created in this manner was then normalised to the rated power of the turbine (15 MW) to end up with a normalised power time series, with a value between 0 and 1 for each hour of the year.

With a normalised power time series now available for both the wind and wave generation, it is possible to compare both time series. Then, different scenarios were considered for the combined generation profiles:

- 15 MW wind turbine standalone (Reference)
- 15 MW wind + 1 MW wave energy generation
- 15 MW wind + 5 MW wave energy generation
- 15 MW wind + 10 MW wave energy generation
- 15 MW wind + 15 MW wave energy generation

For each scenario, a separate power time series was created by multiplying the normalised time series by the installed capacities of the respective technologies for the three wave types – Significant, Wind-Sea and Swell. All the types of waves were considered separately for the 4 combined scenarios, yielding a total of 12 cases next to the reference case.

The analysis focuses on the aggregated generation of the combined technologies, as well as the increase in full-load hours, better approximation of constant (baseload) generation, and the overall capacity factor. This analysis is presented by means of a combined generation duration curve, which uses sorted production values – from smallest to largest – to indicate how often a certain level of production can be expected throughout the year.

It should be noted that in this analysis, only the gross power generation is considered. Wake effects losses from power conversion equipment or cabling are not included.

7.2 Analysis of the results

First, an analysis of the combined generation duration curves and an overview of relevant statistics for the combined generation are presented in Section 7.2.1. Next, a detailed view of the combined power time series is discussed in Section 7.2.2.

7.2.1 Combined generation duration curves – Wind & wave generation

The generation duration curve for the significant wave scenarios and reference case is presented in Figure 11. Figures 12 and 13 show the same duration curves for the different types of waves, the wind-sea and swell waves, respectively. Both the generation duration curves (figures) and these statistics (Table 6) highlight the contribution of (primarily) the swell waves to the increase in constant generation and related full-load hours compared to the wind-sea waves.

It can be seen that the combined generation profile shows an increase in aggregated generation for all hours of the year, both above and below the rated power of the reference wind turbine (shown in the circle, in the 5000h). The increase in baseload generation (left side, <5000h) is approximately 12% and 3% when adding 15MW and 1 MW, respectively, of wave capacity to the 15 MW of wind.

The increase of the total aggregated generation is 143 GWh in the 15 MW wave case, from 89 GWh in the wind-only case. In addition, it can be observed that the combination of the two technologies in a 15 + 15 MW configuration yields a 77% approximation of constant 15 MW production for the significant wave, which is an increase of 13% over the reference wind-only case. In this scenario, the combined capacity factor of the system is 54%. This means the combination of the two technologies can reach higher peak power, with maximum power generation for both technologies occurring for approximately 1000 hours per year. In addition, this profile means that below the rated power of the reference case, the combination can provide more constant power with less variability.

The 87% of the power combined is at the right side of the figure (>5000h) when the wind power is at rated power. That means that having a larger export cable, it would be possible to harness more power from both technologies, not smoothening the wind power profile, though.

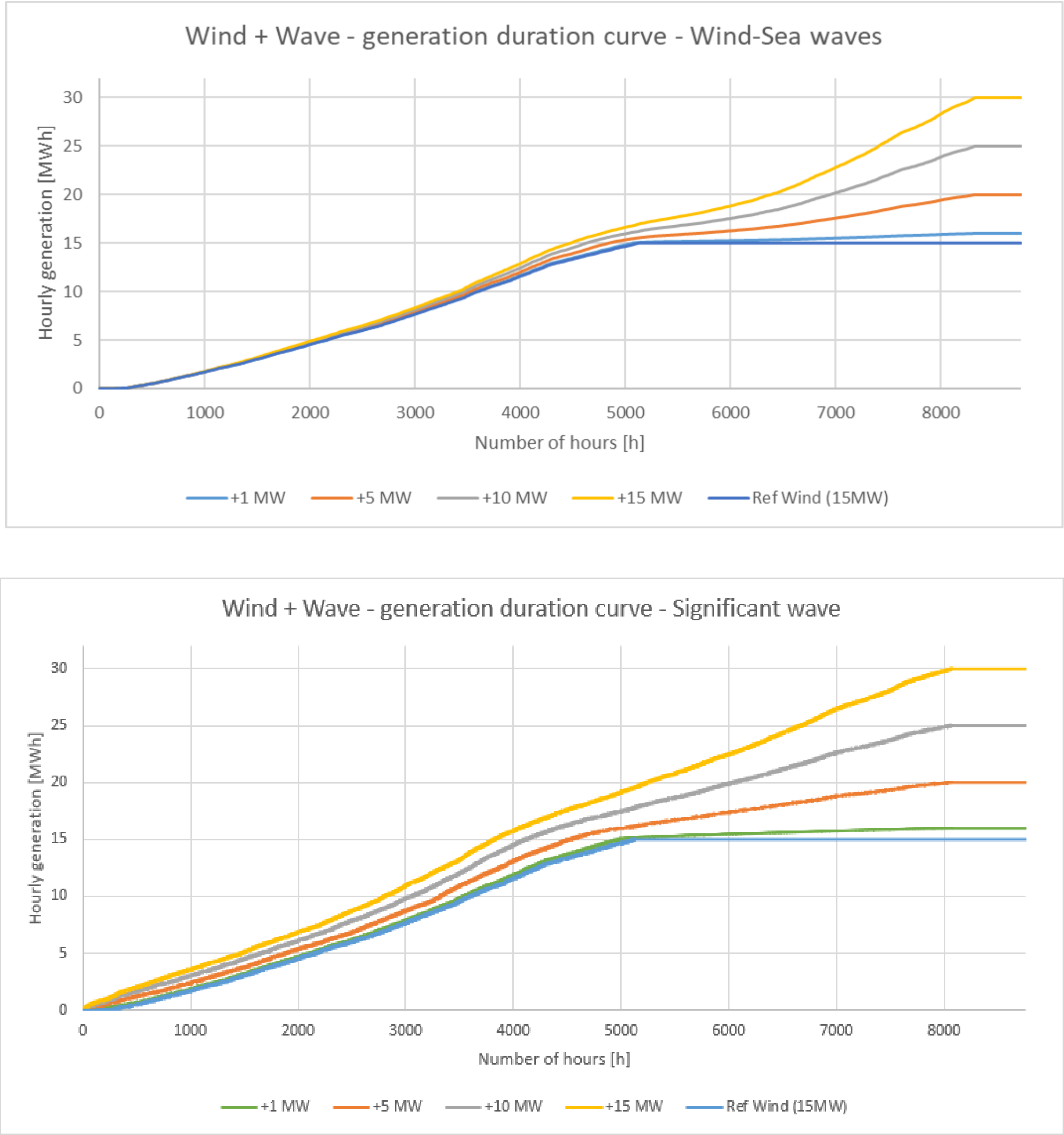


Figure 11: Generation duration curve for the combined generation of different installed capacities of wave energy and wind energy, focusing on the significant waves.

In order to get a clearer understanding of where these two effects stem from, similar generation duration curves are included separately for the wind-sea and swell waves. See

Figure 12 and
Figure 13, respectively.

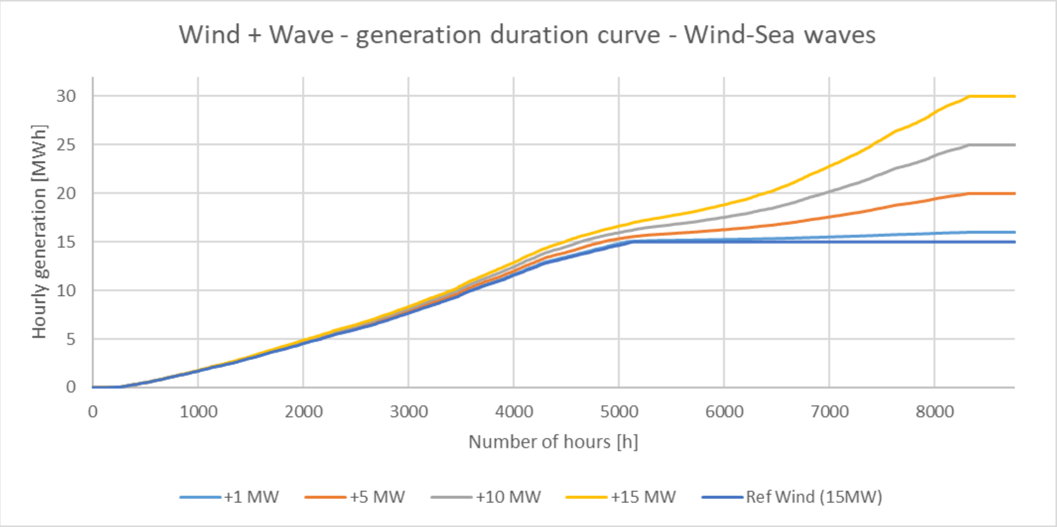


Figure 12: Generation duration curve for the combined generation of different installed capacities of wave energy and wind energy, focusing on the wind-sea waves.

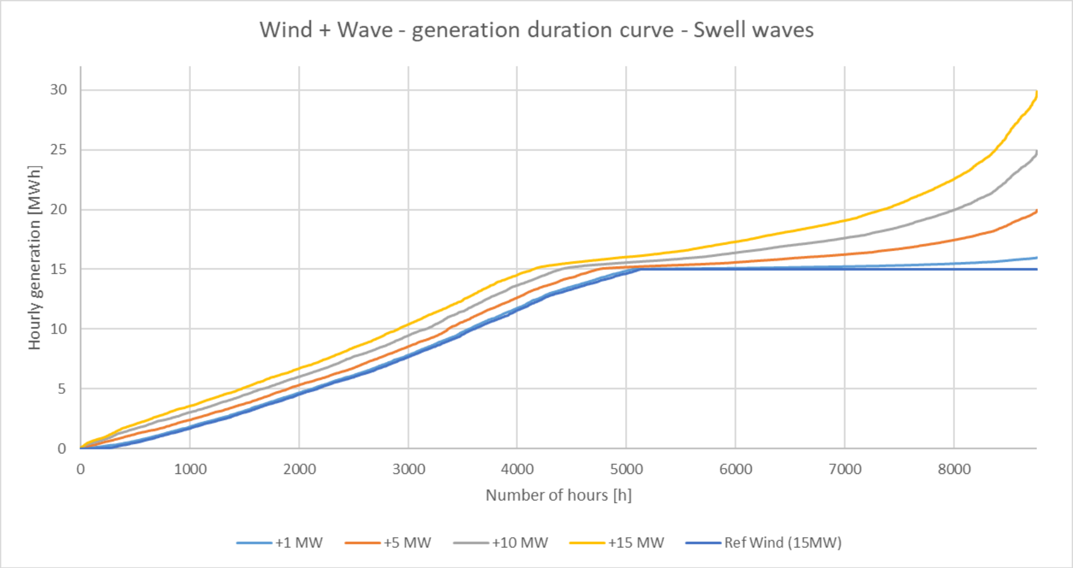


Figure 13: Generation duration curve for the combined generation of different installed capacities of wave energy and wind energy, focusing on the swell waves.

These duration curves show how the effect of the wind-sea waves is primarily in the increase of peak generation of the combined plant, whereas the main effect of the swell waves is in the hours below rated power of the reference wind turbine, with maximum combined power production only occurring in a handful of hours of the year there.
Some key statistics on the combination of wave and wind energy generation are presented in Table 6a.

Table 6a: Overview of key statistics for the 4 sensitivities (adding +1 1, 5, 10, 15 MW) and reference case (15 MW wind turbine) for each of the considered wave types (significant, swell and wind sea waves).

Installed capacity wave energy added to 15 MW wind turbine	**+1 MW**	**+5 MW**	**+10 MW**	**+15 MW**	**Reference - 15 MW wind only**
Total aggregated generation **[GWh]** ***Wind energy + Significant waves***	93	107	125	143	89
Aggregated generation [GWh] ***Wind energy + Wind-Sea only***	91	100	111	122	89
Aggregated generation [GWh] ***Wind energy + Swell only***	91	99	108	118	89

Table 6b shows how much wave power (in hours and %) is added as baseload to the power generated by the 15 MW wind turbine. The reference wind power baseload is estimated as 5929 hours, corresponding to 68% of the total production.

Table 7b: Wave power added as baseload (adding + 1, 5, 10, 15 MW) to the reference case (15 MW wind turbine) for each of the considered wave types (significant, swell and wind-sea waves).

Wave power added as baseload to the reference 15 MW constant production	**+1 MW**	**+5 MW**	**+10 MW**	**+15 MW**
Full-load hours increase - *Significant wave* [h]	+72	+320	+569	+772
Full-load hours increase - *Wind-Sea only* [h]	+18	+80	+143	+197
Full-load hours increase - *Swell only* [h]	+59	+272	+502	+699
Baseload - *Wind energy + Significant waves* [%]	68.5%	71.3%	74.2%	76.5%
Baseload - *Wind energy + Wind-Sea only* [%]	68.0%	68.6%	69.3%	69.9%
Baseload - *Wind energy + Swell only* [%]	68.4%	70.8%	73.4%	75.7%
Increase toward baseload production [%] - *Significant waves*	1%	5%	10%	13%
Increase toward baseload production [%] - *Wind-Sea waves only*	0.3%	1.4%	2.4%	3.3%
Increase toward baseload production [%] - *Swell waves only*	1%	4.6%	8.5%	11.8%

The capacity factor of the wave energy, extracted directly from the power curve, is 41%, while the wind energy selected is estimated at 68%. The capacity factor is a result of the study and not an input. The values of capacity factor come out higher than you are used to seeing for an offshore wind farm (~40 to 55%) because it is for a single wind turbine and no wake effects (~12%), cable losses, electrical conversion losses (~1.5%), nor O&M downtime (~4%) is included in the study. Nor for the wind, nor for the wave, energy losses have been considered. Table 6c indicates the combined capacity factors when the wind is combined with different installed capacities of wave energy.

Table 8c: Combined capacity factors, adding + 1, 5, 10, 15 MW of wave energy generation to the reference case (15 MW wind turbine)

Combined capacity factors 15 MW wind turbine with added wave energy	**+1 MW**	**+5 MW**	**+10 MW**	**+15 MW**	**Reference - 15 MW wind only**
Combined CF (Gross) [%] – Significant wave	66%	61%	57%	54%	68%

7.2.2 Detailed view of combined time series for selected days

In order to better understand the potential smoothening effects of the combined wind-wave profile compared to a wind-only case, the full-time series created for 2019 was inspected. This analysis focused on discovering instances of smoothening, such as peak shaving or valley filling. In total, 5-10 times, with a duration between 1-3 hours, were found displaying such effects throughout 2019, one of which is shown in Figure 14.

This detailed view shows the potential of the wave generation profile to mitigate a drop in wind production by filling the valley created by the reduction in wind power. Such an effect could support in better approximating constant (baseload) generation. In addition, this additional generation could be occurring at a valuable moment in terms of market prices if it is not coinciding with either wind or solar production. This effect needs further investigation and is included as a recommendation for further study.

It should be noted that this smoothening effect is primarily caused by the swell waves, while the wind-sea waves are less present due to their high correlation with the wind speed.

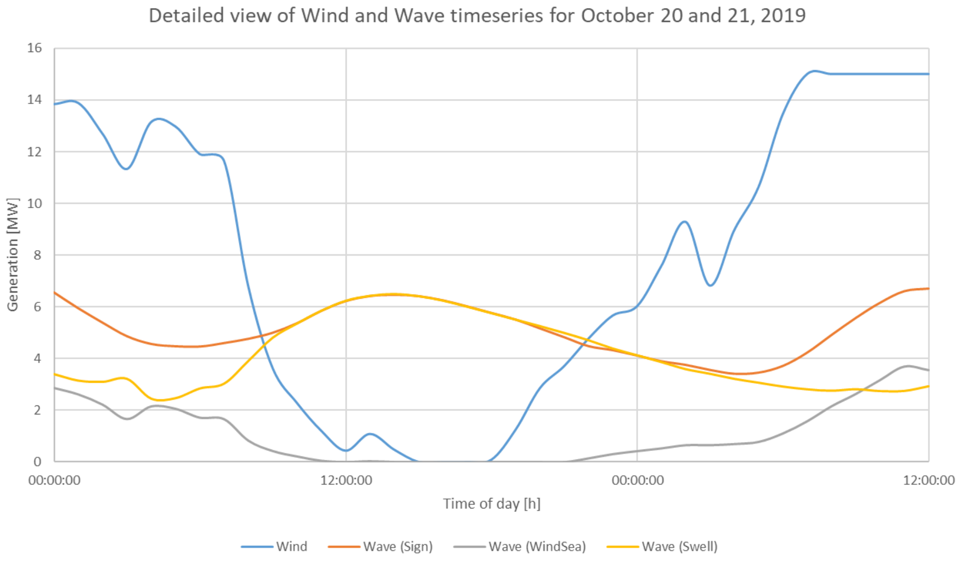


Figure 14: Detailed snapshot of the combined time series of the wind and wave generation profiles for the 20th and 21st of October 2019, with the three wave types included - 15 MW wind + 15 MW wave case.

7.3 Key takeaways

- The combined generation profile of wind and wave generation shows an increase in aggregated generation for all hours of the year, both above and below the rated power of the reference wind turbine.
- Maximum power generation for both technologies occurs for approximately 1000 hours per year and is mainly caused by the wind-sea waves.
- Below the rated power of the reference wind turbine, the combination of wind with wave can provide more constant power with less variability. This effect is mainly caused by the swell waves.
- The total aggregated annual generation of the combined technologies increases to 143 GWh in the 15 MW wave case from 89 GWh in the wind-only case.

- Combining the two technologies in a 15 + 15 MW configuration yields a 77% approximation of constant output of 15 MW production for the significant wave, an increase of 13% over the reference case wind alone. This equates to an additional 12 GWh of generation below a combined production of 15 MW.
- A smoothening effect on the combined generation profile, primarily caused by swell waves, can be observed 5-10 times through the year chosen for the analysis (2019) for a period of 1-3 hours.

8 Conclusions

This study focuses on the resource complementarity for wind and wave energy and how the wave energy resource can contribute to producing a more constant power by combining it with the wind energy resource.

The location selected for the analysis is located inside the Doordewind wind farm, an upcoming wind farm with high wave potential (~15 kW/m). The dataset used for this analysis comes from the Danish Hydrological Institute (DHI), which is publicly available and offers both wind and wave (modelled) data, covering a large timespan (1979-2019), with a fine spatial resolution (sub-2 km) and sufficient temporal resolution.

- **Complementarity of wind and wave resource**:
  - The wind-sea waves are highly correlated with the wind speed and have an average time delay of 1 hour with respect to the wind speed variability. The 1-hour delay provides a small level of complementarity.
  - The swell waves are less correlated and have a delay of 12 hours with the wind speed. Thus, swell waves are more complimentary than wind-sea waves.
  - The full spectrum of the waves, the time lag is approximately 3 hours. Combination of wave and wind resources could then theoretically result in a more constant generation profile due to the delay of the waves with the wind.
- **Combination of wind and wave power profiles**, assuming a 15 MW wind turbine with wave energy, ranging from 1 MW to 15 MW installed capacity, and based on the power matrix provided by the wave community:
  - The total combined annual generation increases by 4.5% (93 GWh) with 1 MW of wave with 15 MW of wind and by 60.7% (143 GWh) with 15 MW wave installed capacity and 15 MW wave, compared to 89 GWh when the wind turbine is standalone. These results/ data are without export cable curtailment.
  - There is an increase to a more constant generation profile and baseload generation combining both technologies. Comparing to 15 MW of constant total generation, combining 15MW wind turbine with different wave capacities, from 1 MW to 15 MW, the increase to a more constant profile ranges from 1% to 13%, respectively.

Applicability of the results

This study has provided insight into the level of complementarity of the two resources, wind and wave, at the Doordewind location in the Dutch North Sea. Conclusions can, therefore, only be made on this: the resource complementarity at this one location. Even then, it needs to be remembered that the data, even though of the highest quality available, is still only modelled and not site-specific measured data.

In order to draw conclusions related to the real-world deployment of wave technology in combination with wind farms, multiple other factors need to be taken into account, including different sites and differing wave characteristics potential, WEC technology readiness levels, LCOE (levelized cost of energy), spatial and layout requirements within an offshore wind farm (that may limit the energy density), and of course the overall business case.

This study looked at combining wave energy generation with wind energy generation. Of course, this is not the only scenario, and potentially, wave farms could be built in areas not intended for offshore wind farms and have their own dedicated export cable. Smoothening potentially, therefore, being achieved at the grid level and not at the farm level.

Additionally, from a wider view, offshore renewable energy covers several energy sources and various technologies, such as wind, wave and floating solar, which are at different stages of development. These come with their own set of challenges and opportunities. The continued development of infrastructure, regulatory frameworks, market design and research and innovation are necessary to provide a long-term perspective for offshore renewable energy and facilitate the required investment.

Further, storage and conversion options in combination with wind farms for a more constant profile, such as the role of the batteries connected to the wind farm and the conversion for green hydrogen, are topics that should also be considered when evaluating the full spectrum of options for smoothening the wind energy generation profiles.

9 References

[1] G. Lavidas, "Selection index for Wave Energy Deployments (SIWED): A near deterministic index for wave energy converters," *Energy 196,* 2020.

[2] H. F. v. d. Zant, A.-C. Pillet, A. Schaap, S. J. Stark, T. A. d. Weijer and B. A. Lehner, "Modeling the combination of wave-, wind- and solar energy in offshore multi-source parks," 2022.

[3] G. Lavidas and K. Blok, "Shifting wave energy perceptions: The case for wave energy converter (WEC) feasibility at milder resources," *Renewable Energy,* vol. 170, pp. 1143-1155, 2021.

[4] E. Gaertner, J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. Barter, N. Abbas, F. Meng, P. Bortolotti, W. Skrzypinski, G. Scott, R. Feil, H. Bredmose, K. Dykes and M. Shields, "Definition of the IEA 15-Megawatt Offshore Reference Wind," National Renewable Energy Laboratory, Golden, CO, 2020.

[5] DHI, "Mike 21 Spectral Wave Model, Scientific Documentation," DHI, 2023.

[6] F. Fusco, G. Nolan and J. V. Ringwood, "Variability reduction through optimal combination of wind/wave resources – An Irish case study," *Energy, Volume 35, Issue 1, https://doi.org/10.1016/j.energy.2009.09.023.,* pp. 314-325, 2010.

[7] J. F. Chozas, J. P. Kofoed and H. C. Sørensen, "Redictability and Variability of Wave and Wind: wave and wind forecasting and diversified energy systems in the Danish North Sea," *DCE Technical Reports No. 156,* 2013.

[8] L. Rusu, "The wave and wind power potential in the western Black Sea," *Renewable Energy, Volume 139, https://doi.org/10.1016/j.renene.2019.03.017.,* pp. 1146-1158, 2019.

[9] Rijksoverheid, “Waar staan en komen de windparken op zee?,” 2023. [Online]. Available: https://windopzee.nl/onderwerpen/wind-zee/waar/.

10 Annexes

10.1 Wind power matrix - IEA_15MW_240_RWT

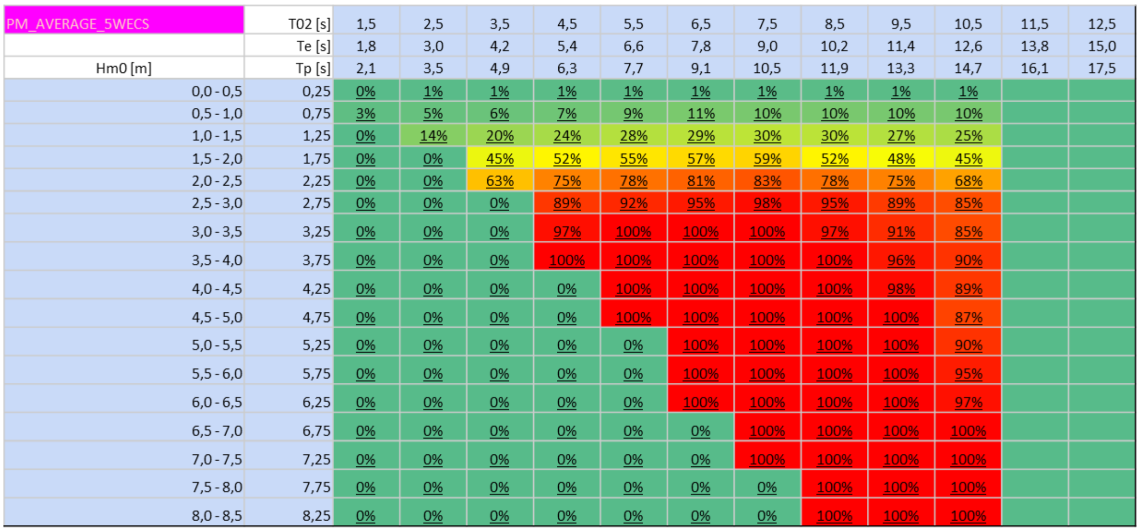
Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine (nrel.gov)
turbine-models/IEA_15MW_240_RWT.csv at master · NREL/turbine-models · GitHub

Wind Speed [m/s]	**Power [kW]**	**Cp [-]**	**Thrust [kN]**	**Ct [-]**
2.999.999.831	70.021.377	0.100335552	593.964.861	0.819748943
3.499.999.916	3.019.937	0.272197208	659.768.436	0.801112031
4	595.088.475	0.359305118	744.019.844	0.808268424
4.500.000.084	964.887.394	0.409156685	844.283.886	0.821910918
4.750.000.126	1.185.081.978	0.42729002	896.218.567	0.822876237
5.000.000.169	1.429.216.889	0.441819614	95.066.647	0.823265981
5.249.999.874	1.695.245.223	0.452708049	1.013.407.273	0.830989358
5.999.999.663	2.656.263.808	0.475270298	1.206.649.681	0.834932456
6.199.999.966	2.957.216.831	0.479478644	1.260.317.718	0.833618598
640.000.027	3.275.743.373	0.482871263	1.315.060.648	0.83180478
6.499.999.747	3.442.669.566	0.484447627	1.340.858.086	0.829011103
655.000.016	3.528.654.678	0.485186337	135.303.462	0.826909201
6.599.999.899	3.614.989.064	0.485905846	1.365.170.435	0.824740997
6.700.000.051	3.791.164.267	0.487114154	1.389.573.781	0.820429675
6.800.000.202	3.971.967.845	0.488094793	1.414.180.748	0.816176257
6.900.000.354	415.558.904	0.488866488	1.437.989.395	0.811200233
6.919.999.845	4.192.387.051	0.488988058	1.442.160.463	0.809740903
6.929.999.928	4.210.773.549	0.489050152	1.443.944.251	0.808780765
694.000.001	4.228.841.377	0.489088858	1.446.095.476	0.808102306
6.950.000.093	4.247.186.435	0.489114531	1.448.433.817	0.807566626
6.960.000.175	4.265.458.105	0.489127764	1.451.063.716	0.807251977
6.969.999.584	4.283.898.392	0.48915576	1.453.280.931	0.80662442
6.980.000.341	4.301.948.494	0.489165047	1.456.152.592	0.806495512

6.989.999.749	4.320.289.911	0.489154466	1.459.581.324	0.806806173
6.999.999.831	4.339.296.326	0.489163867	1.462.408.574	0.806651158
7.499.999.916	533.882.324	0.489224161	1.618.598.616	0.805469658
8	6.481.116.995	0.489263048	1.785.688.325	0.804571567
8.500.000.084	7.774.570.984	0.48928802	1.963.797.766	0.803949121
9.000.000.169	9.229.227.024	0.489293116	215.376.621	0.803904895
9.500.000.253	1.085.504.374	0.489304304	2.354.153.957	0.803708734
1.000.000.034	1.266.125.448	0.489319143	2.565.156.695	0.80345211
102.499.997	13.638.148	0.48938292	2.670.036.159	0.801706154
1.049.999.975	1.466.065.727	0.489378059	2.782.638.159	0.801777393
1.060.000.057	1.499.484.635	0.486507177	2.727.830.431	0.768657554
1.070.000.005	1.499.464.979	0.472991558	2.582.325.993	0.70731525
1.072.000.022	1.499.461.195	0.470349316	256.316.707	0.698507743
1.073.999.971	1.499.455.374	0.467724941	2.545.414.142	0.690211963
1.076.000.055	1.499.452.082	0.465119143	2.528.795.404	0.682335591
1.078.000.004	1.499.455.424	0.462537044	2.513.190.807	0.674835939
1.078.400.034	1.499.452.965	0.462021882	2.510.161.326	0.673371183
1.078.600.049	1.499.453.211	0.461765284	2.508.666.998	0.672646111
1.078.699.989	1.499.453.141	0.461636557	2.507.917.813	0.672283185
1.078.799.997	1.499.451.543	0.46150846	250.717.275	0.671921569
1.078.899.937	1.499.452.466	0.461380941	250.643.983	0.671564033
1.078.950.042	1.499.459.142	0.461317766	2.506.078.932	0.671386994
108.000.002	1.499.453.984	0.459972382	2.498.382.011	0.667639697
1.089.999.968	149.944.265	0.447424184	243.369.366	0.635292304
1.099.999.983	1.499.426.629	0.435324299	2.379.709.865	0.607277698
1.124.999.987	1.499.402.192	0.406934831	2.271.612.586	0.548965866
1.150.000.059	1.499.410.762	0.380965216	2.185.962.064	0.501379105
1.175.000.063	1.499.417.514	0.357157168	2.114.041.428	0.460982977
1.199.999.933	1.499.417.331	0.335295525	2.051.783.979	0.425965654
1.299.999.949	1.499.476.256	0.263718683	1.861.059.797	0.32116631

1.399.999.966	1.499.476.121	0.211136579	1.724.382.126	0.2511023
1.499.999.983	1.499.475.771	0.171651956	1.619.130.709	0.201415182
1.750.000.025	1.499.482.665	0.108080744	1.434.534.952	0.125653944
2.000.000.067	1.499.482.754	0.072394937	1.314.275.979	0.08506697
2.249.999.975	1.499.627.008	0.050842443	122.973.494	0.061026446
2.499.999.882	1.499.762.687	0.037062292	1.168.739.896	0.045814967

10.2 Wave power matrix information



PM_AVERAGE_5WECS	T02 [s]	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5
	Te [s]	1,8	3,0	4,2	5,4	6,6	7,8	9,0	10,2	11,4	12,6	13,8	15,0
Hm0 [m]	Tp [s]	2,1	3,5	4,9	6,3	7,7	9,1	10,5	11,9	13,3	14,7	16,1	17,5
0,0 - 0,5	0,25	0%	1%	1%	1%	1%	1%	1%	1%	1%	1%		
0,5 - 1,0	0,75	3%	5%	6%	7%	9%	11%	10%	10%	10%	10%		
1,0 - 1,5	1,25	0%	14%	20%	24%	28%	29%	30%	30%	27%	25%		
1,5 - 2,0	1,75	0%	0%	45%	52%	55%	57%	59%	52%	48%	45%		
2,0 - 2,5	2,25	0%	0%	63%	75%	78%	81%	83%	78%	75%	68%		
2,5 - 3,0	2,75	0%	0%	0%	89%	92%	95%	98%	95%	89%	85%		
3,0 - 3,5	3,25	0%	0%	0%	97%	100%	100%	100%	97%	91%	85%		
3,5 - 4,0	3,75	0%	0%	0%	100%	100%	100%	100%	100%	96%	90%		
4,0 - 4,5	4,25	0%	0%	0%	0%	100%	100%	100%	100%	98%	89%		
4,5 - 5,0	4,75	0%	0%	0%	0%	100%	100%	100%	100%	100%	87%		
5,0 - 5,5	5,25	0%	0%	0%	0%	0%	100%	100%	100%	100%	90%		
5,5 - 6,0	5,75	0%	0%	0%	0%	0%	100%	100%	100%	100%	95%		
6,0 - 6,5	6,25	0%	0%	0%	0%	0%	100%	100%	100%	100%	97%		
6,5 - 7,0	6,75	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%		
7,0 - 7,5	7,25	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%		
7,5 - 8,0	7,75	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%		
8,0 - 8,5	8,25	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%		

10.3 Wave technology statements

10.3.1 KNSwing, summary and status 2023

Memo in response to the TNO discussion 17-03-2023, Development v Kim Nielsen

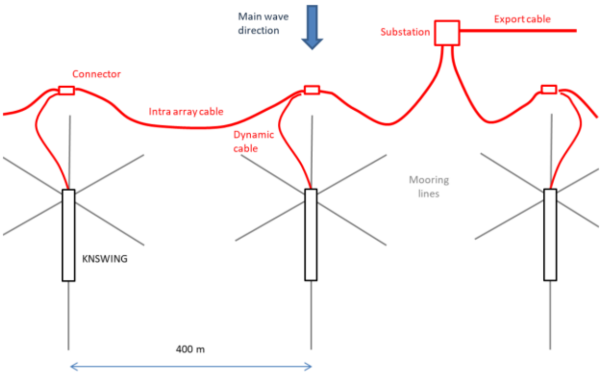
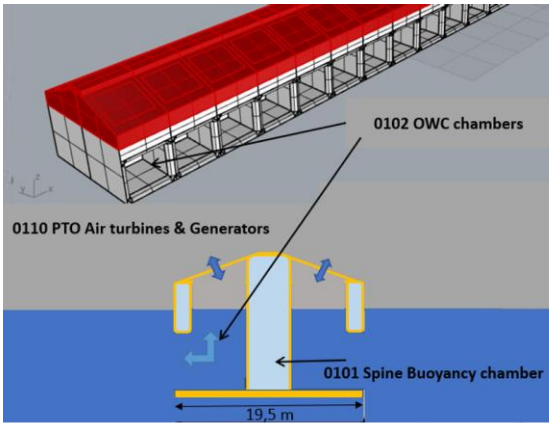


Figure 2. Concept of a KNSWING WEC farm



The 3-meter-long experimental model at HMRC in 2013 – scale 1:50

The Wave Energy Converters (WEC) KNSWING is a 150-meter-long, 20-meter-wide ship-like structure integrating Oscillating Water Columns (OWC) along each side of the hull. The pneumatic power is converted by air-turbines driving generators, which gives a redundant and reliable PTO system with few moving parts. The ship-like structure is suited for mass production in concrete, it can provide high energy absorption from waves, has relatively low mooring forces, low cost concerning tow out for installation, and easy access to mechanical equipment, which are all located above water.
The WEC can be optimised to the local sea conditions. Using an estimated efficiency of the combined air turbines/ generators of 44% and availability of 93%, the annual North Sea electrical production will be about 2700 MWh with a rated power about 1 MW in sea states of about Hs = 3 – 3.5 meter.This gives a capacity factor of 0.3.

The floating structures can support an additional 3000 m^2 of solar panels of approx. 600 kW, which will produce 700 MWh annually, active also on the days with no waves. Experimental tests were conducted at HMRC basin Ireland in 2013, and two rounds of testing were carried out at QUB shallow water basin in Portaferry in 2015, supported by the European Marinet program. Using the same physical model and model sea conditions at both locations, a comparison between the results obtained at the 1m deep HMRC basin and the 0.55m deep Queens facility was possible. In 2022, additional tests were carried out at the AAU test basin, measuring the structural load - the midship bending moment. Results are analysed at the moment.

A summary of results captured from the ECN report is shown below, where the annual average power production in the North Sea, and Belmullet (west coast of Ireland) and other places have been calculated.

Combined with wave data, the annual average power production can be calculated as shown in Table 3 below.

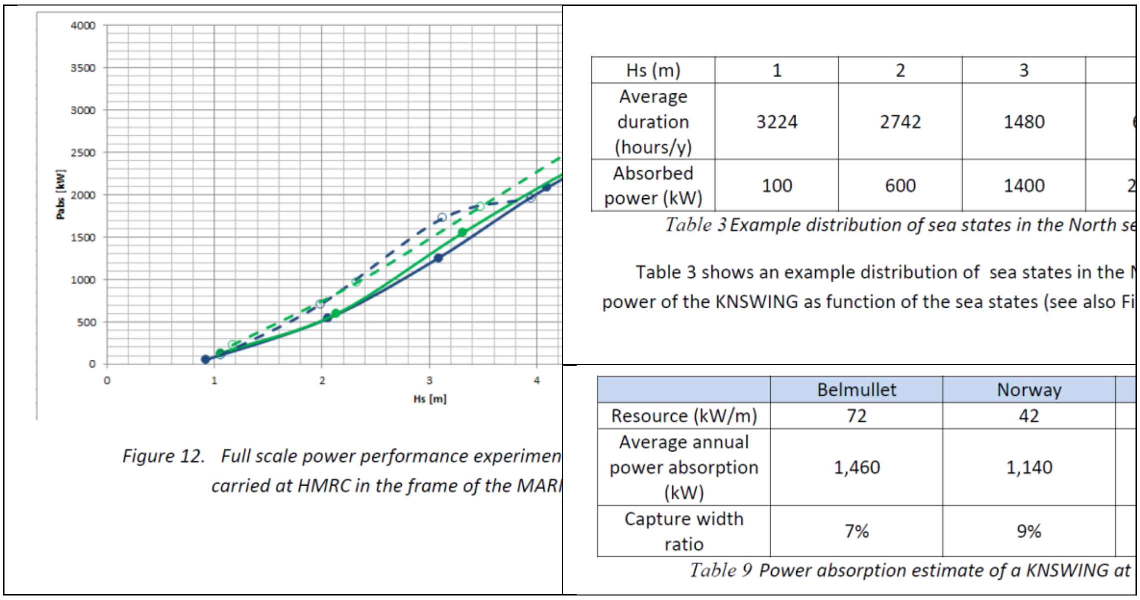


Figure 12. Full scale power performance experimen carried at HMRC in the frame of the MARI

Hs (m)	1	2	3
Average duration (hours/y)	3224	2742	1480
Absorbed power (kW)	100	600	1400

Table 3 Example distribution of sea states in the North se

Table 3 shows an example distribution of sea states in the power of the KNSWING as function of the sea states (see also Fi

	Belmullet	Norway
Resource (kW/m)	72	42
Average annual power absorption (kW)	1,460	1,140
Capture width ratio	7%	9%

Table 9 Power absorption estimate of a KNSWING at

Summery tables from the MEA report october 2019 "Technical submission request" by ECN Aurélien Barbarit, Thomas Soulard, Olivia Thillleul,

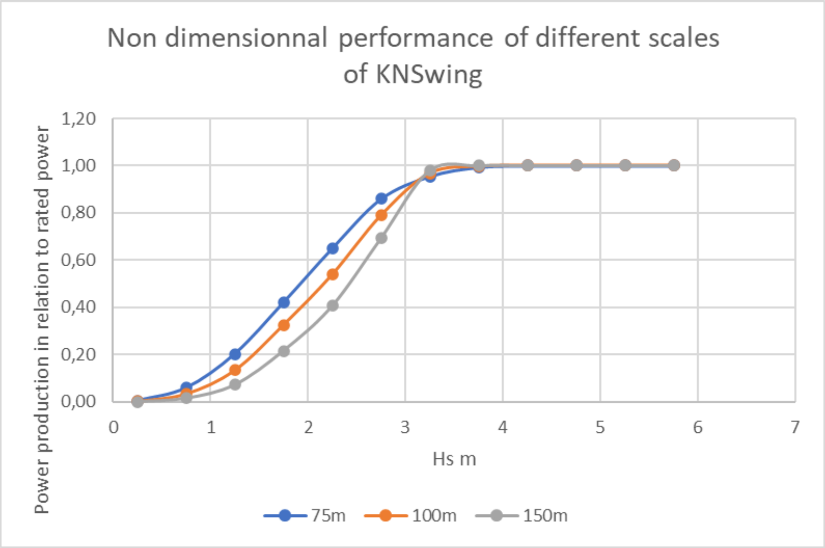
Next pages include calculated power matrices and performance estimates at the location specified for the TNO study – submitted to EWA, via Erwin Meijboom, February and March 2023. These are based on numerical models verified by small scale experiments.

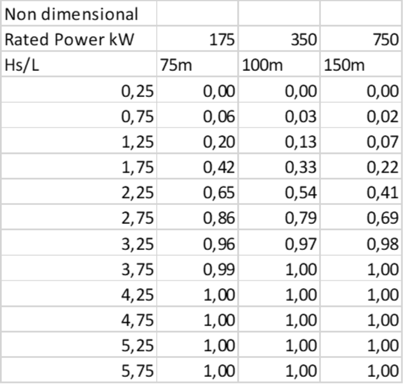
Scatter diagram (hours /year)														
Hs/T02	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5		Tz ave	dp	
0,25	25	396	131	10	0	0	0	0	0	0	563	2,72	0,01	
0,75		624	1245	290	60	4	1	1	0	0	2224	3,41	0,28	
1,25		0	1171	687	125	41	6	1	0	0	2032	4,04	0,84	
1,75		0	37	1244	160	42	11	1	0	0	1494	4,66	1,40	
2,25		0	0	459	415	27	9	1	0	0	911	5,05	1,53	
2,75		0	0	21	520	46	6	2	1	0	596	5,58	1,65	
3,25		0	0	0	253	124	4	1	0	0	383	5,85	1,56	
3,75		0	0	0	35	191	5	1	0	0	232	6,38	1,37	
4,25		0	0	0	1	124	16	0	0	0	141	6,61	1,11	
4,75		0	0	0	0	47	40	0	0	0	88	6,96	0,90	
5,25		0	0	0	0	8	43	1	0	0	52	7,36	0,69	
5,75		0	0	0	0	1	21	4	0	0	25	7,60	0,42	
6,25		0	0	0	0	0	7	7	0	0	14	8,00	0,29	
6,75		0	0	0	0	0	2	4	0	0	6	8,21	0,15	
7,25		0	0	0	0	0	0	3	1	0	4	8,75	0,11	
7,75		0	0	0	0	0	0	0	2	0	2	9,50	0,07	
8,25		0	0	0	0	0	0	0	1	0	1	9,50	0,04	
8,75		0	0	0	0	0	0	0	1	0	1	9,50	0,04	
9,25		0	0	0	0	0	0	0	0	0	0			
											0			
											8768		12,45	kW/m

Eleactical Power Matrix 75 m													
PTO eff	50%												
Rated Power		175	kW										
Hs/T02	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5		Pave kW	DP
0,25	0	0	1	2	1	1	1	0	0	0		1	0
0,75		4	12	14	11	8	6	4	3	2		10	3
1,25		0	34	39	32	23	16	11	7	5		35	8
1,75		0	67	77	63	45	31	21	14	10		74	13
2,25		0	0	127	103	74	50	34	24	17		114	12
2,75		0	0	175	154	110	75	51	35	25		150	10
3,25		0	0	0	175	154	105	72	49	35		167	7
3,75		0	0	0	175	175	140	95	66	46		174	5
4,25		0	0	0	175	175	175	123	84	59		175	3
4,75		0	0	0	0	175	175	153	105	74		175	2
5,25		0	0	0	0	175	175	175	129	90		175	1
5,75		0	0	0	0	175	175	175	154	108		175	1
											Pave	63	kW
											AEP	556	MWh
											CF	0,36	

Eleactical Power Matrix 100 m													
PTO eff	50%												
Rated Power		350	kW										
Hs/T02	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5			
0,25	0	0	2	2	2	2	1	1	1	1		1	0
0,75		3	14	21	21	17	13	9	7	5		12	3
1,25		0	38	59	58	47	35	25	18	13		47	11
1,75		0	75	116	114	93	69	50	35	26		114	19
2,25		0	0	192	189	153	114	82	59	42		189	20
2,75		0	0	287	282	229	170	122	88	63		276	19
3,25		0	0	0	350	319	238	171	122	88		338	15
3,75		0	0	0	350	350	316	228	163	117		349	9
4,25		0	0	0	350	350	350	292	209	151		350	6
4,75		0	0	0	0	350	350	350	262	188		350	3
5,25		0	0	0	0	350	350	350	319	230		350	2
5,75		0	0	0	0	350	350	350	350	276		350	1
											Pave	108	kW
											AEP	946	MWh
											CF	0,31	

Eleactical Power Matrix 150 m													
PTO eff	50%												
Rated Power		750	kW										
Hs/T02	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5		Pave	DP
0,25	0	0	1	3	4	4	4	3	2	2		0	0
0,75		1	11	29	39	39	34	28	21	16		11	3
1,25		0	31	80	109	110	95	77	59	45		54	13
1,75		0	61	157	213	215	187	150	117	89		162	28
2,25		0	0	259	352	355	309	248	193	147		305	32
2,75		0	0	387	525	530	462	371	288	219		519	35
3,25		0	0	0	734	741	645	518	402	307		734	32
3,75		0	0	0	750	750	750	690	535	408		750	20
4,25		0	0	0	750	750	750	750	687	524		750	12
4,75		0	0	0	0	750	750	750	750	655		750	7
5,25		0	0	0	0	750	750	750	750	750		750	4
5,75		0	0	0	0	750	750	750	750	750		750	2
											Pave	188	kW
											AEP	1650	MWh
											CF	0,25	





Non dimensional			
Rated Power kW	175	350	750
Hs/L	75m	100m	150m
0,25	0,00	0,00	0,00
0,75	0,06	0,03	0,02
1,25	0,20	0,13	0,07
1,75	0,42	0,33	0,22
2,25	0,65	0,54	0,41
2,75	0,86	0,79	0,69
3,25	0,96	0,97	0,98
3,75	0,99	1,00	1,00
4,25	1,00	1,00	1,00
4,75	1,00	1,00	1,00
5,25	1,00	1,00	1,00
5,75	1,00	1,00	1,00

10.3.2 Dutch Wave Power

Normalised power matrix Dutch Wave Power accountability:
The normalised power matrix was created based on our numerical model in combination with validation tests at the Deltares Deltagoot and MARIN concept basin tests.

The tests by Deltares and MARIN used regular and irregular waves . For regular waves more than 20 wave heights and wave period combinations were tested and a couple of JONSWAP settings for the irregular waves.

These test results were used to optimise our numerical model, which forms the basis for the normalised power matrix we provided.

10.3.3 Slow Mill

Statement for the TNO-study on wind - wave generation April 4, 2023, Description of the technology Slow Mill is a heave-and-surge wave energy convertor that utilises both the up and down and the back-and-forth motion of the waves to generate electricity. It is a novel, lightweight device, designed for North Sea like conditions. Compared to the ocean waves, North Sea wave heights are relatively lower with a higher frequency. Due to its size and its unique, patented blade system the Slow Mill gets into resonance with the waves to take off power with a high efficiency.

The device width is 20 meters and is attached to the sea floor with a gravity anchor (50 tons). The power take-off (PTO) consists of a pump with a piston length of 5 meters and a hydraulic system that drives a hydro motor that drives an electrical generator. Currently, a 1:2.5 scale model (8 m width, 40 kW), the Slow Mill40, has been build and is undergoing sea trials (TRL 5). In 2023/2024, demonstration will take place with a full-scale model (20m width, 400 kW) and cable to land (TRL 6).

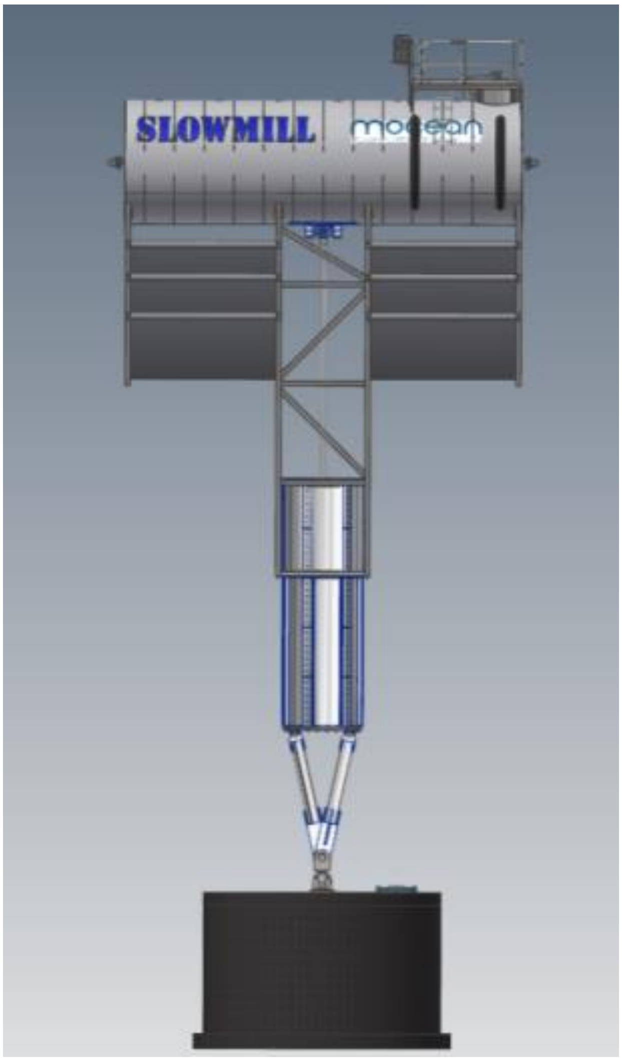


Figure 1: Scale model Slow Mill (1:2.5)

Methodology for testing Simulations

A model of the Slow Mill was built, and simulations in Orcaflex under different wave climate conditions were conducted. The outcomes were used to design the experimental tests. Also, this model is continuously used to simulate and verify observed behaviour and improving and optimising the technology. Experiments Experimental tests were conducted at Marin and Deltares. In 2017, a 1:12 scale model was tested in the Marin flume under regular and irregular wave conditions. Efficiency was 15,8% at Hs 2m and Tz 3.5s. The annual energy production of a 14m model at the location Eierlandse Gat is calculated at 112 MWh. In 2021, at the Deltares Delta flume, an enhanced 1:8 Slow Mill model was tested, also in regular and irregular wave conditions. Efficiency was 22,8% at Hs 2.5m and T 4.5s. Overall, efficiency was improved by 50-100% compared to the test results at Marin.

10.3.4 WaveHexapod

The technology is based on 3 PTO with 6 legs. Legs are made with robot generators. The calculation we made for the power matrix is based on a simulation.

10.3.5 Weco

Explanation device

Weco is developing a terminator-type WEC. The principle is based on floating bodies that use the horizontal motion (surge) to capture the power of the waves. The motion of the bodies is converted to electrical power through an electromechanical system. An artist's impression of what a person would see when sailing by is depicted below.

Method for the power matrix

The power matrix is based on simulation that is partly validated by experiments. It incorporates a linear second-order differential equation with hydrodynamic coefficients that were calculated using Boundary Element Method software. The WEC with PTO is simulated in the time domain for sea states using a JONSWAP spectrum. The PTO is optimised for maximum generated energy throughout the year using reactive control. The hydrodynamic coefficients were validated at University College Cork at a scale of 1:25.

Postadres
Postbus 24100
3502 MC Utrecht

Bezoekadres
Arthur van Schendelstraat 550
Utrecht

T +31 30 73 70 541
E secretariaat@tki-offshoreenergy.nl
T www.tki-offshoreenergy.nl