Environmental data for the planning of off-shore wind parks from the EnerGEO Platform of Integrated Assessment (PIA)

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Abstract
The EU-sponsored EnerGEO project aims at providing decision makers with a modelling platform to assess the environmental impacts of different sources of renewable energy. One of the pillars of the project is the Wind Energy Pilot, addressing the effects of offshore wind parks on air pollution and energy use. The methods used in the pilot and the underlying environmental databases are integrated into a WebGIS client tool and made available to the public. This paper is dedicated to describing the environmental databases and supporting data incorporated in the client tool. A 27-km resolution, 11-year wind database is created using the WRF model. The wind database is used to assess the wind climate in the north-west Atlantic region and to derive the potential power output from offshore wind parks. Auxiliary data concerning water depth, distance to shore and distance to the nearest suitable port are created to aid the planning and maintenance phases. Seasonal workability conditions are assessed using a 20-year wave database. The distance at which future wind parks should be placed to exhibit different wind climates is investigated.

1. Introduction

The EU-sponsored EnerGEO project aims at providing a versatile modelling platform that enables planners, environmentalists and governments to calculate, forecast and monitor the environmental impact of changes in the way energy is produced. The project is organised in four pilots, focusing on different types of renewable energy. One of these is the Wind Energy Pilot, assessing the effects of offshore wind parks on air pollution and energy use throughout their entire life cycle. The objective of the wind pilot is twofold:

1. Provide decision-makers with the information needed for the selection of future windpark locations based on administrative, technical and environmental criteria;
2. Assess the environmental performance of wind farms at the selected locations.

The first objective is fulfilled using environmental databases, including information on the wind climate, wave conditions and water depths. The second objective is addressed by carrying out a full life cycle assessment (LCA). The environmental databases and the LCA are integrated into a WebGIS tool (Blanc et al 2012). With this tool, the environmental performance of offshore wind parks can be assessed over their life cycle.

This paper presents the environmental databases used in the wind pilot and their integration in the WebGIS client tool. For a description of the LCA for the wind pilot see Blanc et al 2012.

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2. Methodology

The wind pilot encompasses several environmental databases which are used to provide information products for decision makers, as well as for the LCA. The databases cover north-west Europe and a part of the Atlantic. The data set includes: an 11-year wind database, a 20-year wave database, a map of the distance to shore for all offshore locations, a map of the distance to the nearest accessible harbour and a high-resolution depth chart. In the following, the wave and wind models used for producing the multi-year wind and wave databases are described.

2.1 The wind database

The wind database is created using the so-called Weather Research and Forecasting model "WRF" (Skamarock et al 2005). WRF is a state-of-the-art, open source model, intensively used in operational forecasting environments and for atmospheric research. WRF is a so-called limited area model, operating on a region of the globe. It is less computationally intensive than global models and allows the use of much higher spatial resolutions (1 km or better). A limited area model requires information on the state of the atmosphere along its lateral boundaries. For creating the wind database, the WRF model is initialised and forced at the outer boundaries by data from the final analysis (FNL) of the Global Forecast System (GFS), available from the National Centers for Environmental Prediction (NCEP) from 2000 onwards. This data is a historical collection of all "best estimate" analysis results from the GFS, incorporating a large variety of observations.

The WRF model domain covers the north-west Atlantic (see figure 1). WRF is configured with a 27-km horizontal resolution (adequate over open sea and appropriate for large-scale weather analysis), 31 vertical levels and an output interval of 1 hour. The initial and boundary conditions are taken from FNL (6-hourly data, 1° resolution). The land-use classifications are provided by MODIS (1-km resolution). The model was run for the period January 2000 – December 2011. The resulting database includes, amongst other meteorological variables, the surface values and vertical profiles of the wind components.

2.2 The wave database

The wave model used to create the wave database is WAVEWATCH III (Tolman 2002), developed at NOAA/NCEP. The model can be applied on spatial scales larger than 1 to 10 km, outside the surf zone. The WAVEWATCH III model domain used for creating the wave database covers the area from 40°N to 66°N and 15°W to 31°E. The model was run at a 10'x10' resolution. The driving winds were provided by the European Centre for Medium-range Weather Forecasts (ECMWF) global model. The wave database covers the last 20 years.

3. Results

One of the most important factors when selecting future wind park locations is the power output which can be expected from the turbines. This can be estimated based on the wind climate of a given region. Various types of geographical information are also of great importance: the water depth has to be suitable for the selected turbine funding, the distance to the closest power grid/shore determines the costs of under-sea cabling, the distance to the closest suitable port influences the costs of deploying and later repairing the turbines. Maintenance schedules are highly affected by the local wave conditions, therefore the wave climate should also be taken into account during the decision process. Another consideration is the relative placing of various wind parks in order to minimise the changes in power output due to variations in wind conditions. In the following, these aspects are considered one by one.

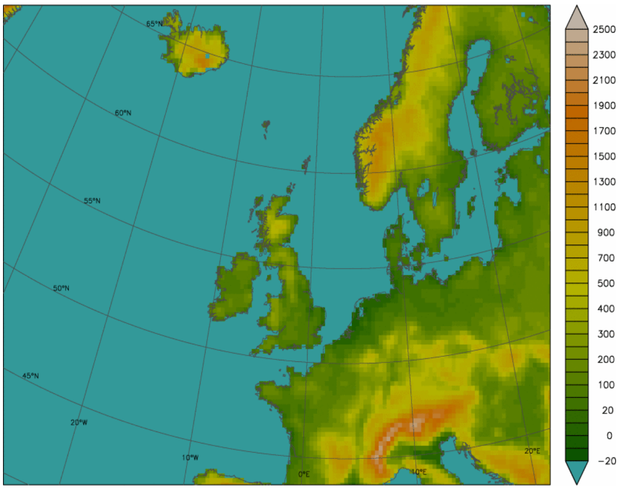


Figure 1
Orography map (heights in m) of the 27-km resolution WRF model domain.

3.1 Wind turbine electrical power output

The relationship between the electrical power generated by a wind turbine and the wind speed at hub height is described by the so-called power curve. Figure 2 reports the power curve which corresponds to the Areva 5 MW turbine selected for our project. At low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. The wind speed at which the turbine first starts to rotate and generate power is called the "cut-in speed" and is typically between 3 and 4 m/s. As the wind speed rises above the cut-in speed, the level of electrical ouput power rises rapidly. However, typically somewhere between 12 and 17 m/s, the power output that the electrical generator can produce reaches its limit. This limit is called the "rated power output" and the related wind speed the "rate output wind speed". At higher wind speeds, the power output is limited to this maximum level (typically by adjusting the blade angles). As the wind speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. The wind speed where this happens is called the "cut-out speed" and is usually around 25 m/s.

Given the properties of the wind turbine power curve, the local wind climate is decisive when assessing the expected energy output from an offshore wind park. The left panel of figure 3 shows the mean wind speed offshore at hub height (taken to be 100 m), determined from the 11-year WRF wind hindcast data. The highest values are reached in the Atlantic, but also the shallower North Sea shows high wind speeds.

For design studies, the variability of the wind speed is also important. The right panel of figure 3 shows a histogram of the model wind speeds at one particular location in the North Sea (53.1°N, 2.2°E). For an overview of the variability, the standard deviation of the wind speed time series is plotted in the left panel of figure 4.

Applying the power curve to the 11-year wind speed time series gives a time series of produced power. The average power production per turbine is shown in figure 4. The maximum power output of about 3 MW is reached in the Atlantic. In the North Sea values of over 2.5 MW can be attained which is more than half of the maximum possible production (assuming no turbine failures). The inter-annual variability in wind speed affects the yearly power production. Figure 5 shows the standard deviation of the yearly power averages. In the North Sea a variation of one standard deviation in the yearly production amounts to a 7% change in power output.

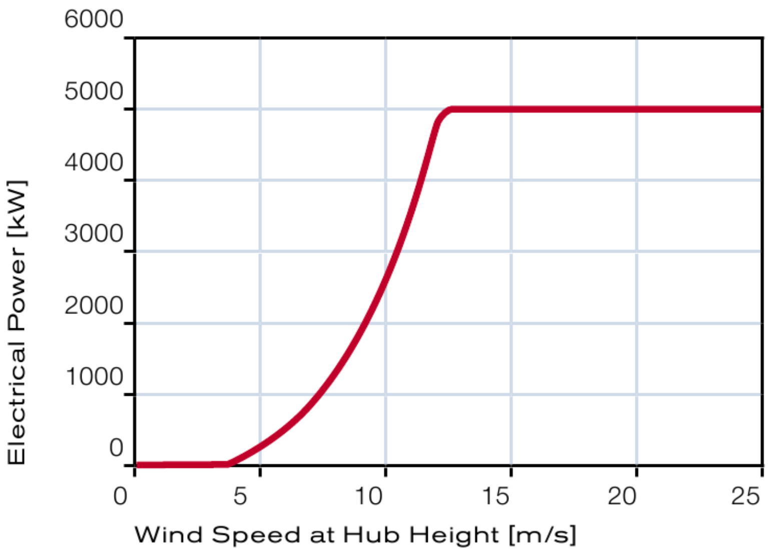


Figure 2
Power curve for a 5 MW turbine (source : Version: 07/ 2010. ©AREVA Wind GmbH). For wind speeds below 4 m/s or above 25 m/s no power is produced. For wind speeds between 12.5 m/s and 25 m/s the power production is constant at 5000 kW. Between these two regimes the power output increases rapidly with increasing wind speed.

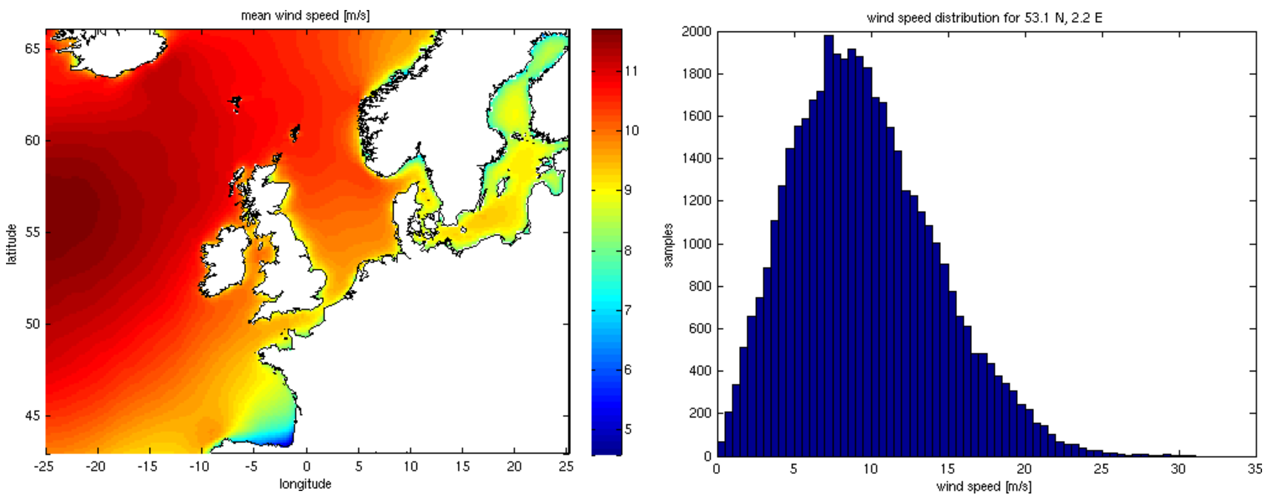


Figure 3
Left: Mean wind speeds at hub height (100 m) in m/s based on the 11-year wind database. Right: Histogram of the wind speed distribution at 53.1°N, 2.2°E based on the 11-year wind database.

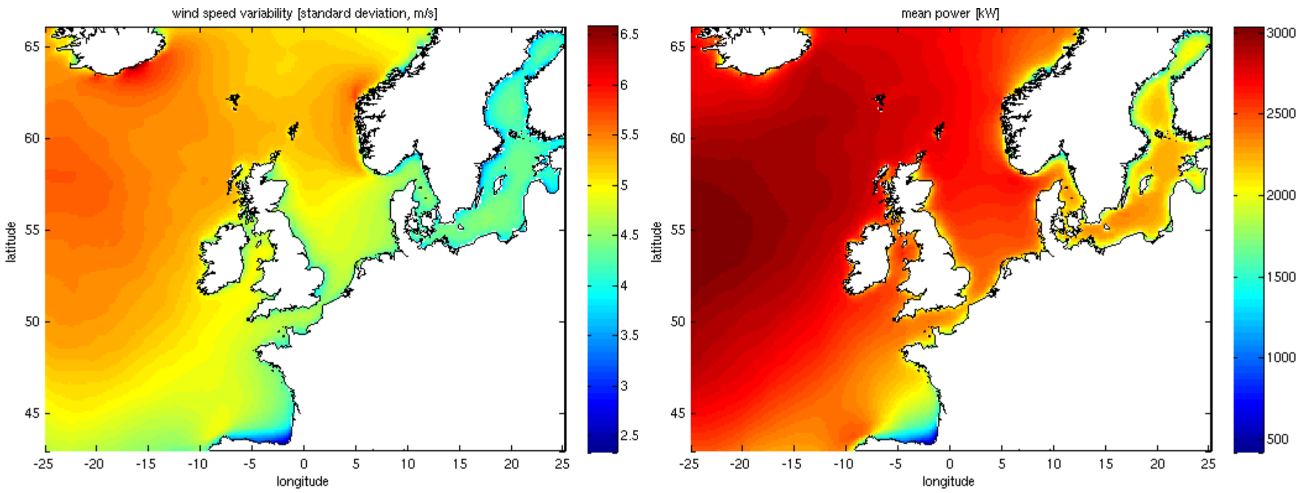


Figure 4

Left: Standard deviation of the wind speeds at hub height (100 m) based on the 11-year wind database.
Right: Average power production (in kW) for a 5 MW turbine based on the 11-year wind database.

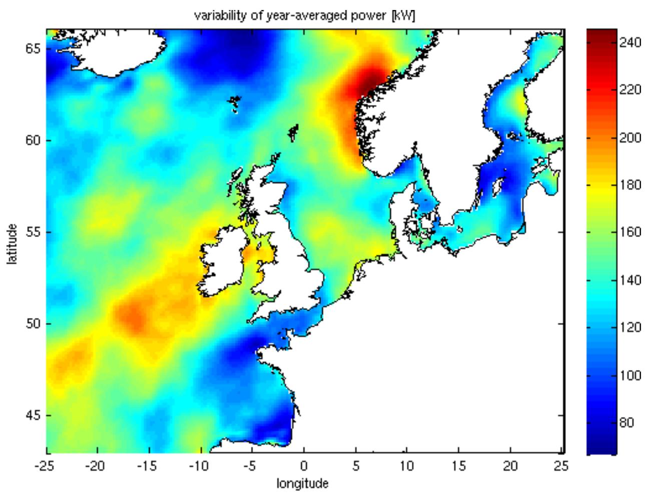


Figure 5

Standard deviation of the mean power for the 11-year wind database in kW.

3.2 Accessibility and workability

In addition to the properties of the local wind climate, various types of geographical information are also essential during the planning phase of a wind farm. These information include the water depth, the distance to the shore/nearest power grid and the distance to the nearest suitable port. During the operational phase of a wind park the ability of doing maintenance is also crucial. This is primarily determined by the local wave conditions.

The type of turbine foundation to be used depends on the local water depth. The left panel of figure 6 shows the water depth in the pilot area. In most parts, water depths exceed 1 km which is too deep for turbines with fixed foundations. The right panel of figure 6 shows the areas with water depths up to 200 m with deeper areas masked out. The depth fields were created using Admiralty Chart data. These data, consisting of contour lines and point measurements, were interpolated to a regular grid with the help of dedicated software, developed at BMT ARGOSS. In shallow waters the quality of the gridded depth charts is better than that of available open source bathymetric data.

The left panel of figure 7 depicts the distance to shore which is essential when calculating the costs of the laying and maintenance of cables. The distance to the closest suitable port is important both during the building phase and when considering maintenance. The right panel of figure 7 shows the distance to the nearest port with a minimum draught of 10 m.

The maintenance of offshore wind parks is typically carried out by ships. A wave height of 1.5 m – 2 m is generally the limit for safe personnel transfer from ship to turbine. The 20-year wave database was analysed to distinguish between periods with significant wave heights below or above 1.5 m. Example seasonal statistics for the winter and summer periods are shown in figure 8. During autumn (not shown) and winter the unworkable fraction of time is close to 100% on the Atlantic and above 65 to 70% in most of the North Sea. Maintenance in the Baltic Sea is much less hampered by the occurrence of high waves.

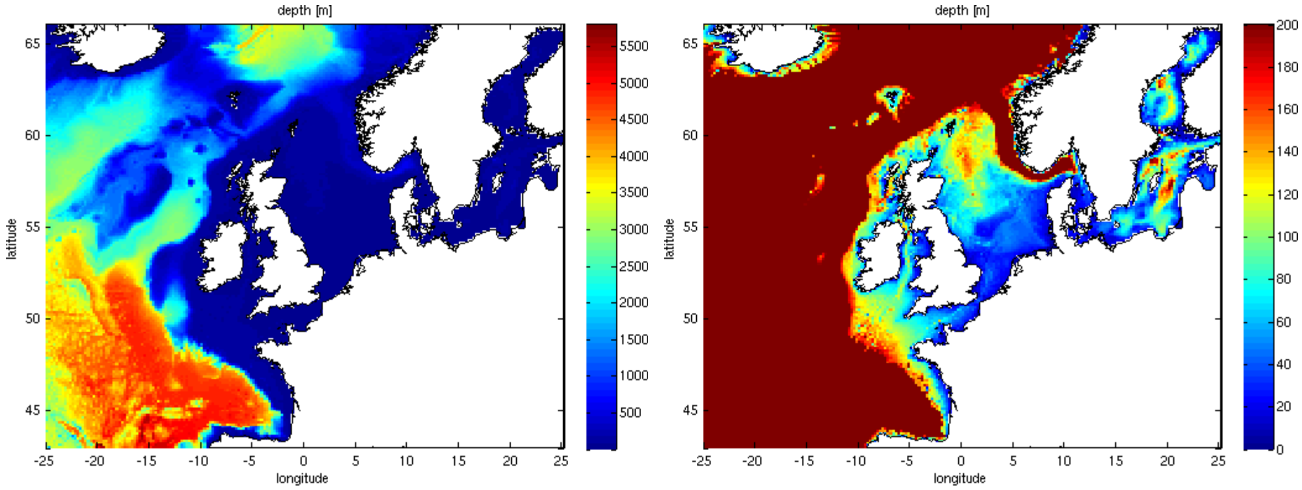
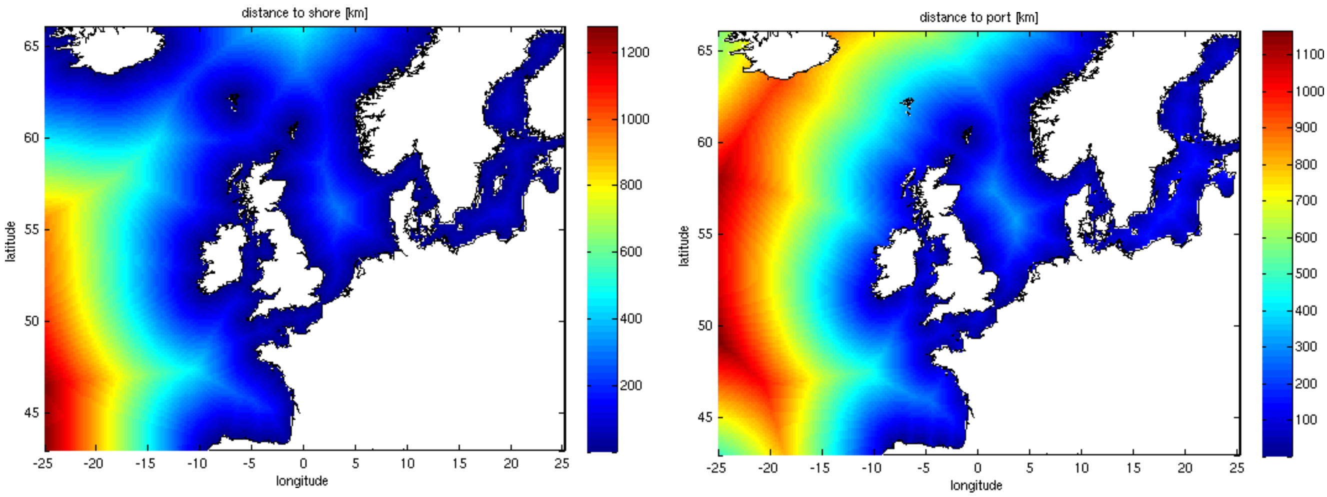


Figure 6

Left: Water depth in the pilot area in m. Right: Areas with a water depth up to 200 m.



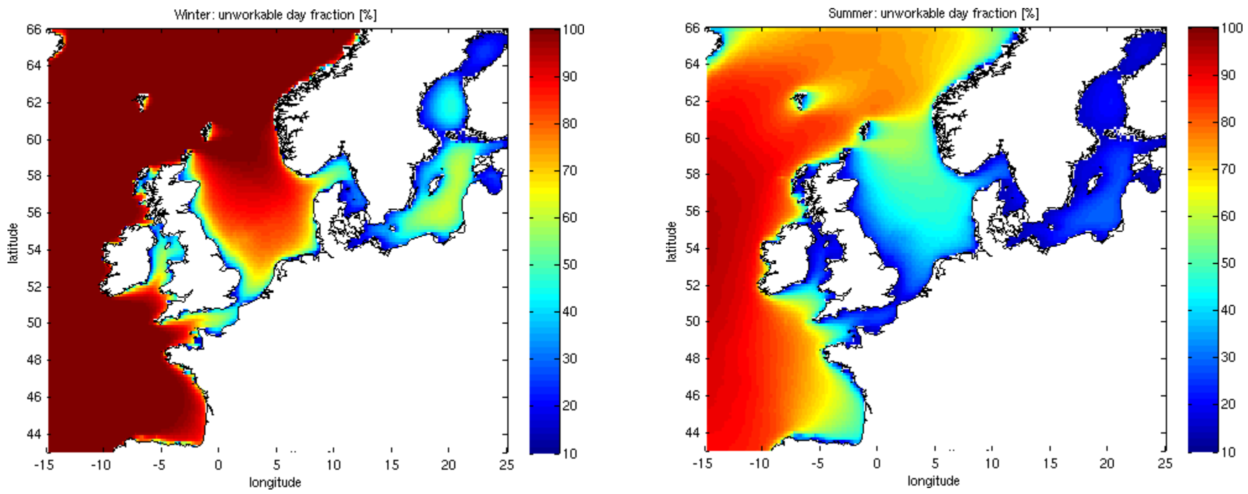


Figure 7

Left: Distance to shore in km. Right: Distance (km) to the nearest port with a minimum draught of 10 m.

Figure 8

Percentage of the time when no maintenance can be done (significant wave heights exceeding 1.5 m). Left: winter, right: summer.

3.3 Intermittency

The electricity output from a wind park fluctuates strongly due to local changes in wind speed. To satisfy demand, this often means that electricity needs to be harnessed from other sources. One way to mitigate the cosequences of intermittency is to combine the production of different parks, hoping that if one park cannot deliver, another one can. However, if all parks are concentrated in one area, a period of low wind will affect them all. A relevant question is therefore: how far apart should two wind parks be positioned for their energy production to be uncorrelated? To test this, the correlation between wind speed time series at all locations and at one location off the British coast is calculated. The result is presented in figure 9 and shows that at distances of about 600 km the correlation is reduced to about 0.5.

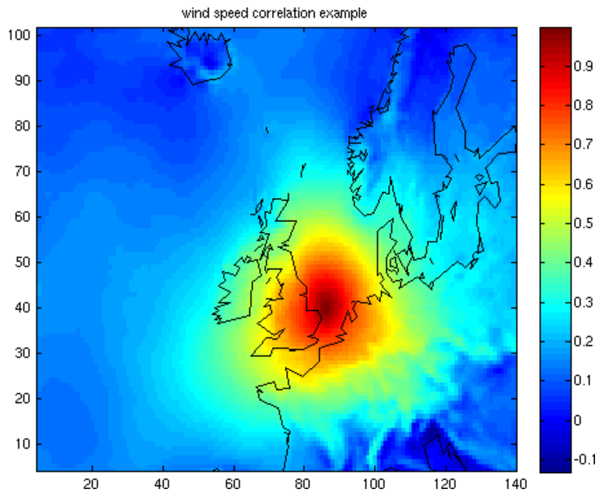


Figure 9
Correlation of wind speeds between one location off the English coast and all other locations on the map.

Next, three locations, placed far apart, are selected. The power production is analysed separately for each site and also for their combination. One location is in the North Sea off the English coast, another in the Baltic Sea, off the Swedish coast and the last one north of NW Spain. For simplicity, one turbine is assumed at each location. The results are shown in figure 10 in the form of power histograms. In these histograms the x-axis shows the power bins and the y-axis the number of samples, i.e., the number of hours in the 11-year time series during which the power production falls inside a given power bin. Three histograms show the power production at the individual locations and one depicts their combined power production, calculated from the sum of the three power time series. Each individual power histogram shows two high values: one at zero power (for wind speeds between 0 and 4 m/s or more than 25 m/s) and one at the maximum 5000 kW level (for wind speeds between 12.5 and 25 m/s). The peak at zero (when other sources need to take the energy production over) is the one which should ideally be eliminated. In the combined power histogram this peak is no longer present, meaning that temporary power shortages due to low wind speeds can be balanced by a careful distribution of wind parks.

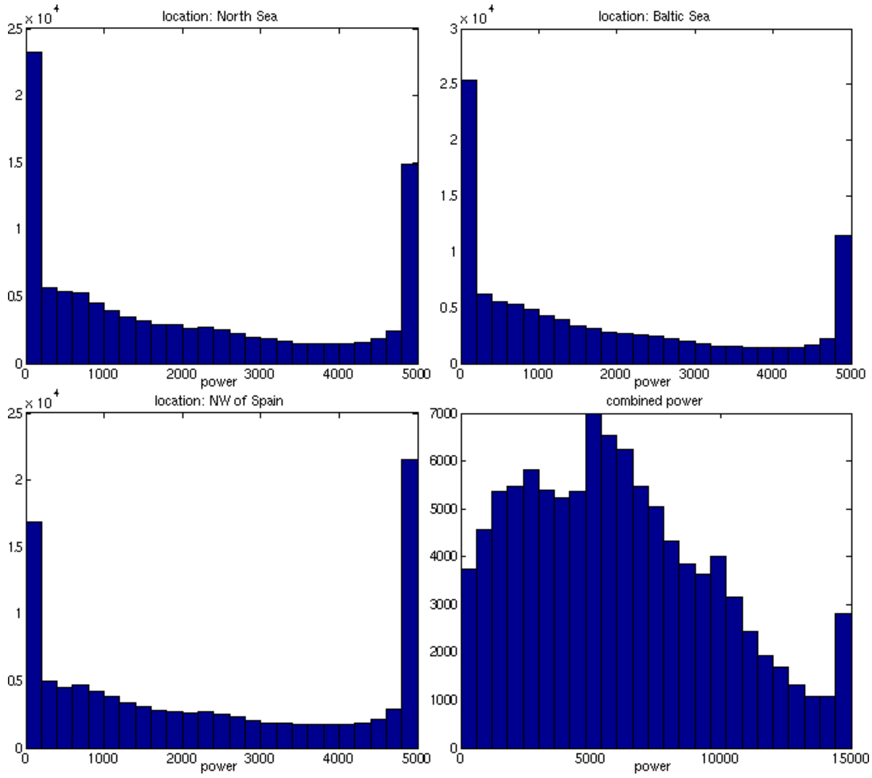


Figure 10

Histograms of power production at three separate locations and their combination (bottom right). The y-axes show the number of hours in the 11-year wind time series when the power production fell into a given power bin (x axes).

4. WebGIS client tool

The environmental data sets and life cycle analyses are integrated into a WebGIS client tool[2]. This WebGIS client is easily accessible from the Internet and is meant to be used by energy operators, energy policy decision-makers as well as offshore wind parks developers. Figure 11 shows a screenshot of the client tool. The environmental impacts and supporting data are visualised in the form of maps. These maps have been deployed in a GeoServer as Web Map Services (WMS) to ease their dissemination in line with previous works (Ménard et al 2012). WMS is a standard defined by Open Geospatial Consortium (OGC) and follows the interoperability rules of the Global Earth Observation System of Systems (GEOSS)

The client tool can be used to perform a life cycle assessment for wind parks (Blanc et al. 2012). The environmental data on which the life cycle assesment is based can also be visualised separately. In order to achieve this, all the information described in this paper were added to the client tool in the form of map layers. These maps are prepared in advance (e.g., workability maps, wind speed maps, etc.). They are presented on an equidistant latitude-longitude grid. Since the original wind database uses a Lambert

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[2] http://viewer.webservice-energy.org/energeo_wind_pilot/index.htm

projection, the data had to be converted to the regular lat-lon grid using Delaunay triangulation. When clicking on a specific area of the map, the numerical value of the corresponding variable appears.

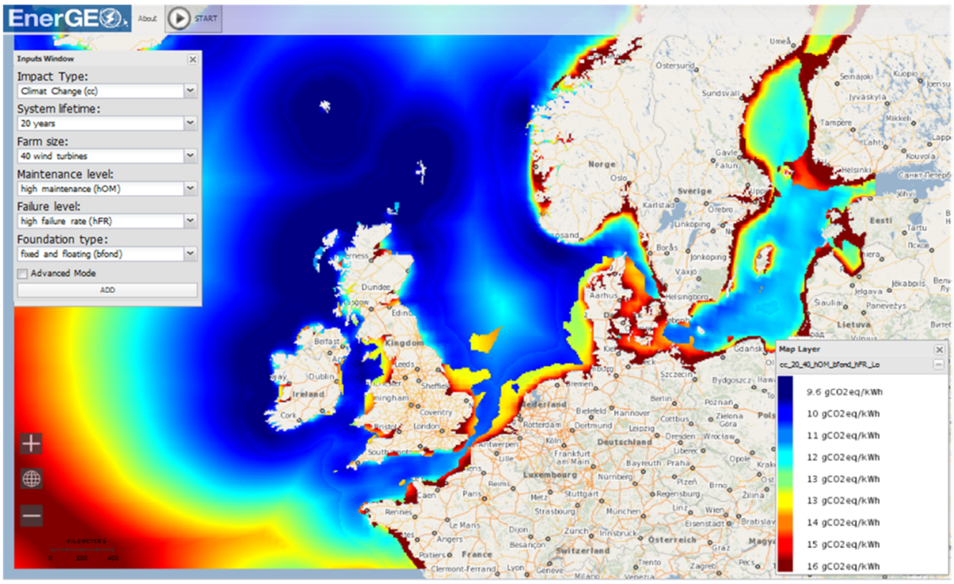

Figure 11
Screenshot of the web map service developed for EnerGEO, showing an environmental map for climate change expressed in g CO_2 eq/kWh (source: http://viewer.webservice-energy.org/energeo_wind_pilot/index.htm).

5. Summary and conclusions

In this EnerGEO pilot an 11-year wind data set is created for offshore areas in north-west Europe using the WRF model. The data is used to assess the wind climate in the region and to derive the expected power output from offshore wind farms. Additional data sets concerning water depth, distance to shore and distance to ports are created to aid the planning phases. Using a 20-year wave database, the percentage of time when no maintenance can be done (significant wave heights exceeding 1.5 m) is identified for each season.

The 11-year wind database is also used to investigate the statistical characteristics of the intermittency of the wind speeds and their effect on the power output. It is found that one way to mitigate intermittency effects is to combine the contribution from wind parks at different locations into an European energy grid. A correlation analysis is used to estimate how far apart wind parks should be placed: at distances of about 600 km the correlation in energy production drops to 0.5. As an example, the statistical power production for the combination of three turbines (one in the North Sea, one in the Baltic sea, and one north-west of Spain) is determined and found to be much more homogeneous than that of the individual turbines.

Condensed user information, derived from the produced data sets, is made available in the EnerGEO wind pilot WebGIS client tool. In the near future, the data will also be linked to various GEO portals to support decision makers in the planning of offshore wind parks.

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