Ref. Ares(2024)2334065 - 28/03/2024

Reference scenarios / D3.1

WP3, T3.1

Authors: Pieter M. O. Gebraad (YWR); Samuel Kainz (TUM); Abhinav Anand (TUM); Adrien Guillore (TUM); Julian Quick (DTU); Deniz Gökhan Dirik (DTU)

SUDOCO is funded by the European Union under the Horizon Europe Programme (Grant Agreement 101122256). Views and opinions expressed herein are those of the author(s) and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Technical references

PROJECT INFORMATION

Project Acronym	SUDOCO
Project Title	Sustainable resilient data-enabled offshore wind farm and control co-design
Grant Number	101122256
Project Duration	October 2023 – September 2027

DOCUMENT INFORMATION

Deliverable No.	D3.1
Dissemination level*	PU
Work Package	WP3 – Value function models
Task	T3.1 – Scenario Definition
Lead beneficiary	2 (YWR)
Contributing beneficiary/ies	3 (DTU), 4(TUM)
Due date of deliverable	31 March 2024
Actual submission date	28 March 2024

* PU = Public, SEN = Sensitive, EU classified = RESTREINT-UE/EU-RESTRICTED, CONFIDENTIEL-UE/EU-CONFIDENTIAL, SECRET-UE/EU-SECRET under Decision 2015/444

DOCUMENT HISTORY:

v	Date	Beneficiary	Author	Description
0.1	14/03/2024	YWR	P.M.O. Gebraad	First draft
0.2	19/03/2024	TUM	Samuel Kainz	Second draft
0.3	21/03/2024	TUM	A. Anand, S. Kainz and A Guillore	Adding of clustering, events and synergies section

Funded by
the European Union.

0.4	21/03/2024	YWR	P.M.O. Gebraad	Third draft; exploitation sections integrated
0.5	25/03/2024	DTU	J. Quick, D.G. Dirik	Fourth version, final draft for partners' review
0.6	26/03/2024	YWR	P.M.O. Gebraad, A. C. Masoliver	Reviews from the partners
1.0	27/03/2024	YWR, DTU, TUM	All authors	Final version

Executive summary

This deliverable report summarizes the Reference Scenarios used for techno-economic and environmental model development in the SUDOCO project. The scenarios consist of reference wind park designs in The Netherlands, Portugal, and Denmark.

The Dutch case is defined in most detail and is based on Hollandse Kust Noord wind park which is used as a reference case for studies and field experiments throughout the different work packages of the SUDOCO project.

The Portuguese case is a floating wind park to be able to study the economic benefits of wind park control for future floating wind parks.

Finally, the Danish case consists of a future wind park cluster and will be used as a reference to study larger scale effects of wind parks interacting with each other.

For each of the cases we describe the information defined and gathered in terms of geographic, technical, market, and environmental conditions.

Table of contents

Funded by
the European Union.

1 Introduction

This report describes three wind park scenarios to be used as reference cases for techno-economic and environmental studies of wind park control in the SUDOCO project:

- A scenario based on Hollandse Kust Noord wind park. The park is used as a reference case throughout the SUDOCO project for case studies and field experiments.
- A scenario with a hypothetical but realistic design for a 1386 MW floating wind park in an area designated for floating wind energy in Portugal. The Scenario is relevant to include because in the SUDOCO project several studies will be done to see the impact of wind park control in the large floating wind parks to be developed in the future.
- A "cluster scenario" where we look at the impact of wind park control in a larger cluster of wind parks interacting with each other as neighbouring wind parks. We base the case on a scenario for a cluster of wind parks connected to the future Danish Energy Island in the North Sea.

1.1 Data repository

The definitions and data on each of the reference scenarios are shared between the SUDOCO project partners in a GitHub repository[1].

1.2 Disclaimer

The Hollandse Kust Noord (HKN) reference case was based on a combination of public information, and information shared by SHL and Crosswind, with many additional technical and financial assumptions. The resulting yield assessment and business case is in no way claimed to be representing the real offshore wind park Hollandse Kust Noord.

---

[1] https://github.com/youwind/SUDOCO/tree/main/reference_cases%203_1

Funded by
the European Union.

2 Reference Scenarios

Several datasets are provided to give context to each of the three examined sites. Each site is characterized using geographic, technical, environmental, and economic data.

Environmental data is characterized using long-term ERA5 historical wind and wave datasets, as well as a separate weather data set that only encompasses 2012. This is because the economic data is based on a detailed energy system simulation which assumed every year contains the weather observed during 2012.

Electricity prices are based on the Balmorel energy systems model, assuming an aggressive electrification scenario with an explicit representation of uncertainty in technology costs. This simulation did not cover Portugal, so weather-price data is not available for this site, and instead a subsidy scheme is assumed for the Floating Wind Park case.

2.1 Scenario Hollandse Kust Noord

The scenario is based on the Hollandse Kust Noord (HKN) wind park project in the Dutch part of the North Sea, developed by SHL and Eneco in the Crosswind consortium. The reference case is not an exact representation of the HKN project, but uses similar technical specifications, based on public information and information shared by SHL and assumptions based on the geographic location and the Dutch market.

2.1.1 Geographic and technical

The following geographic information defining the wind park are included in the Data Repository in the form of geojson files:

Table 2.1.1.1: Geographic definitions for HKN case

Geographic information	Definition	Source / assumption
Turbine positions	Latitude and longitude	HKN layout, shared by SHL
Array cabling layout	Latitude and longitude of cable sections	Youwind's own assumption based on cable capacity. Generated by a spanning tree algorithm.
Bathymetry at turbine positions	Water depth in meters, included in turbine position geojson	GEBCO (2024), values lie between 20 and 26 m
Export cable trajectory, offshore and onshore substation locations	Cable sections and substation locations	Netherlands Enterprise Agency (RVO, 2019)

Funded by
the European Union.

Neighbouring wind parks' turbine positions	For wind parks: Hollandse Kust Zuid (HKZ), Luchterduinen, Offshore Wind farm Egmond aan Zee (OWEZ), Prinses Amalia	DeepOWT (2022), OpenStreetMap / WAB-S (2024)
Service harbour	Eemshaven	Crosswind

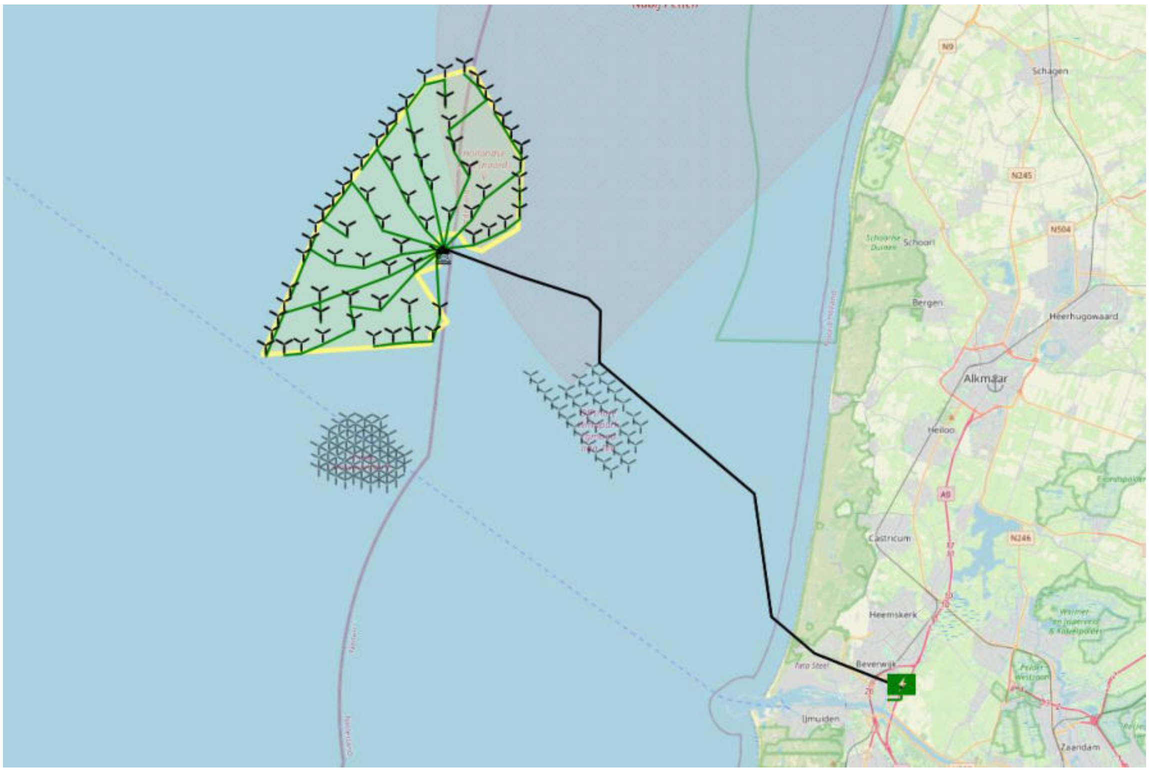


Figure 2.1.1.1a: Map of geographic information defined for HKN, with turbine positions (black turbine icons), onshore and offshore substation, array cabling (green line), export cables trajectory (black line).

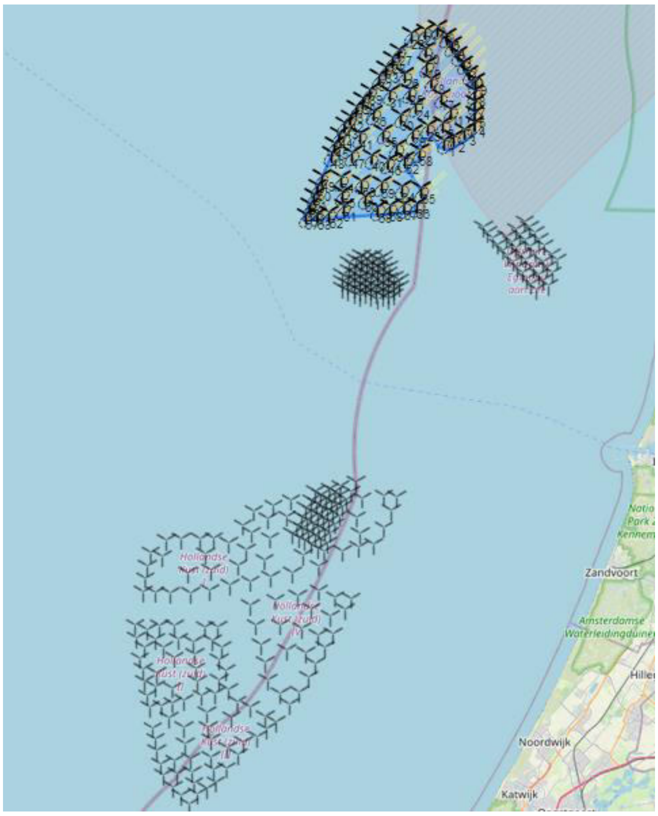


Figure 2.1.1.1b: Overview of wind park with all neighbouring wind parks considered.

The following components are used in the HKN reference wind park definition.

Table 2.1.1.2: Overview of components of the HKN case

Component	Definition, parameterization	Source / assumption
Wind turbine at HKN	Power and thrust curve, rotor diameter, hub height	SGRE provided a turbine definition based on a scaled version of the Innwind 10 MW that is close in terms of power and thrust curve to the SG-11-200 used at HKN.
Neighbouring wind park's turbines	Thrust curves, rotor diameter, hub height	Youwind's assumptions
Turbine support structure	Monopile	Own weight and cost function based on bathymetry
Export cables	2 export cables, each with maximum capacity 380 MW, Voltage 220 kV, AC 3-phase	Capacity and voltage given by TenneT (2020), otherwise own assumptions
Array cables	AC, 66 kV, Cable capacity 80 MW	Own assumptions
Onshore substation	Beverwijk onshore substation	TenneT (2020)
Offshore substation	High voltage substation HKN	TenneT (2020)
Baseload Power Hub energy storage facility	A pilot storage system, built on a dedicated offshore platform, consisting of - 1 MWe/5 MWhe lithium-ion BESS	SHL / Crosswind

Funded by
the European Union.

	- 2.5 MW electrolyser - 1,200 kg of 30-40 bar H2 gas storage - 1.0 MWe fuel cell Flow diagram included in repository.

The HKN Scenario relates to the reference case defined in SUDOCO Work Package 1.1 with the difference that instead of using the IEA-22-MW reference turbine and a scaled layout, we use a turbine that is close to the wind turbine used in the real Hollandse Kust Noord wind park, and the real positions. This makes that we can compare to reference case from WP 1.1 in terms of wake losses and wake dynamics, but that in the economic and environmental evaluation we adhere to some of the real wind park properties and stay close to the true environmental and geographic conditions, to make an estimate of the cost and economics of a commercial wind park operating with or without wind park control.

Note that the storage facility is a based on a demonstration project at HKN that aims at delivering at least 20% of the average electricity production of a single wind turbine (i.e. 1 MW) during 99% of the time independent of wind conditions. In the real HKN project, this demonstration project runs for 2 years, and includes a 0.5 MW floating solar plant. In the SUDOCO project, when studying the use of storage with wind park control in future wind parks, the general recommendation is that the storage facility is to be scaled up to represent a storage facility for the full wind park rather than a single wind turbine.

2.1.2 Market and business case

Based on the technical definition of the wind park, and combining it with pricing information, cost modelling, and market assumptions, the economic performance of the wind park project can be evaluated. In this section we present a baseline calculation as an example, and describe the assumptions for more advanced modelling of the HKN park in the local market conditions. In other work packages of SUDOCO, the techno-economic modelling with be used to evaluate the economic impact of wind park control.

Business case evaluation for HKN

Table 2.1.2.1: Financial condition parameters

Parameter	Definition	Source / assumption
Currency + year of reference	€, 2020	Own assumption
Inflation rates	2.50%	Stehly et al., 2021
Discount rate	5.29%	Stehly et al., 2021

By specifying basic financial conditions as in Table 2.1.2.1, and combining them with cost models, and price assumptions, a wind park business case for the reference wind parks can be prepared. As an example, a business case evaluation by Youwind has been included in

Appendix A based on an assumed Power Purchase Agreement scheme. This baseline business case assumes that no wind park control is used to reduce wake losses, and it does not include energy storage facilities.

Advanced market condition data

For more advanced studies of the economic impact of wind park control in weather-dependent market conditions, the electricity prices are based on the Balmorel energy systems model, assuming an aggressive electrification scenario with an explicit representation of uncertainty in technology costs.

The electricity prices forecasted by Balmorel are coupled with the ERA5 wind data to examine correlations in the environmental and economic conditions. The relationships between the price and wind speed and direction in the HKN site are shown below. There is a clear negative correlation between electricity price and wind speed. There is a complex relationship between the price and direction. While the mean price is not greatly affected by direction, there appears to be a correlation between wind direction and peak electricity prices (approximated as the 90th percentile of a given wind direction bin).

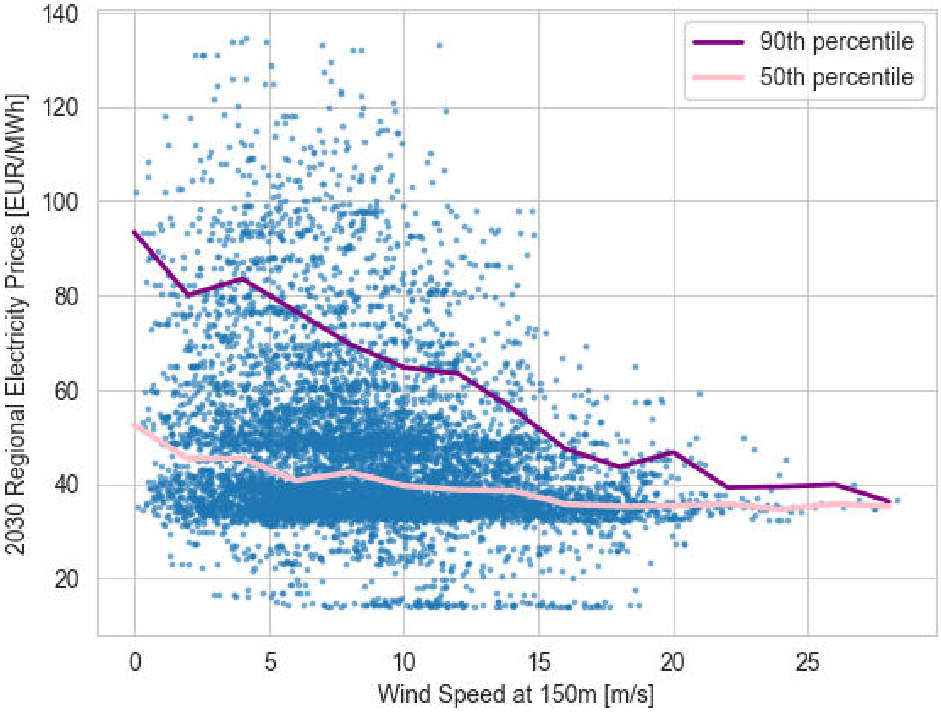


Figure 2.1.2.1: 2030 forecasted NL-region electricity prices vs. ERA5 wind speed for HKN site. Percentiles calculated for 2 m/s wind speed bins.

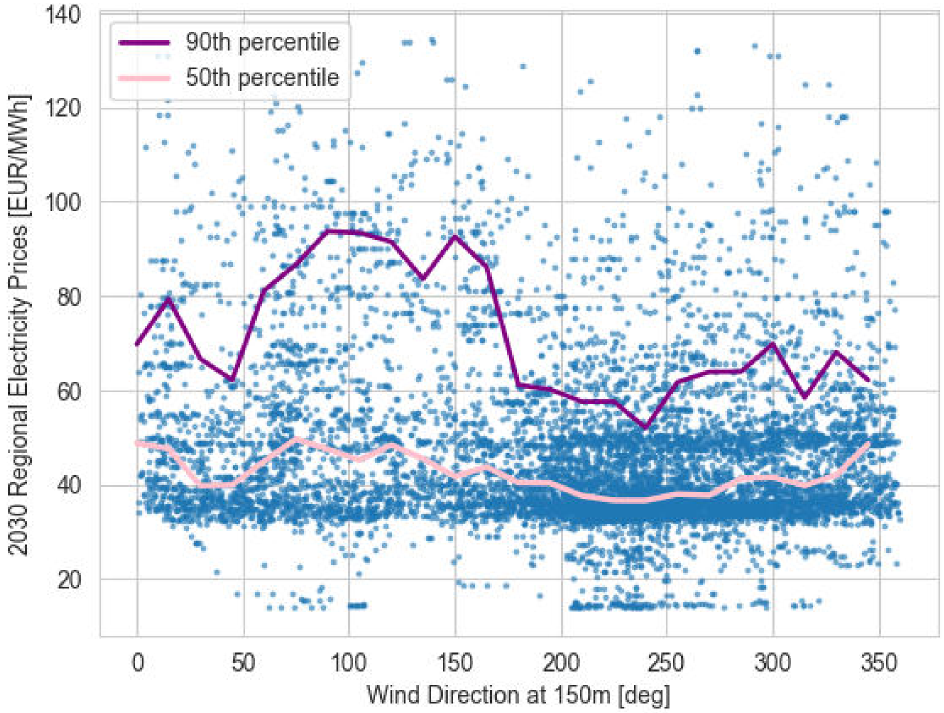


Figure 2.1.2.2: 2030 forecasted NL region electricity prices vs. ERA5 wind direction for HKN site. Percentiles calculated for 15-degree wind direction bins.

The Balmorel model is used to make projections about potential future energy markets, using the sector coupling structure presented in (Gea-Bermúdez, 2021; Swisher, 2022; Gea-Bermúdez, 2023). The Balmorel model is solved in two stages. The first stage is the capacity expansion optimization, which is used to analyse the energy transitions towards 2050. The capacity expansion optimization is solved at limited temporal granularity (limited number of weeks for each scenario year, 2025, 2035, and 2045 to reduce computational complexity) and aims at finding the needed investment in generation and transmission to meet the electricity, heat and transportation demands for the lowest cost to society. The capacity expansion considers both capital and operational expenditures (CAPEX and OPEX) to optimize investment decisions. After the capacity expansion optimization is solved, a dispatch run is done, considering all hours of the scenario year, which is equivalent to day-ahead or spot market. The electricity prices presented in this paper are based on this dispatch run, where only the operational and maintenance costs (fixed and variable) play a role, given a generation and transmission capacity per region. While the variable OPEX costs of wind and solar technologies are virtually zero, their fixed OPEX costs (which account for maintenance and labour costs) can impact electricity prices.

The different regions of Europe modelled in this study are shown in the Figure 2.1.2.3. The renewable energy generation uses the ERA5 weather data set, with wind modelled as presented in (Murcia, 2022). The technology CAPEX and OPEX are based on a Danish Energy Agency catalogue, which provides technology costs for several years. These projections are all used in Balmorel for the different years.

Funded by
the European Union.

Figure 2.1.2.3: A map depicting the different European regions modeled in this study. DK1-DK2, NO1-NO5, and SE1-SE4 represent the existing electricity market bidding zones of Denmark, Norway, and Sweden. Germany (DE) is split into four regions – east, west, north and south. BE, EE, FIN, FR, LI, LV, NL, PL, and UK represent Belgium, Estonia, Finland, France, Lithuania, Latvia, Netherlands, Poland, and the United Kingdom, respectively.

The results associated with the baseline model are shown in Figure 2.1.2.4. The baseline model reflects the EU's decarbonization initiatives in terms of variable renewable energy (VRE) dominant electricity generation, electrification of transport and heat sectors, and production of green hydrogen. The transition is expected to result in more than a twofold increase in electricity demand by 2045 compared to 2025, as shown in panel (a). Towards 2045, VRE technologies, especially wind and solar, dominate the generation mix, while some of the required flexibility in the electricity sector is contributed by combined heat and power (CHP), thermal, and hydro generators, as illustrated in panel (b). The fossil-fuel-driven heat and hydrogen sectors will transition to electricity as a primary source. Starting from 2035, the major portion of heating demand will be met by heat pumps. Also, electrolyzer operations will cater to heating needs as shown in panel (c). Apart from controllable generators, VRE uptake is driven by the energy storage operations across all sectors, as depicted in panel (d). Electric vehicles operating in grid-to-vehicle and vehicle-to-grid modes result in deferred investments in short-term energy storage.

Funded by
the European Union.

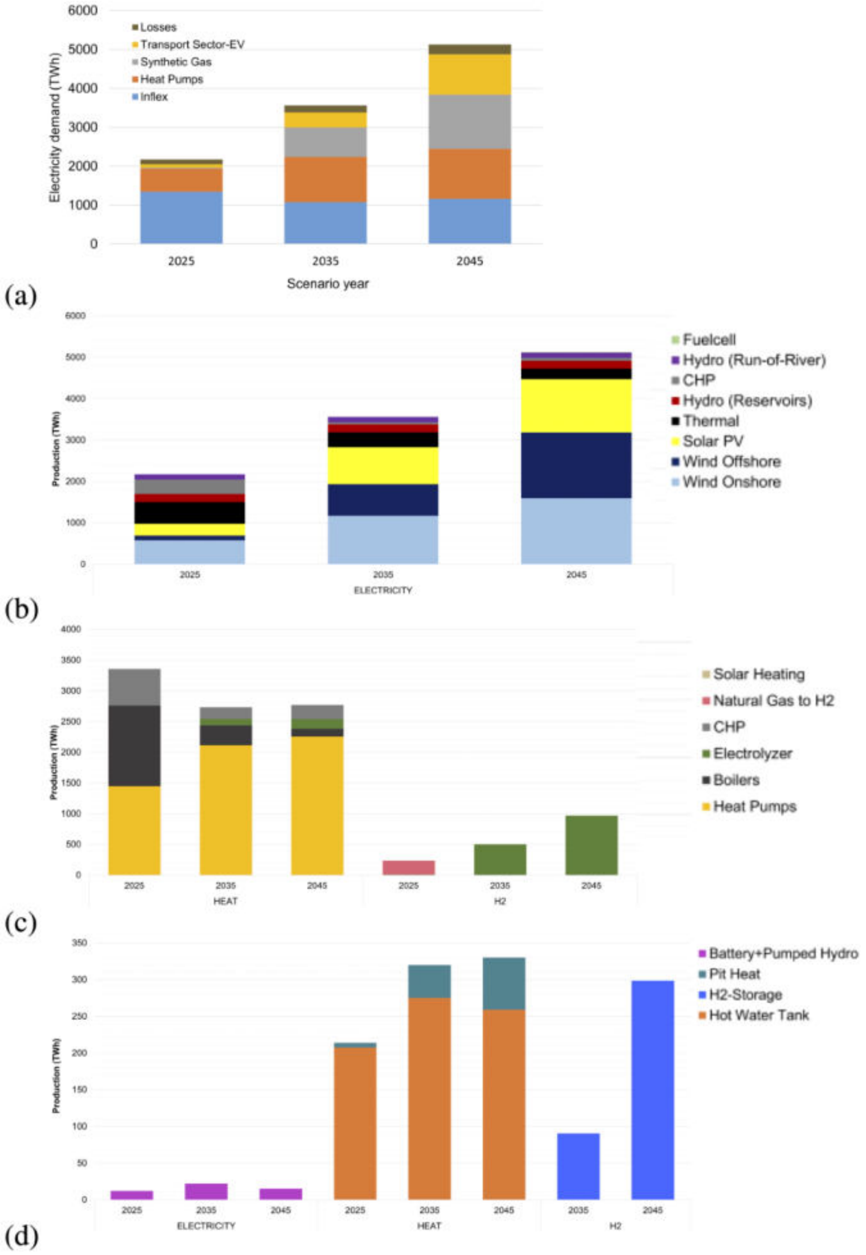
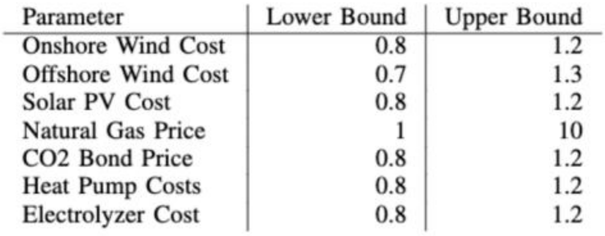


Figure 2.1.2.4: Simulation results associated with the baseline technology costs model: (a) Sector-wise electricity demand. (b) Technology-wise electricity production. (c) Heat and hydrogen production. (d) Energy storage dispatch for each scenario year. These are the aggregated results across all regions.

The uncertainty in the underlying CAPEX and OPEX assumptions is modelled by multiplying the technology cost evolution for both CAPEX and OPEX by a constant cost factor across time. The multiplicative factors associated with each technology cost are shown in the table below. A multiplicative factor of one corresponds to the baseline case presented in the previous figure, it assumes the cost projections originally made by the Danish Energy Agency.

Lower and upper bounds of cost multipliers considered in the energy system simulation



Parameter	Lower Bound	Upper Bound
Onshore Wind Cost	0.8	1.2
Offshore Wind Cost	0.7	1.3
Solar PV Cost	0.8	1.2
Natural Gas Price	1	10
CO2 Bond Price	0.8	1.2
Heat Pump Costs	0.8	1.2
Electrolyzer Cost	0.8	1.2

A multiple output support vector regression (MSVR) surrogate model was trained to predict the electricity prices as a function of the uncertainty cost factors using 34 model evaluations. The first 12 model evaluations were selected by changing one input at a time. These evaluations were also used to internally inspect the Balmorel configuration used in this study. The remaining 22 samples were randomly selected using the Latin hypercube sampling method. Individual MSVR models were trained to predict each region- and scenario-year-specific electricity price timeseries.

An example evaluation of the surrogate is shown in Figure 2.1.2.5:

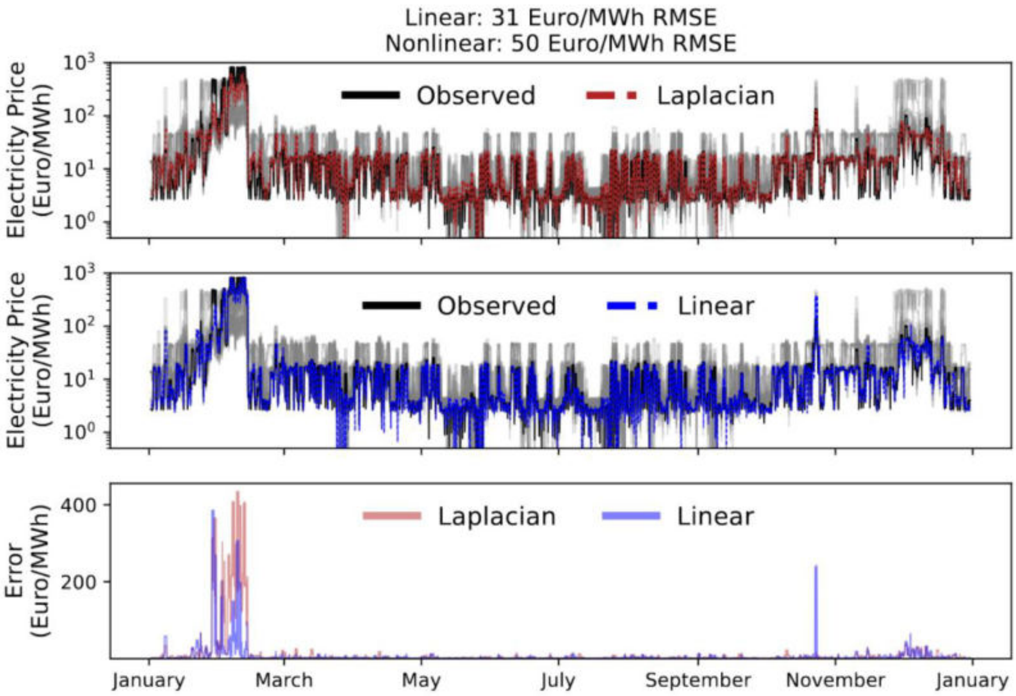


Figure 2.1.2.5: The prediction of the leave-one-out model for the UK region in 2045 compared to the excluded data. The grey lines show the timeseries associated with each sampled observation.

2.1.3 Environment

ERA5 reanalysis data for the year 2012 is used as the reference weather data since the electricity market prices are coupled with the atmospheric conditions of the same year. A long-term dataset is also available from ERA5. Figure 2.1.3.1 shows the wind rose for HKN at the nearest-grid-cell in the ERA5 data set. Preliminary wind farm flow simulations using this reference data are run using hourly 2012 reanalysis data as a time-series in PyWake (Pedersen et al., 2023), using the provided turbine coordinates. Wake losses for 10 ± 2m/s wind speed bin and 5-degree wind direction bins are shown in Figure 2.1.3.2.

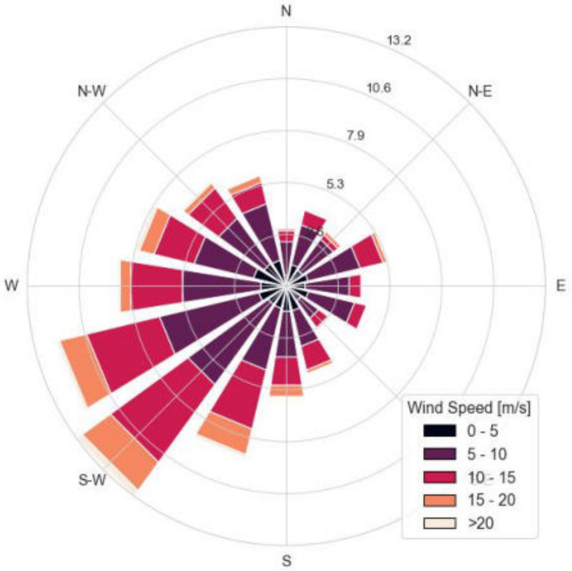


Figure 2.1.3.1: ERA5 annual wind speed and direction distribution for HKN scenario.

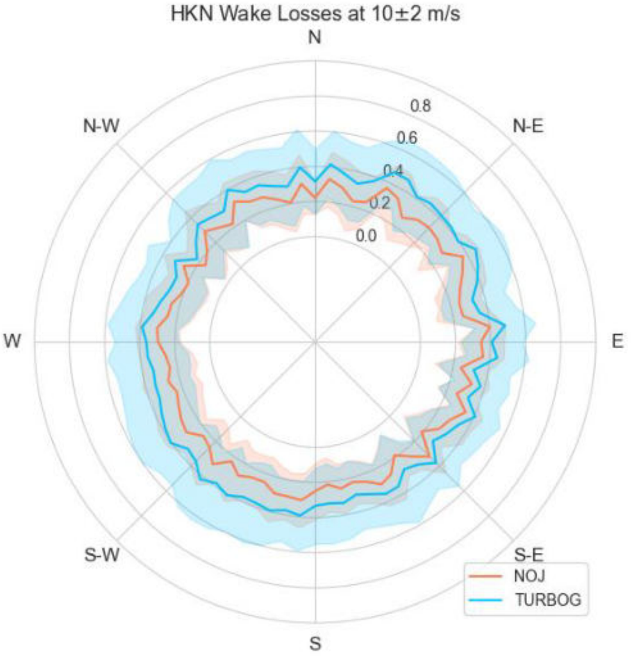


Figure 2.1.3.2: Simulated wake losses at HKN at 10 ± 2 m/s wind speed, per 5-degree wind direction bins, using PyWake default literature models: TURBOG (Pedersen, 2022) and NOJ (Jensen, 1983)

The model development in Task 3.3 requires specification of the scenarios based on which the frameworks for grid greenhouse gas prediction and life-cycle assessment (LCA) are built.

To estimate the greenhouse gas emissions related to the wind farm over its entire life cycle (from cradle to grave), a Life Cycle Assessment (LCA) methodology is applied. TUM develops the in-house tool “Design and Evaluation Toolchain with Eco-Conscious Targets” (DETECT). It can realize holistic evaluation of the carbon footprint of a wind farm plant using LCA. First, a total bill of materials is estimated based on scaling laws for each component and various technology types. Then, the environmental LCA model relates all activities to greenhouse gases emissions. The life-cycle stages (and all related processes) that are included are the raw material extraction and processing, the transportation of materials, the manufacturing of turbine components, the transportation of components, the wind plant installation, the operation and maintenance, the decommission and finally the end-of-life treatments. More details about the DETECT tool can be found in Kainz et al., 2024. Table 2.1.3.1 lists the main data sources and scenarios considered for this LCA model development in the project.

On the other hand, the grid greenhouse gas emission model aims to predict the displaced CO2 emissions tied with the generation technology that the wind power plant displaces. Identification of such a power plant can be done by formulating merit-order based dispatch synthesized using dynamic time-series of generation, demand, fuel costs, and other relevant parameters. This results in a time-series of displaced emission corresponding to the generation technology operating at margin. The resulting surrogate model can thus map the environmental conditions, grid generation mix, as well as other relevant parameters to displaced grid emission. Such a surrogate model can be trained either using historic open-source time-series data and/or the time-series data utilized in the model developments in Task3.2, to predict the grid CO2 emissions. Table 2.1.3.1 lists the main data sources and assumptions for the grid greenhouse gas emission model development.

Table 2.1.3.1: Definitions for LCA and grid greenhouse gas emission model development as relevant for the HKN wind farm.

Parameter / subject	Definition	Source / assumption
LCA method		
Emission factor database	Ecoinvent	Wernet, 2016
Geographic scope of emission factors	European datasets where possible, otherwise global datasets	Own assumption
LCA system model	Allocation, cut-off by classification. Extended with Circular Footprint Formula.	Wernet, 2016; European Commission, 2021
Life cycle impact assessment method	Global Warming Potential following the IPCC2013 method	IPCC, 2014
Wind farm installation		
Transport distances from OEM to port	see Table 2.1.3.2	
Vessel logistics for installation	as reported in reference	Maness, 2017

Funded by
the European Union.

Distance to installation port	230 km	Approximate distance to the two installation ports: Antwerp (BE) and Eemshaven (NL) according to 4coffshore, 2024.
Wind farm operation		
Design lifetime	25 years	Own assumption.
Distance to service port	40 km	Approximate distance to service port IJmuiden (NL) according to 4coffshore, 2024.
Failure rates	as reported in reference	Carroll, 2016
Downtimes	as reported in reference	Carroll, 2016
Performance losses	2%	Clifton, 2016
Transformer efficiency	99.4%	Hardy, 2019
Cable losses	dependent on current flow, calculated as suggested for economic analysis in the reference	Worzyk, 2009
Vessel logistics for O&M	vessel called from port each time a reparation / service activity is required (conservative approach)	Own assumption
End-of-Life		
Vessel logistics for decommissioning	Reversed installation. Scour protection material is left on seafloor.	Maness, 2017
Distance to decommissioning port	230 km	Same as the installation port.
Truck distance to waste management facility	200 km	Razdan, 2019
Recycling, landfill and incineration rates	As reported in reference	Razdan, 2019
Allocation of recycling credits and burdens	Circular Footprint Formula	European Commission, 2021
Marine information for scour and corrosion protection design.		
Climatic region	Temperate (7-12°C)	DNV, 2010
Corrosion protection material	Aluminium	DNV, 2016
Support Structure Coating	Epoxy / Polyester	DNV, 2016
Scour depth equilibrium	1.3 [-] (steady current)	DNV, 2014
Soil friction angle	33.5° (medium density sand)	DNV, 2014
Scour rock density	2600 kg/m³	Maness, 2017
Scour protection depth	1 m	Own assumption
Electric design		
Array voltage	66 kV	RVO, 2019
Export voltage	220 kV	RVO, 2019
Frequency	50 Hz	Own assumption

Collection network topology	radial	Own assumption
Grid CO2 displacements		
Market zone	Netherlands	Own assumption
Grid generation mix	Time series	Database such as ENTSOE-E transparency platform
Power demand	Time series	Database such as ENTSOE-E transparency platform
Spot market price	Time series	Database such as ENTSOE-E, transparency platform
Emissions of generation mix	Technology-specific emission factors from ecoinvent	Wernet, 2016
Technology / power plant operating at the margin	Calculated through static or dynamic merit order	Static merit orders (e.g., EWI Merit-Order tool or modelled through time series of variable operational costs)
Weather data	Time series	Based on reanalysis (ERA5)

Table 2.1.3.2: Assumed transport distances from OEM production site to port, based on Razdan, 2019

Component	Truck [km]	Marine transport [km]
Blades	900	1900
Hub	300	3100
Nacelle	800	0
Tower	500	4500
Support Structure	500	4500
Scour Protection	0	0
Array Cables	600	0
Export Cable	600	0
Offshore Substation	500	4500

Funded by
the European Union.

2.2 Scenario "Floating Wind Park"

For the purpose of studying the impact of wind park control on future floating wind parks, we designed a hypothetical reference wind park in one of the development areas designated by the Portuguese government for floating wind energy.

2.2.1 Geographic and technical

The geographic information defining the wind park are included in the Data Repository in the form of geojson files. Table 2.2.1.1 and Figure 2.2.1.1 give an overview of the geographic definitions for the wind park case and Table 2.2.1.2 gives an overview of the technical equipment.

Table 2.2.1.1: Geographic definitions for equipment placement for Floating Wind Park case

Geographic information	Definition	Source / assumption
Turbine positions	Latitude and longitude, 63 positions	YWR designed a wind park with a staggered layout with 11 rotor diameters spacing between turbines along dominant wind direction, 5.5 rotor diameters in crosswind direction. The positioning avoids deepest areas of the designated area, and concentrates on the North part, where, based on previous study, lowest LCOE is expected. Figure 2.2.1.2 shows a wake simulation of the park in the dominant wind direction.
Array cabling layout	Latitude and longitude of cable sections	Own assumption based on cable capacity. Generated by a spanning tree algorithm by YWR.
Bathymetry at turbine positions	Water depth in meters, included in turbine position geojson	GEBCO (2024), values lie between 110 and 150 m
Export cable trajectory, offshore and onshore substation locations	Cable sections and locations	Trajectory assumed based on nearest large onshore substation (Subestaçao de Canelas)
Harbour (installation, operation and maintenance)	Port of Leixoes	
Soil conditions	Mud to muddy Sand	

Funded by
the European Union.

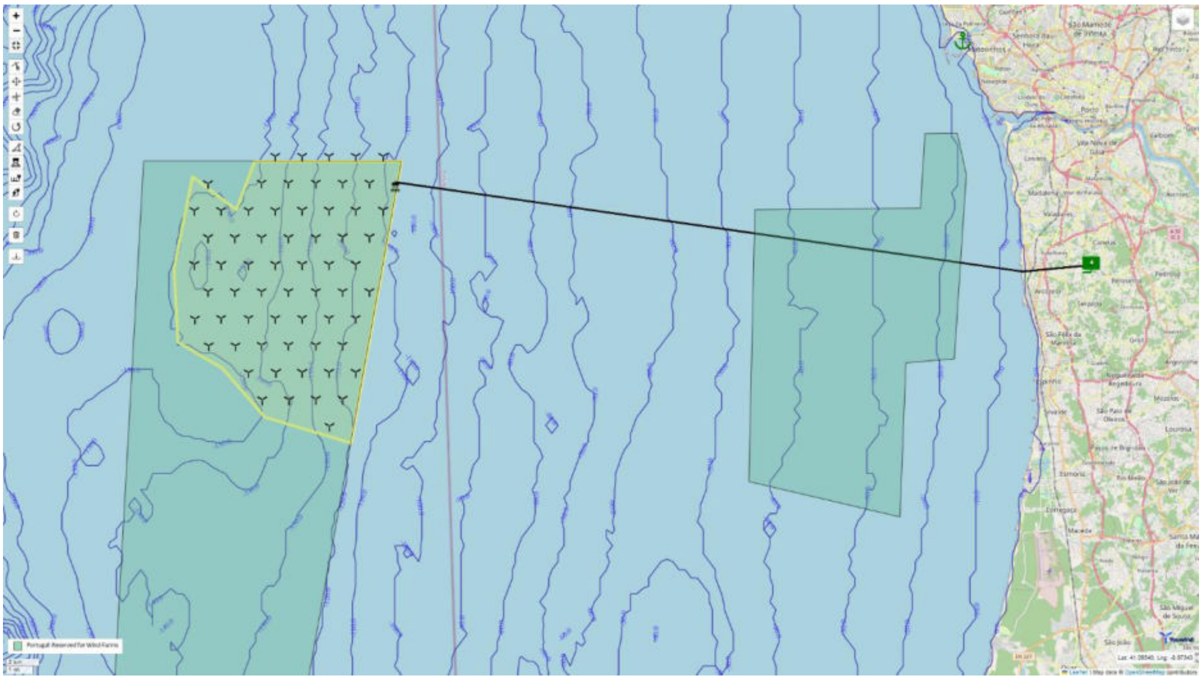


Figure 2.2.1.1: Map of the ”Floating wind park” scenario with turbine positions, export cable, onshore and offshore substation.

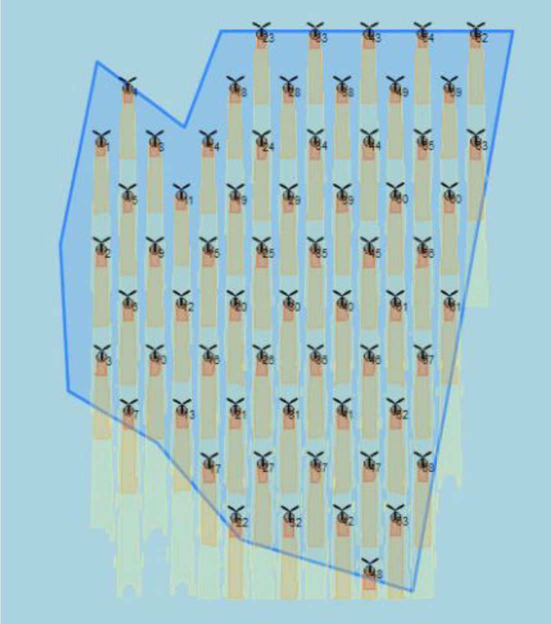


Figure 2.2.1.2: A wake simulation of the floating wind park with NOJ model (Jensen, 1983) in the dominant wind direction (North)

Funded by
the European Union.

Table 2.2.1.2: Components of Floating Wind Park

Component	Definition, parameterization	Source / assumption
Wind turbine	IEA-22-280-RWT	22MW offshore reference wind turbine developed by the IEA Wind Task 37[2]
Turbine support structure	IEA-22-280-RWT semi-submersible type floater	Corresponding floater designed in IEA Wind Task 37
Export cables	220 kV cables for floating platforms, 465 MW capacity, AC 3-phase	
Array cables	66 kV cables, 88.6 MW capacity, AC 3-phase	NREL[3]
Onshore substation	1386 MW capacity	
Offshore substation	1386 MW capacity	

2.2.2 Market and business case

By specifying the market conditions, and combining with pricing assumptions and cost models, a wind park business case for the reference wind parks can be prepared. As an example, a business case evaluation by Youwind has been included in Appendix A. For this case, a simple subsidy-based pricing was assumed.

2.2.3 Environment

Hourly ERA5 wind and wave dataset between 1995 and 2019 at floating park scenario coordinates is shared in the data repository. A summary of the available data is plotted as a monthly aggregated data variables in Figure 2.2.3.1, and a wind and wave rose is Figure 2.2.3.2. The wave height, and periods peak in the winter months. The wind flow predominantly comes from the North, while the wave flow predominantly comes from the Northwest. Correlations are examined in Figure 2.2.3.4. Wind and wave direction are sometimes misaligned. As expected, the significant wave height is strongly correlated with the wind speed. Extreme wave conditions will be estimated based on the methodology presented in (Larsén, 2015).

---

[2] https://github.com/IEAWindTask37/IEA-22-280-RWT

[3] https://github.com/WISDEM/ORBIT/tree/electrical-refactor/library/cables

Funded by
the European Union.

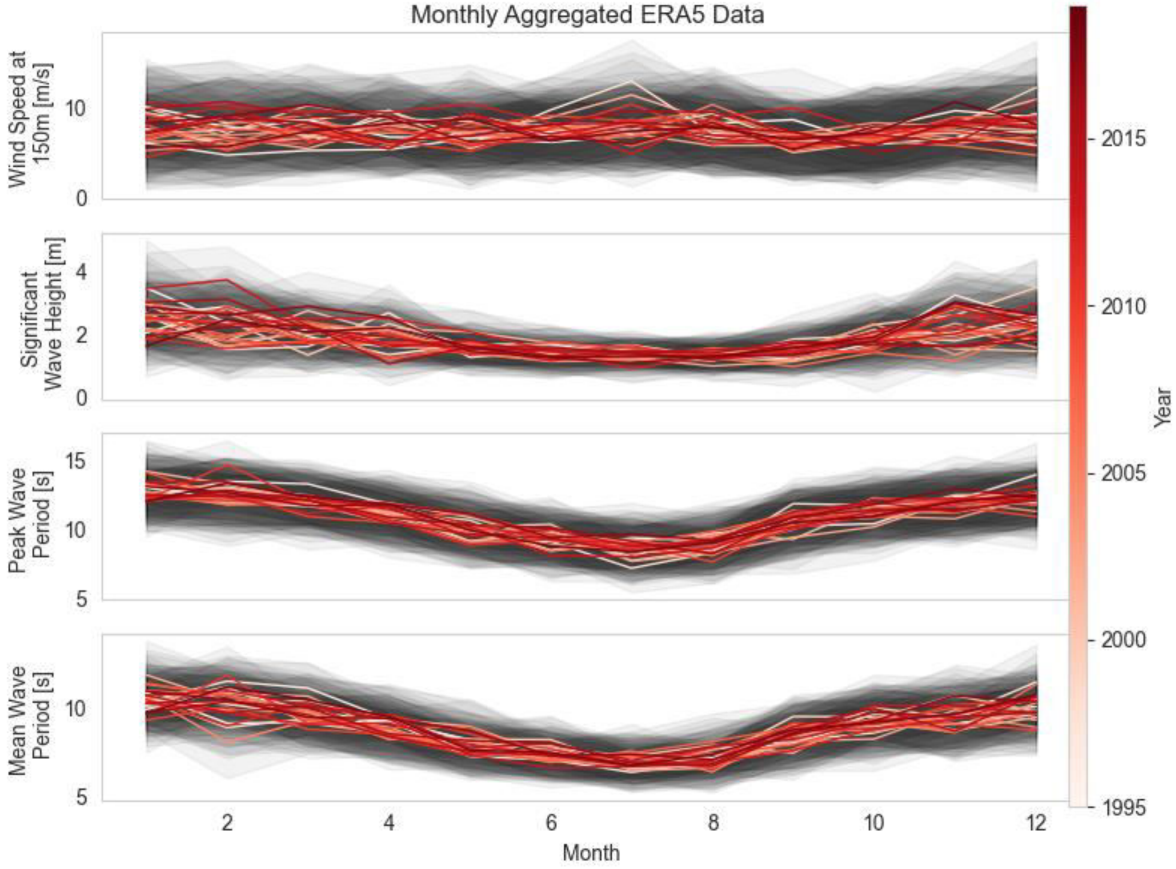


Figure 2.2.3.1: Monthly aggregated 25-year ERA5 wind and wave data. The monthly average is plotted for each month, using different colours to denote the year number. The grey colours indicate the variability in each month-year of data.

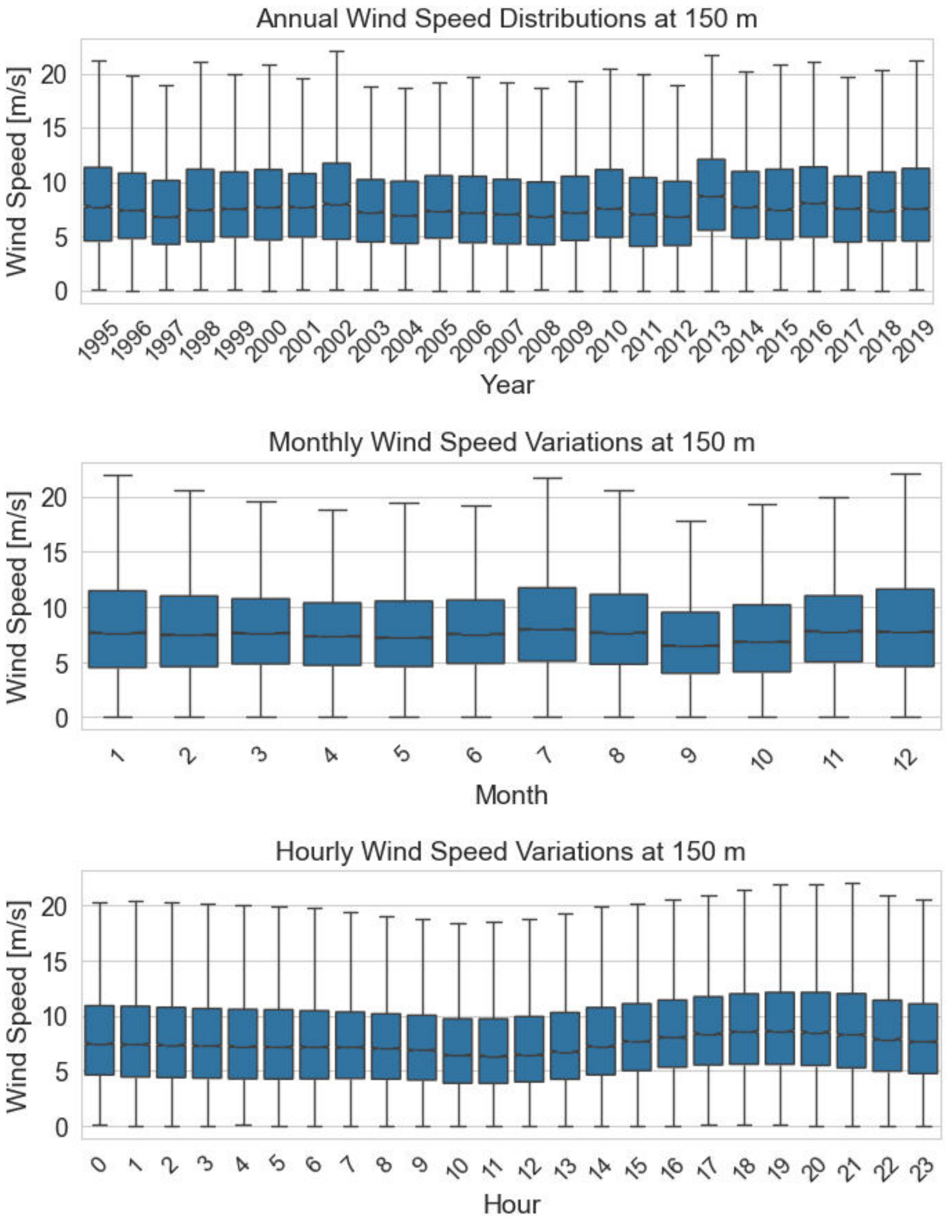


Figure 2.2.3.2 (Top) 25-Year inter-annual variability of the wind speed. (Middle) Annual variability of the wind speed. (Bottom): Diurnal variability of the wind speed.

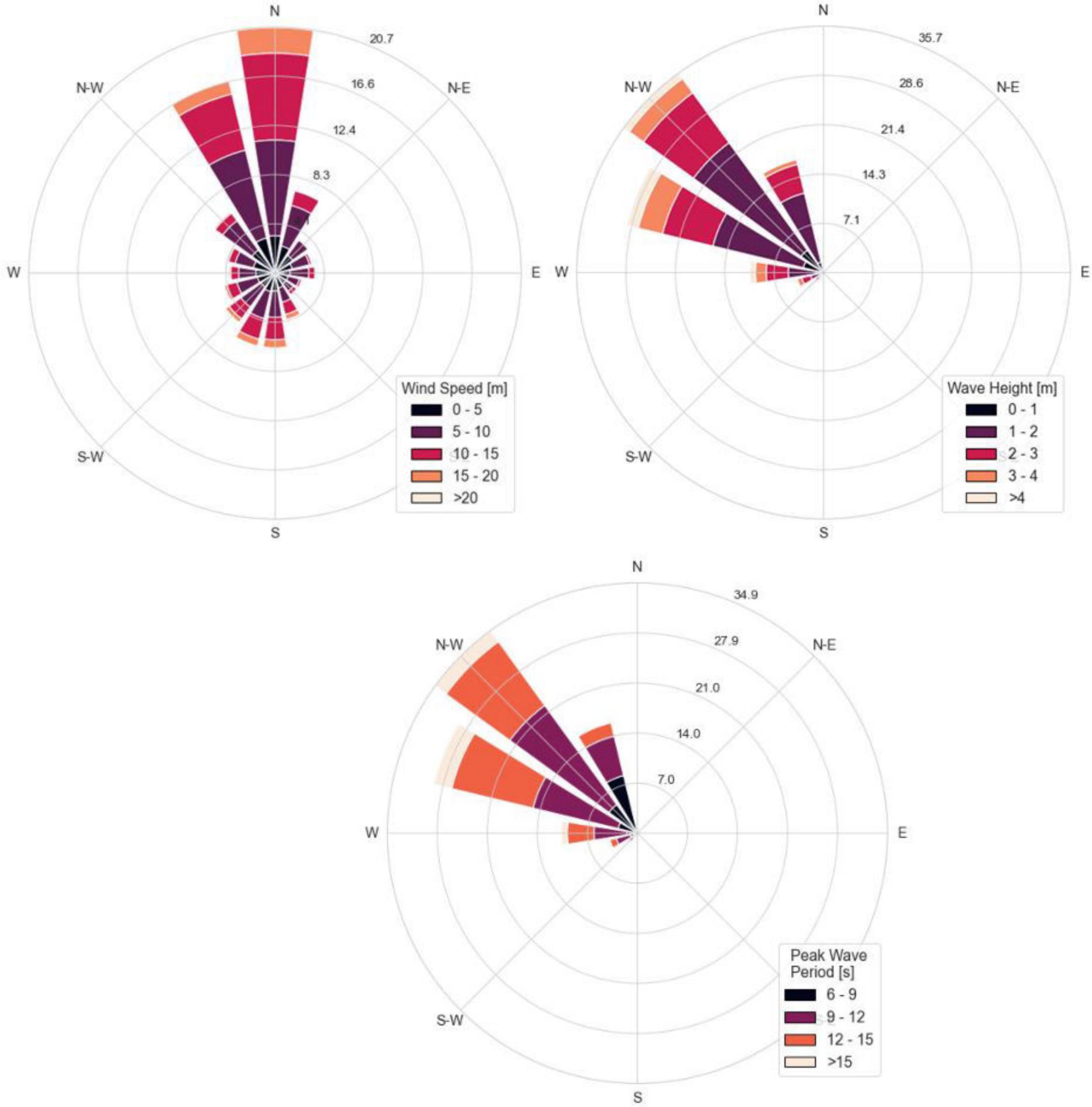


Figure 2.2.3.3: 25-year ERA5 wind rose (on the left) and the wave rose for wave height (on the right) and peak wave period (at the bottom) at nearest grid cell to the floating wind park.

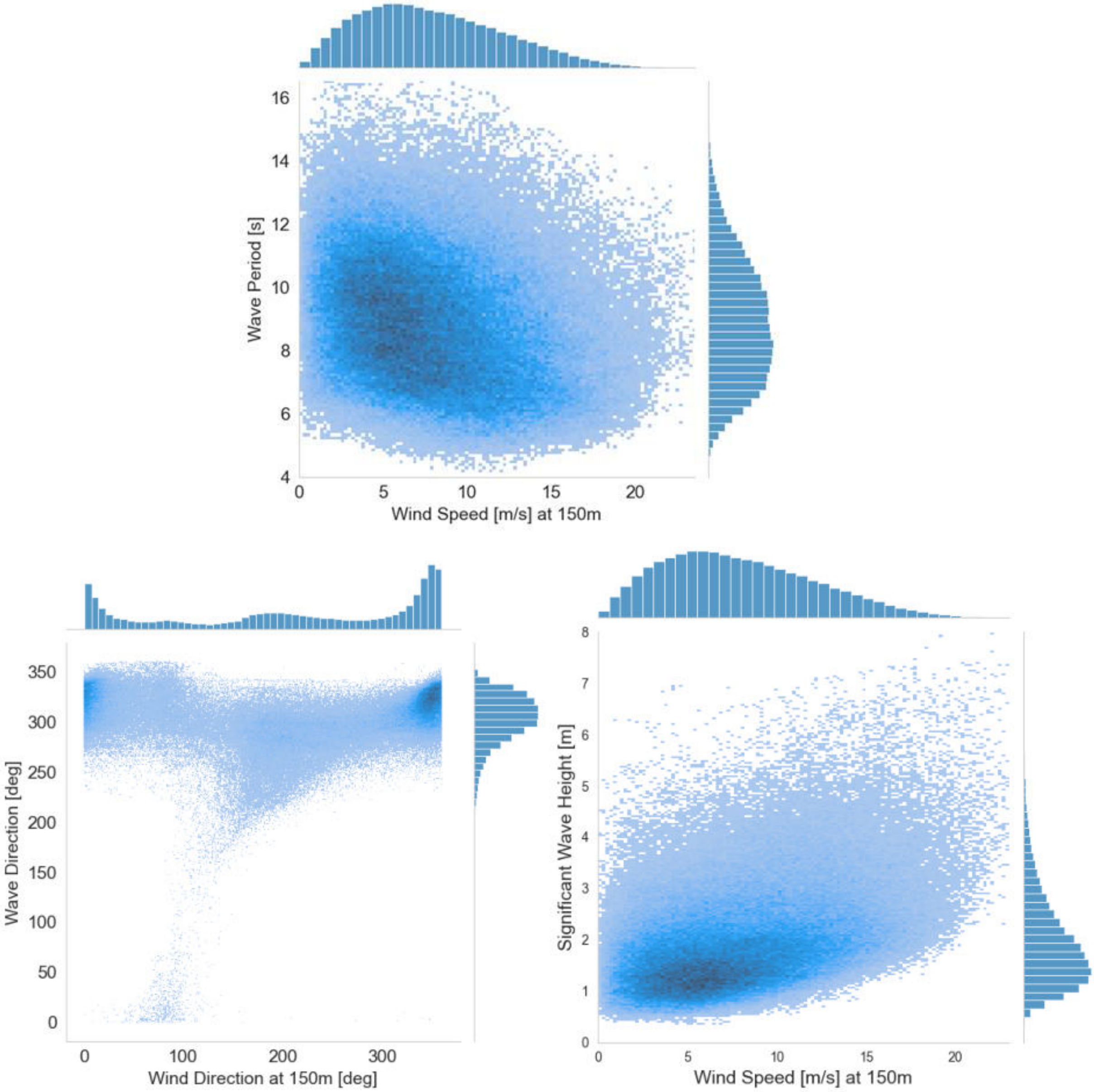


Figure 2.2.3.4: 25-year data set of wave period, wind speed, wind direction, wave direction, and significant wave height. Joint distributions of these data are visualized.

Considering the coupled forecasted electricity prices coupling for the year 2012, ERA5 2012 weather data is used for the preliminary wind farm flow simulations. Wind rose for the year 2012 is available in Figure 2.2.3.5. Wind farm flow is simulated using the hourly 2012 reanalysis weather data as a time-series. Resulting wake losses at 10 m/s are available in *Figure 2.2.3.6.*

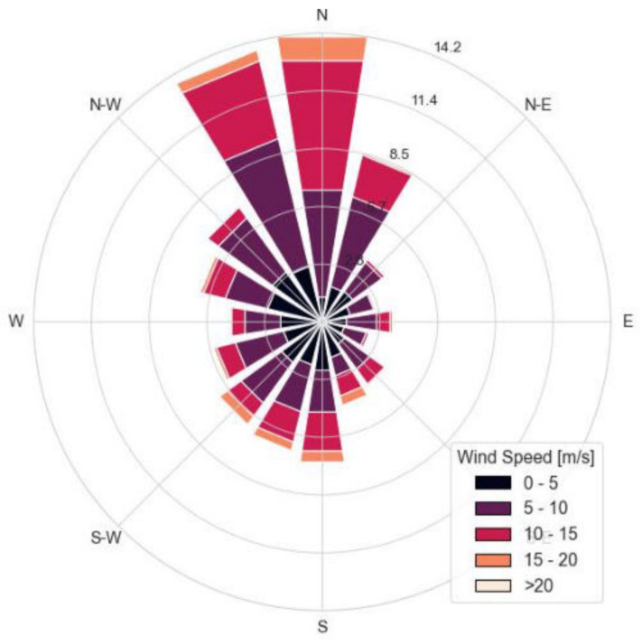


Figure 2.2.3.5: ERA5 annual wind speed and direction distribution at Floating Park scenario nearest-grid-cell.

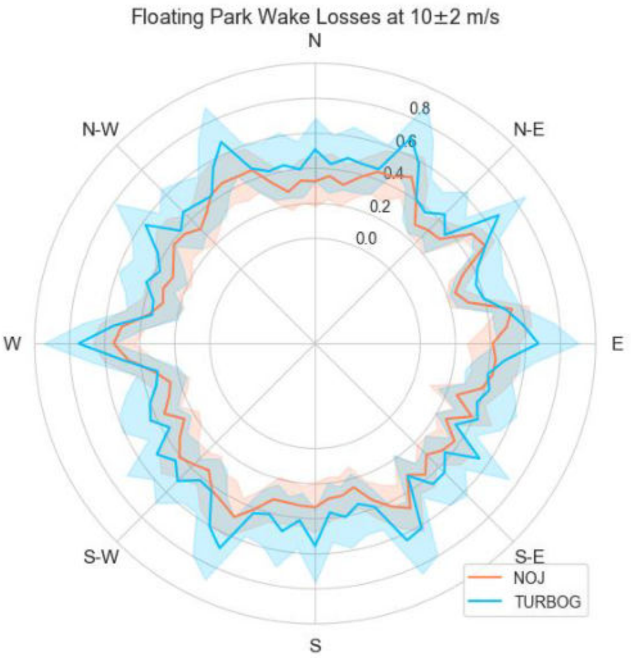


Figure 2.2.3.6: Simulated wake losses for Floating Wind Park at 10 ± 2 m/s wind speed, per 5-degree wind direction bins, using PyWake default literature models, TURBOG (Pedersen, 2022) and NOJ (Jensen, 1983)

For environmental studies in this scenario, the same method and assumptions are used as described in 2.1.3. The technology type for the DETECT tool and market zones for greenhouse gas displacements will be adapted accordingly.
Table 2.2.3.1 lists the site-specific parameters for the floating case. All other definitions are equal to the HKN case.

Table 2.2.3.1: Definitions for the LCA and grid greenhouse gas emission model development as relevant for the floating wind park. All other definitions are equal to the assumptions taken for the HKN wind farm.

Parameter / subject	Definition	Source / assumption
Wind farm installation		
Distance to installation port	230 km	Assumed the same as for HKN
Wind farm operation		
Distance to service port	40 km	Approximate distance to service port Port of Leixoes
End-of-Life		
Distance to decommissioning port	230 km	Assumed the same as for HKN
Marine information for scour and corrosion protection design.		
Climatic region	Sub-Tropical (12-20°C)	DNV, 2010
Scour protection	Not required for floating case	
Grid CO2 displacements		
Market zone	Portugal	Own assumption

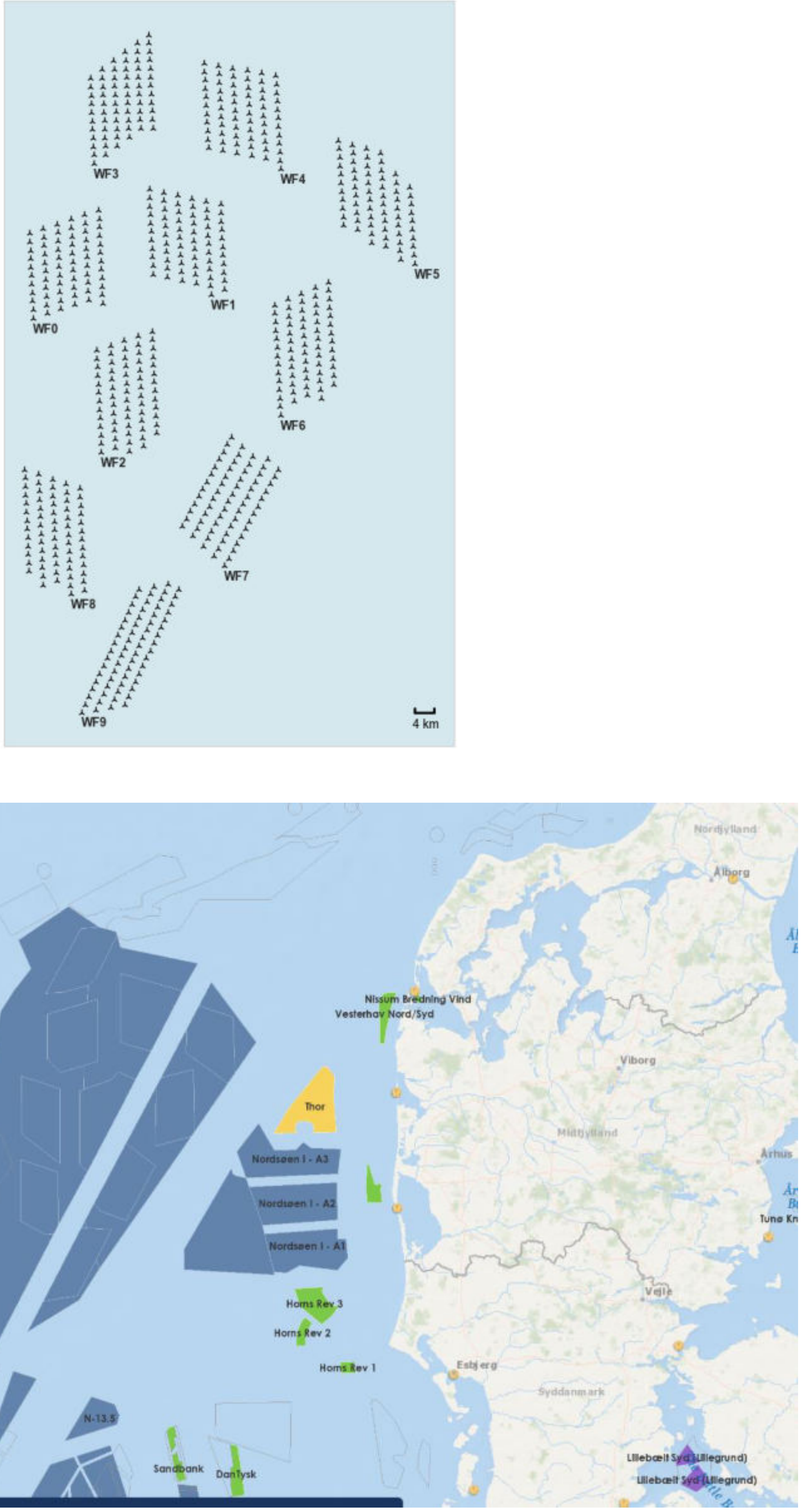
2.3 Scenario “Danish Energy Island Cluster”

The third reference case is to be used to study the effect of wind park control in a large cluster of wind parks, and is based on tender areas in the Danish part of the North Sea.

2.3.1 Geographic and technical

The boundary of each wind park is provided as polygons using UTM coordinates based on public data of wind park development areas the North Sea. This is visualized in Figure 2.3.1.1. Each wind park is assumed to have a capacity of 1000 MW, and DTU generated optimized turbine positions for each wind park with the TOPFARM toolset.

Funded by
the European Union.



(this image is copied as a visual aid from https://www.4coffshore.com/windfarms/)
Fig 2.3.1.1: Optimized turbine coordinates using provided polygon boundaries.

Funded by
the European Union.

Geographic information	Definition	Source / assumption
Turbine positions	Synthetic	TOPFARM Smart Start Optimization
Array cabling layout	To be provided	-
Bathymetry at turbine positions	Water depth in meters, available as netcdf file.	GEBCO (2024)

The provided bathymetry data is shown in Figure 2.3.1.2. The Danish energy island case has depths that range between 25 and 60 meters.

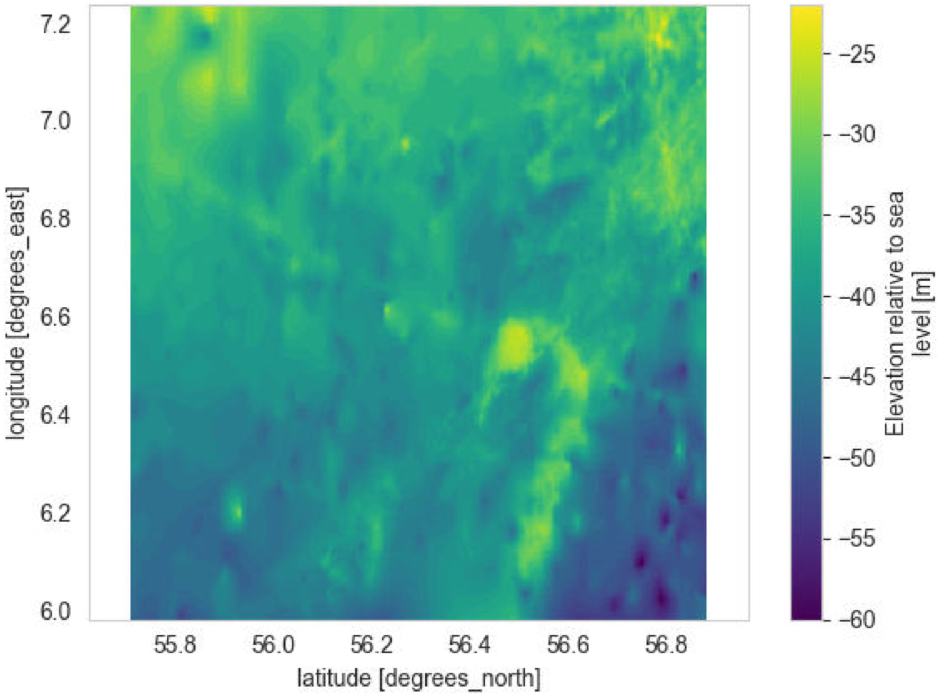


Figure 2.3.1.2: Bathymetry at turbine positions for Danish energy site (GEBCO, 2024)

Component	Definition, parameterization	Source / assumption
Wind turbine	IEA-22-280-RWT	22MW offshore reference wind turbine developed by the IEA Wind Task 55
Turbine support structure	IEA-22-280-RWT Monopile	22MW offshore reference monopile foundation developed by the IEA Wind Task 55

2.3.2 Market and business case

For the Danish Energy Cluster, Balmorel finds a negligible correlation between the median price of electricity and the wind speed. However, larger electricity prices (e.g., the 90th percentile), we see a clear correlation between speed and price. Similarly, there appears to be a correlation between peak electricity prices and wind direction.

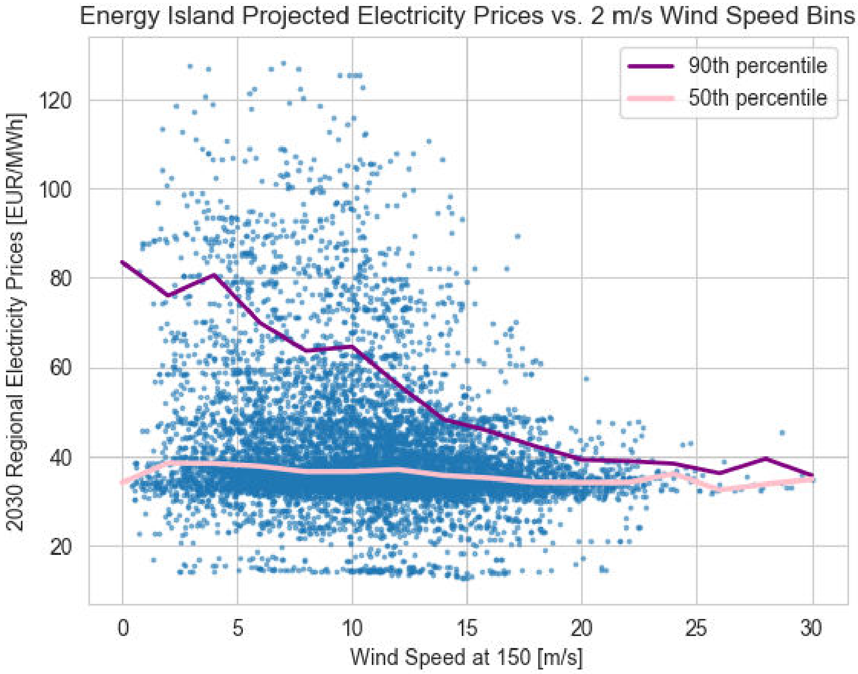


Figure 2.3.2.3: 2030 forecasted DK1 region electricity prices vs. ERA5 wind speed for Danish Energy Island case. Percentiles calculated for 2 m/s wind speed bins.

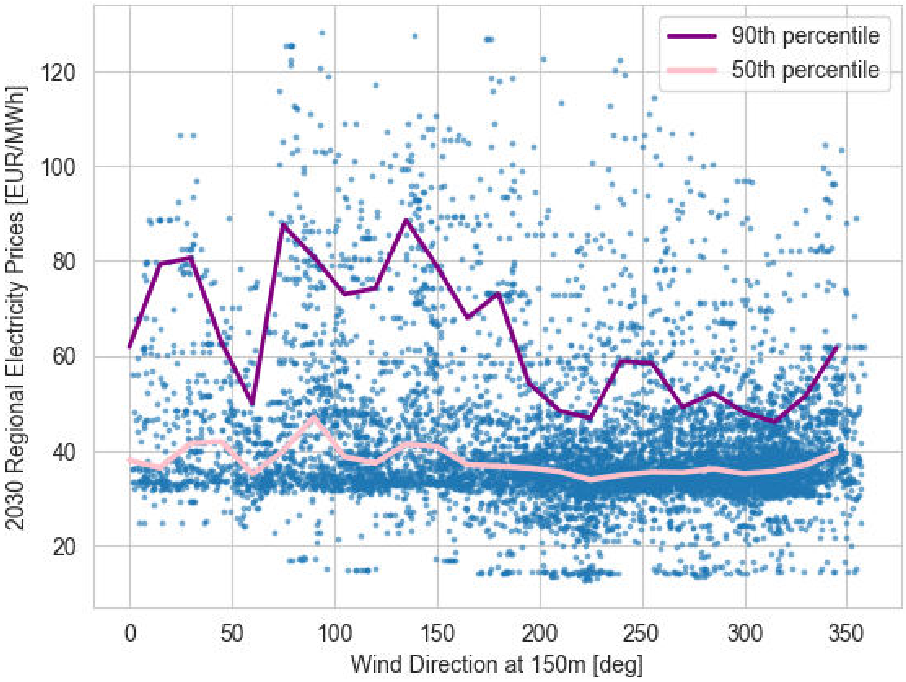


Figure 2.3.2.4: 2030 forecasted DK1 region electricity prices vs. ERA5 wind direction for Danish Energy Island case. Percentiles calculated for 15-degree wind direction bins.

Funded by
the European Union.

2.3.3 Environment

The wind resource is characterized using ERA5 data. The data is available as hourly timeseries. Wind rose at the nearest ERA5 grid cell to the energy island plotted in Figure 2.3.3.5. Wind farm flow is simulated using the 2012 ERA5 wind data, and the preliminary simulation results for 10 ± 2 m/s wind speed bin and 5-degree wind direction are visualized in Figure 2.3.3.6.

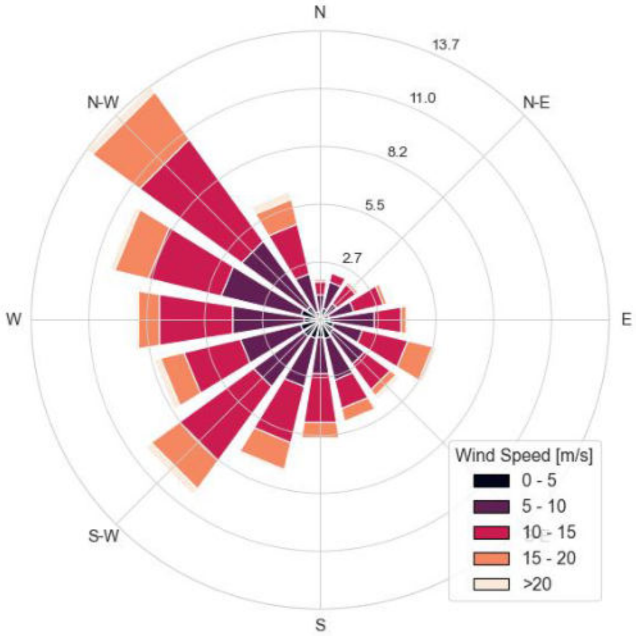


Figure 2.3.3.5: ERA5 annual wind speed and direction distribution at Danish Energy Island.

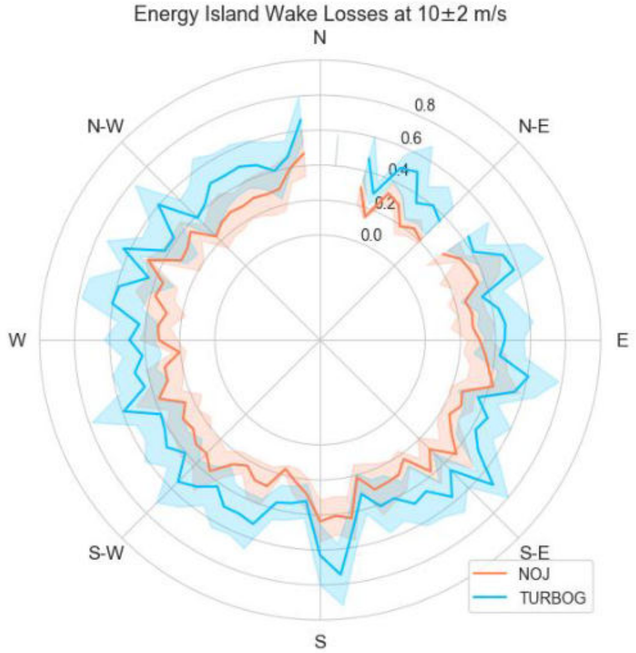


Figure 2.3.3.6: Simulated wake losses for Danish Energy Island at 10 ± 2 m/s wind speed, per 5-degree wind direction bins, using PyWake default literature models, TURBOG (Pedersen, 2022) and NOJ (Jensen, 1983) Losses from north and north-east are missing due to small number of samples within the bins.

Funded by
the European Union.

For environmental studies in this scenario (if applicable), the same method and assumptions are used as described in Section 2.1.3. The technology type for the DETECT tool and market zones for greenhouse gas displacements will be adapted accordingly.

3 Conclusions

This report gave an overview of the different wind park reference cases' definitions and data sources. The wind park reference cases are to be used for studies of economic and environmental impact assessments of wind park control. For the main case, the HKN park, the market and environmental conditions have been defined in most detail, and it will be used in the SUDOCO project for in-depth studies of the impact evaluation and optimization of wind park control. A baseline business case study for the wind park based on the definitions was attached. The other cases, Floating Wind Park and Danish Energy Island Cluster, are to be used in the SUDOCO project for specific impact assessments of wind park control in respectively floating wind parks and large clusters of wind parks.

Funded by
the European Union.

4 References

Carroll J, McDonald A and McMillan D; 2016; Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines; Wind Energy 19, p1107–1119

Clifton A, Smith A and Fields M; 2016; Wind Plant Preconstruction Energy Estimates: Current Practice and Opportunities; Tech. Rep. TP-5000-64735 NREL

Det Norske Veritas (DNV); 2014; Design of offshore wind turbine structures; DNV-OS-J101 Offshore Standard

Det Norske Veritas (DNV); 2010; Cathodic protection design; DNV-RP-B401 Recommended Practice

Det Norske Veritas (DNV); 2016; Corrosion protection for wind turbines; DNVGL-RP-0416 Recommended Practice

European Commission; 2021; Commission Recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations, C(2021)9332

Hardy S, Van Brusselen K, Hendrix S, Van Hertem D and Ergun H; 2019; Techno-Economic Analysis of HVAC, HVDC and OFAC Offshore Wind Power Connections; 2019 IEEE Milan PowerTech, pp 1–6

IPCC; 2014; Climate change 2013: The physical science basis (WMO IPCC) ISBN 978-1-107-66182-0

Kainz S, Guillore A and Bottasso C L; 2024; How do technological choices affect the economic and environmental performance of offshore wind farms? *J. Phys.: Conf. Ser.* (in review for the TORQUE 2024 conference).

Maness M, Maples B and Smith A; 2017; NREL Offshore Balance-of-System Model; Tech. Rep. TP-6A20-66874

Razdan P and Garrett P; 2019; Life Cycle Assessment of Electricity Production from an onshore V117-4.2 MW Wind Plant; Tech. rep. VESTAS

RVO (Netherlands Enterprise Agency); 2019; Hollandse Kust (noord) Wind Farm Zone Project and Site Description

Stehly T and Duffy P; 2021; 2020 Cost of Wind Energy Review; Tech. Rep. TP-5000-81209 NREL

Wernet G., Bauer C., Steubing B., Reinhard J.; 2016; The ecoinvent database version 3 (part I): overview and methodology; Int J Life Cycle Assess 21, p1218-1230

Worzyk T; 2009; Submarine Power Cables: Design, Installation, Repair, Environmental Aspects Power Systems; Springer Berlin Heidelberg, ISBN 9783642012709

4C Offshore; 2024; Hollandse Kust Noord Offshore Wind Farm; https://www.4coffshore.com/windfarms/netherlands/hollandse-kust-noord-netherlands-nl0f.html

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., 2020. The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), pp.1999-2049.

Mads M. Pedersen, Alexander Meyer Forsting, Paul van der Laan, Riccardo Riva, Leonardo A. Alcayaga Romàn, Javier Criado Risco, Mikkel Friis-Møller, Julian Quick, Jens Peter Schøler Christiansen, Rafael Valotta Rodrigues, Bjarke Tobias Olsen and Pierre-Elouan Réthoré. (2023, February). PyWake 2.5.0: An open-source wind farm simulation tool. DTU Wind, Technical University of Denmark.

Jensen, N. O., 1983. A note on wind generator interaction. Risø National Laboratory. Risø-M No. 2411.

Pedersen, J.G., Svensson, E., Poulsen, L. and Nygaard, N. G, 2022. Turbulence Optimized Park model with Gaussian wake profile. J. Phys.: Conf. Ser. 2265 022063

Gea-Bermúdez, J., Jensen, I.G., Münster, M., Koivisto, M., Kirkerud, J.G., Chen, Y.K. and Ravn, H., 2021. The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050. Applied Energy, 289, p.116685.

Swisher, P., Leon, J.P.M., Gea-Bermúdez, J., Koivisto, M., Madsen, H.A. and Münster, M., 2022. Competitiveness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050. Applied Energy, 306, p.118043.

Gea-Bermúdez, J., Bramstoft, R., Koivisto, M., Kitzing, L. and Ramos, A., 2023. Going offshore or not: Where to generate hydrogen in future integrated energy systems?. Energy Policy, 174, p.113382.

Funded by
the European Union.

J. P. Murcia, M. J. Koivisto, G. Luzia, B. T. Olsen, A. N. Hahmann, P. E. Sørensen, and M. Als, “Validation of European-scale simulated wind speed and wind generation time series,” Applied Energy, vol. 305, p. 117794, 2022.

Larsén, X.G., Kalogeri, C., Galanis, G. and Kallos, G., 2015. A statistical methodology for the estimation of extreme wave conditions for offshore renewable applications. Renewable Energy, 80, pp.205-218.

GEBCO - The General Bathymetric Chart of the Oceans, 2024, https://www.gebco.net/data_and_products/gridded_bathymetry_data/

DeepOWT, 2022, A global offshore wind turbine dataset; DOI 10.5281/zenodo.5933966

WAB-S, 2024. World Wind Turbine Map, https://turbinemap.wab-s.de/

TenneT, 2022, Offshore Grid Hollandse Kust (Noord) - Documentation. https://offshore-documents.tennet.eu/nl/tender-hollandse-kust-noord-documentation

Youwind Solution, a web-based app for wind park data, engineering and finance, 2024. http://app.youwindrenewables.com

Funded by
the European Union.

5 Appendix A

In this Appendix we include a business case overview of the different reference wind park cases, based on the Youwind Solution (2024) model. They are included to demonstrate that the different component, market, and geographic layout assumptions as described above can be used to model the park's yield, costs and financial performance using techno-economic modelling. This baseline case assumes no wind park control to reduce wake losses, and it does not include the energy storage facility. It can be used as a baseline comparison for different financial modelling efforts in other Work Packages.

5.1 Appendix A.1 "Hollandse Kust Noord" financial scenario overview

Turbine assumptions	
Turbine	Innwind 10MW scaled to SG 11.0-200 DD
Turbine unit cost (million)	€10.00
Turbine design life (years)	25
Installation time (days/position)	3.0

Foundation assumptions	
Foundation Category	Monopile
Calculated foundation steel weight (tons)	979.7
Fabrication steel price (currency/ton)	€2,410.00
Concrete (m³, per turbine position)	0.0
Concrete price (currency/m³)	€250.00
Foundation scour protection cost (currency, per turbine position)	€500,000.00
Installation time (days/position)	2.5

Array Cable assumptions	
Array cable	NREL XLPE 630mm 66kV
Total price of fabrication and installation, static part (million/km)	€0.35
Total price of fabrication and installation, dynamic part (million/km)	€0.50
Calculated Array Cable Length, static part (km)	114.22
Calculated Array Cable Length, dynamic part (km)	0.0

Export Cable assumptions	
Cable total length (km)	83.76
Total price of fabrication and installation (million/km)	€2.50
Number of export cables	2

Production overview

Mean wind speed at hub height (m/s)	9.47
Gross AEP (MWh)	3,917,436
Production capacity (MW)	759.0
Export capacity (MW)	759.0
Net P(50) AEP (MWh/a)	3,359,698
P90 P50 Ratio	0.91
Capacity factor (Gross, %)	58.9
Capacity factor (Net, %)	50.5
Full load hours (h/y)	4426

Efficiency and availability (%)		
Wake effect (NOJ model, k=0.04)	**Total wake effect (%)**	93.2
	Internal wake loss efficiency (%)	93.3
	External wake loss efficiency (%)	99.9
Availability	**Total availability (%)**	95.47
	Turbine availability (%)	98.0
	Balance of plant efficiency (%)	99.8
	Array Cable Availability (%)	99.1
	Export Cable Availability (%)	99.0
	Grid availability (%)	99.5
Electrical	**Total electrical (%)**	97.42
	Array Cable Efficiency (%)	98.8
	Export Cable Efficiency (%)	99.2
	Offshore substation efficiency (%)	99.4
Curtailments and operational strategies	**Total curtailment (%)**	98.9
	Curtailment efficiency (%)	98.9
Overall efficiency (%)		85.8

CAPEX (million)	
Total CAPEX (million)	€1,670.51
Total CAPEX (million / MW)	€2.20
Turbine cost (million)	€724.93
Turbine installation cost (million)	€55.96
Foundation fabrication cost (million)	€207.40
Foundation platform and transition piece fabrication cost (million)	€171.16
Foundation concrete base fabrication and scour protection cost (million)	€36.25
Foundation installation cost (million)	€49.43
Harbor and logistics (million)	€15.00
Array cables cost (million)	€42.00
Export cables cost (million)	€220.00
Offshore substation cost (million)	€78.80
Platform cost (million)	€78.80
Onshore substation cost (million)	€84.05
Platform cost (million)	€84.05

Funded by
the European Union.

Engineering development cost (million)	€22.17
Environmental surveys cost (million)	€7.39
Insurances under construction cost (million)	€14.78
Budget contingency cost (million)	€73.92
Decommissioning cost (million)	€73.92

Yearly OPEX (million)	
Turbine service agreement (million/yr)	€26.22
Offshore logistics (million/yr)	€9.66
Technicians and contractors (million/yr)	€2.76
Balance of Plant (million/yr)	€3.45
Facility cost (million/yr)	€4.14
Surveys and inspections (million/yr)	€0.69
Insurance cost (million/yr)	€2.76
Total OPEX (million/yr)	€49.68
Total OPEX (thousands/MW)	€65,454.55
Total OPEX (thousands/position)	€720.00
Project lifetime (years)	25
Total lifetime OPEX (million)	€1,304.88

For this case study, the above was combined with an example Power Purchase Agreement (PPA) year-to-year price table:

PPA example for HKN The Netherlands	
Year 1 to year 5	€55
Year 6 to 15	€40
Year 16 to 20	€70
Year 21 to 25	€65
Financial indicators	
Project lifetime (years)	25
Project IRR (%)	6.37
LCOE (currency/MWh)	€59.82
NPV (million)	€233.86
Average EBITDA (million)	€190.58

5.2 Appendix A.2 “Floating wind park” financial scenario overview

Turbine assumptions	
Turbine	IEA-22-280-RWT
Turbine unit cost (million)	€25.00
Turbine design life (years)	25
Installation time (days/position)	4.0

Foundation assumptions	
Mooring system type	catenary
Mooring tethering line cost (currency/m, per tethering line)	€700.00
Number of moor tethering lines	4
Average mooring tethering line length (m)	602.7
Mooring anchor price (currency, per individual anchor)	€150,000.00
Average steel weight foundation, excluding mooring cables (tons)	4500.0
Average steel weight transition piece (tons)	200.0
Calculated foundation steel weight (tons)	4700.0
Fabrication steel price (currency/ton)	€3,500.00
Foundation scour protection cost (currency, per turbine position)	€20,000.00
Installation time (days/position)	15.0

Array Cable assumptions	
Array cable	NREL XLPE 630mm 66kV
Total price of fabrication and installation, static part (million/km)	€0.35
Total price of fabrication and installation, dynamic part (million/km)	€0.50
Calculated Array Cable Length, static part (km)	183.04
Calculated Array Cable Length, dynamic part (km)	47.25

Export Cable assumptions	
Export cable	220 kV Floating 465 MW
Cable total length (km)	170.46
Total price of fabrication and installation (million/km)	€1.30
Number of export cables	4

Production overview	
Mean wind speed at hub height (m/s)	8.71
Gross AEP (MWh)	6,061,688
Air density adjustment (%)	No adjustment made
Production capacity (MW)	1,386.0
Export capacity (MW)	1,386.0
Net P(50) AEP (MWh/a)	4,767,265

Efficiency and availability (%)

Wake effect (NOJ model, k=0.04)	**Total wake efficiency (%)**	87.0
	Internal wake loss efficiency (%)	87.0
Availability	**Total availability (%)**	92.58
	Turbine availability (%)	96.0
	Balance of plant efficiency (%)	99.8
	Array Cable Availability (%)	99.1
	Export Cable Availability (%)	98.0
	Grid availability (%)	99.5
Electrical	**Total electrical (%)**	98.11
	Array Cable Efficiency (%)	98.8
	Export Cable Efficiency (%)	99.3
Environmental	**Total environmental (%)**	99.5
	Blade degradation efficiency (%)	99.5
Overall efficiency (%)		78.6

CAPEX (million)	
Total CAPEX (million)	€4,219.62
Total CAPEX (million / MW)	€3.04
Turbine cost (million)	€1,704.83
Turbine installation cost (million)	€19.09
Foundation fabrication cost (million)	€1,279.14
Foundation mooring fabrication cost (million)	€156.00
Foundation platform and transition piece fabrication cost (million)	€1,121.78
Foundation concrete base fabrication and scour protection cost (million)	€1.36
Foundation installation cost (million)	€71.60
Harbor and logistics (million)	€15.00
Array cables cost (million)	€94.92
Export cables cost (million)	€239.86
Offshore substation cost (million)	€113.66
Platform cost (million)	€113.66
Onshore substation cost (million)	€129.89
Platform cost (million)	€129.89
Engineering development cost (million)	€110.08
Environmental surveys cost (million)	€36.69
Insurances under construction cost (million)	€36.69
Budget contingency cost (million)	€183.46
Decommissioning cost (million)	€183.46

Yearly OPEX (million)	
Turbine service agreement (million/yr)	€20.16
Offshore logistics (million/yr)	€7.56
Technicians and contractors (million/yr)	€2.21
Balance of Plant (million/yr)	€2.84
Facility cost (million/yr)	€2.84

Surveys and inspections (million/yr)	€0.63
Insurance cost (million/yr)	€2.52
Total OPEX (million/yr)	€38.75
Total OPEX (thousands/MW)	€27,954.55
Total OPEX (thousands/position)	€615.00
Total lifetime OPEX (million)	€1,048.47

The above was combined with a subsidy scheme to arrive at the following financial indicators.

Subsidy and Project Financial indicators	
Bid price at FID (€/MWh)	€120.00
Market price after subsidy (€/MWh)	€65.00
Number of years with subsidy	20
Project lifetime (years)	25
Project IRR (%)	11.45
LCOE (currency/MWh)	€85.28
NPV (million)	€4,659.58
Average EBITDA (million)	€731.94