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Offshore Wind Atlas of the Dutch part of the North Sea

A.J. Brand

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A J Brand
ECN Wind Energy, P.O. Box 1, NL 1755 ZG Petten, Netherlands
E: brand@ecn.nl, T: +31 224 56 4775, F: +31 224 56 8214

Abstract A wind resource map of the Dutch part of the North Sea was made. The methodology (which can be applied to any region in the world), an example of the wind resource and the validation of the wind data are presented.

Key words Wind atlas, Offshore, North Sea

1. Introduction

Dutch offshore wind energy will be developed in the Dutch part of the North Sea, also known as the Netherlands Exclusive Economic Zone (NEEZ). To date there are two sites: OWEZ (previously known as NSW Egmond) and Princess Amalia Wind Farm (Q7-WP), and more are being developed.

The wind speed at turbine hub height is the primary parameter that determines the energy production of a wind turbine. State-of-the-art offshore hub height is 60 meter, but it may increase to 150 meter within five to ten years. Maps with the average wind speed between 60 and 150 meter above mean sea level therefore contain information for a rough estimate of the average energy production. For a realistic production estimate and for design purposes more detailed information is needed: the distribution of the wind speed and the wind direction (site selection or farm design), and the distributions of the turbulence intensity and of stability class (turbine design).

In the past wind resource maps of the North Sea were based on observations from a small number of meteo stations [1][2][3][4][5]. Consequently these maps lack detail and their quality can not be assessed.

To overcome this, it was decided to combine data from:

- The numerical weather prediction model HiRLAM, and
- The meteorological stations at the North Sea [6].

This innovative approach, a variation to the Numerical Wind Atlas method [7], gives a realistic wind map because:

- The resource map is geographically detailed, and
- The observed data is used to validate rather than create the map.

The so created Offshore Wind Atlas of the Dutch part of the North Sea contains [8][9]:

- The mean wind speed at heights between 60 and 150 meter,
- Distributions of wind speed and direction, turbulence intensity and stability class.

And, although not contained in the Offshore Wind Atlas, time series with these wind data are available. Like all wind resource maps the Offshore Wind Atlas gives a description of the past (period 1997 to 2002 in this case) but gives only an indication of the future.

This paper presents the methods that were used in order to create the Offshore Wind Atlas of the Dutch part of the North Sea (section 2), examples of the wind resource (section 3), and the validation of the wind speed in the atlas (section 4).

2. Method

2.1. Overview

The method to create the Offshore Wind Atlas is built up of five steps:

1) A medium term period and a representative year are selected.
2) The wind speed, the wind direction, the shear stress and the stability length in the representative year are calculated.
3) The accuracy of the calculated wind speed in the representative year is determined.

4) The mean wind speed in the medium term period is calculated by applying a two layer model.
5) The turbulence intensity and the stability class in the representative year are determined.

Note this method is quite general so that it can be applied to any region in the world.

2.2. Selection of medium term period and representative year

In the Dutch part of the North Sea measured wind data is available from six offshore meteo stations in the form of the potential wind speed [6]. (The potential wind speed is a fictitious measured wind speed at a height of 10 m, with a surface roughness length of 0.2 mm, and assuming a neutral wind speed profile [5].)

The periods with valid data are presented in table 1 [10]. The common period is from 1997 to 2002. This period of 6 years therefore is selected as the medium term period.

Table 1: The periods with valid data

Meteo station	Period
K13 Alpha	*1990 - 2002*
Meetpost Noordwijk	*1990 - 2002*
Europlatform	*1990 - 2002*
Lichteiland Goeree	*1993 - 2002*
Oosterschelde	*1982 - 2002*
Vlakte v.d. Raan	*1997 - 2002*

In general the wind speed distribution over a year is not equal to the wind speed distribution over a longer period. As an example table 2 shows the annual variation for the station K13 Alpha [10]. (In this table the distribution of the potential wind speed is expressed in the scale parameter A and the shape parameter k of the Weibull distribution.) Nevertheless the year 2002 could be selected as the year with a wind speed distribution that represents the distribution over the longer period 1997-2002 [10].

Table 2: Annual variation for the station K13 Alpha

Year	A [m/s]	k [-]
1997	*8.55*	*2.14*
1998	*9.43*	*2.41*
1999	*9.19*	*2.14*
2000	*9.02*	*2.03*
2001	*8.67*	*2.22*
2002	*9.01*	*2.21*
1997 - 2002	*8.98*	*2.19*

2.3. Calculation of wind speed, wind direction, shear stress and stability length

The wind speed, the wind direction, the shear stress and the stability length in the representative year 2002 are calculated from HiRLAM output, at:

1) The anemometer heights of the offshore meteo stations, and
2) Four heights (60 m, 90 m, 120 m and 150 m) in a grid covering the North Sea.

HiRLAM (High Resolution Limited Area Model) is a numerical weather prediction model operated by KNMI. It gives hourly values of the ten-minute averages of the two wind speed components, the temperature and the pressure at (in this case) two heights and in a course grid. From these data in a grid point first the shear stress and the stability length and next the wind speed at the given height are calculated. To this end the Businger-Dyer profiles and the Charnock roughness length are applied. Subsequently the shear stress, the stability length and the wind speed components in the location are calculated by interpolating between the four adjacent grid points.

2.4. Accuracy of the calculated wind speed

Since measured wind speed is available in the form of the potential wind speed, the only way to establish the accuracy of the calculated wind speed is to reduce it into the potential wind speed. By defining the error in a calculated value as the difference between the measured and the calculated value in any of the 6 offshore meteo stations it is concluded that:

- The systematic error in the potential wind speed ranges between the meteo stations from –0.8 m/s to +0.1 m/s, with a mean of –0.3 m/s, and
- The stochastic error in the potential wind speed ranges between the stations from 2.2 m/s to 3.3 m/s, with a mean of 2.7 m/s.

This means that averaged over the year 2002 the calculated potential wind speed is 0.3 m/s larger than the measured one. A given calculated potential wind speed however differs from the measured one, with a standard deviation of 2.7 m/s (figure 1).

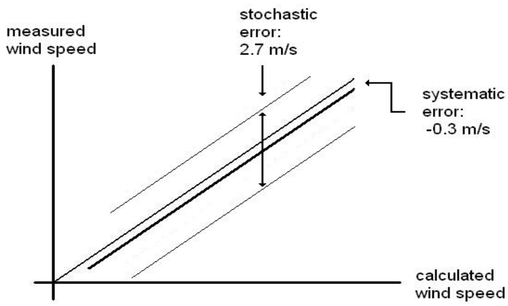

Figure 1: Difference between measured and calculated potential wind speed

From the small systematic error we conclude that the mean of the calculated wind speed is a realistic estimate for the mean of the measured wind speed. On the other hand, because of the large stochastic error, the standard deviation of the calculated wind speed must be compensated in order to get a realistic estimate for the standard deviation of the measured wind speed.

2.5. Two-layer model: mean boundary layer parameters and wind speeds

Mean values of the wind speed at 1500 m, the shear stress and the stability length are determined from the mean calculated wind speed at 60 m, 90 m, 120 m and 150 m in the grid covering the North Sea. To this end a two-layer model for the mean wind speed was developed (figure 2), with a mean velocity profile that is slightly stable in the lower layer.

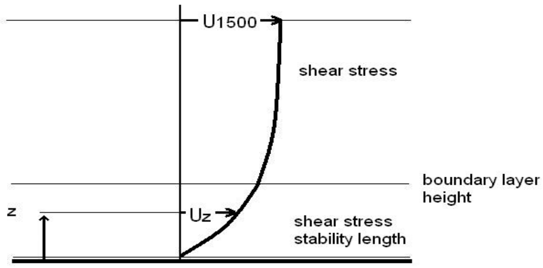

Figure 2: Two-layer model

The mean wind speed U_z at height z is given by:

$$U_z = U_{1500} + (u_* / \kappa) (\ln(z / z_{1500}) - 5 (z - h) / L) \quad \text{for } z_0 \le z \le h,$$

and

$$U_z = U_{1500} + (u_* / \kappa) \ln(z / z_{1500}) \quad \text{for } h \le z \le z_{1500},$$

where U_{1500} is the wind speed at a height of 1500 m, u_* is the shear stress and L is the stability length. The parameter h is the boundary layer height, which depends on the shear stress u_* and the latitude φ:

$$h = u_* / f' ,$$

with $f' = 2\,\Omega \sin(\varphi) \exp(A)$, where $\Omega = 7.27\ 10^{-5}$ 1/s (angular velocity of earth rotation) and A = 1.9 (a constant).

Subsequently, the mean wind speed is calculated at:

- Four heights (60 m, 90 m, 120 m and 150 m) in a fine grid in order to create the wind maps.
- The anemometer heights of the six offshore meteo stations, in order to establish the accuracy of the wind maps.

To this end the two-layer model is applied to the mean values of the wind speed at 1500 m, the shear stress and the stability length.

2.6. Turbulence intensity and stability class

The turbulence intensity I is derived from the shear stress u_* by using [5]: $I = 2.5\ u_*$. Seven stability classes are defined on basis of the inverse stability length 1/L; see table 3.

Table 3: The seven stability classes

Inverse stability length [1/m]	Stability class
$1/L \le -0.01$	*Very unstable*
$-0.01 < 1/L \le -0.001$	*Unstable*
$-0.001 < 1/L \le -0.0001$	*Slightly unstable*
$-0.0001 < 1/L \le 0.0001$	*Neutral*
$0.0001 < 1/L \le 0.001$	*Slightly stable*
$0.001 < 1/L \le 0.01$	*Stable*
$1/L > 0.01$	*Very stable*

3. Examples of the wind resource

In this section as an example of the content of the Offshore Wind Atlas the wind resource at a height of 60 m above sea level in the period 1997-2002 is presented. The map with the mean wind speed is shown in figure 3a. The distributions of wind speed, wind direction, turbulence intensity and stability class are available in the five locations which are shown in figure 3b. The distributions of the wind speed average and the wind speed standard deviation in one of these locations are presented in table 4, where the frequency gives the relative occurrence. The turbulence intensity and the stability class distribution in the same location are presented in the tables 5 and 6.

4. Validation: Accuracy of mean calculated wind speed

The accuracy of the mean wind speed according to the map in the medium term period 1997-2002 is determined by comparing it to the mean wind speed as measured in the offshore meteo stations. Again, both the calculated and the measured wind speed are reduced to the potential wind speed. The result is presented in table 7.

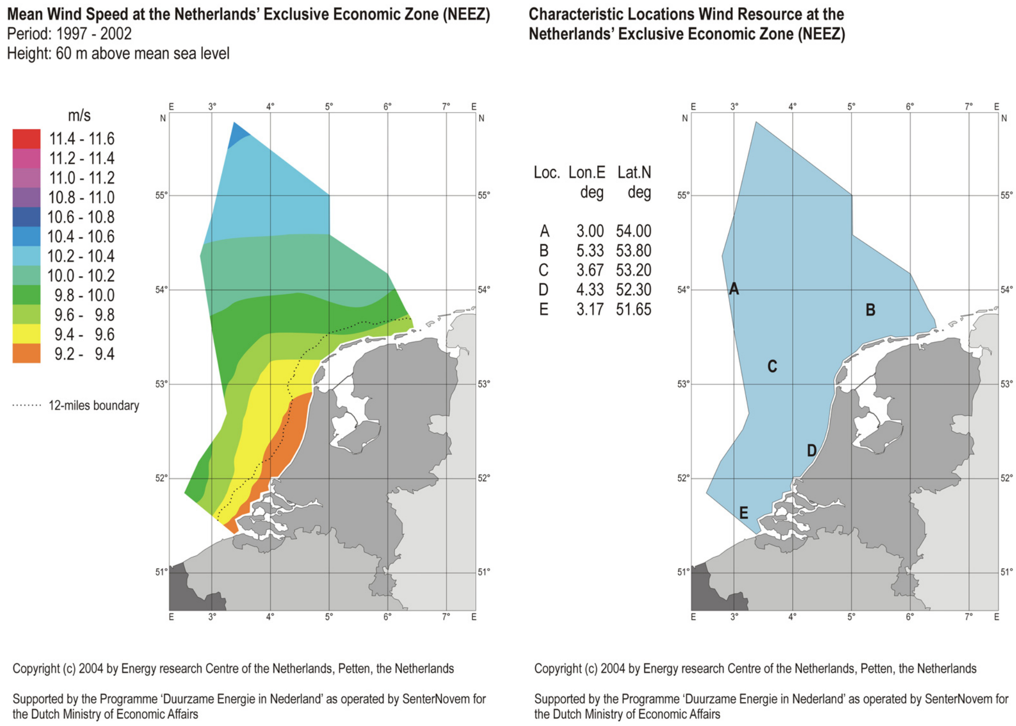

Figure 3: (a) Wind speed map at 60 m, and (b) locations with the distributions

Table 4: Distributions of the wind speed average and standard deviation at 60 m in location A

	Wind direction sector [deg]												
	–15 - +15	15 - 45	45 - 75	75 - 135	105 - 135	135 - 175	175 - 205	205 - 235	235 - 265	265 - 295	295 - 315	315 - 345	uni
Frequency [%]	*6*	*5*	*5*	*7*	*7*	*8*	*12*	*15*	*12*	*10*	*7*	*6*	*100*
Average [m/s]	*9.5*	*7.8*	*8.0*	*10.5*	*8.5*	*8.9*	*8.6*	*10.8*	*11.4*	*11.4*	*10.5*	*8.5*	*9.8*
St. Deviation [m/s]	*4.6*	*3.4*	*3.1*	*5.2*	*3.6*	*3.7*	*3.8*	*4.3*	*4.8*	*5.7*	*5.3*	*3.8*	*4.5*

Table 5: Distribution of turbulence intensity at 60 m in location A

	Turbulence intensity [m/s]									
	0.00-0.25	0.25-0.50	0.50-0.75	0.75-1.00	1.00-1.25	1.25-1.50	1.50-1.75	1.75-2.00	2.25-2.50	>2.50
Frequency [%]	*7*	*17*	*27*	*21*	*13*	*7*	*5*	*2*	*1*	*0*

Table 6: Stability class distribution in location A

	Stability class						
	Very Unstable	Unstable	Slightly Unstable	Neutral	Slightly Stable	Stable	Very Stable
Frequency [%]	*35*	*23*	*7*	*2*	*5*	*25*	*3*

Table 7: Potential wind speed as measured and according to the map

	Average potential wind speed [m/s] (1997-2002)	
Meteo station	Measured	Map
K13 Alpha	*8.1*	*8.2*
Meetpost Noordwijk	*7.5*	*7.5*
Europlatform	*7.8*	*7.8*
Lichteiland Goeree	*7.6*	*7.7*
Oosterschelde	*7.3*	*7.8*
Vlakte v.d. Raan	*7.3*	*7.6*

This table shows that the difference between the measured potential wind speed and the potential wind speed according to the map is between –0.5 m/s and 0.0 m/s. This corresponds to a

99% confidence interval for the measured potential wind speed that ranges from (U_{map} – 0.5) m/s to (U_{map} + 0.2) m/s, where U_{map} is the potential wind speed according to the map.

5. Summary

A wind resource map of the Dutch part of the North Sea was made by combining data from two sources: the numerical weather prediction model HiRLAM and the meteorological stations at the North Sea. The method consists of five steps:

1) The medium term period 1997-2002 and the representative year 2002 are selected.
2) The wind speed, the wind direction, the shear stress and the stability length in the year 2002 are calculated.
3) The accuracy of the calculated wind speed in the year 2002 is determined.
4) The mean wind speed in the period 1997-2002 is calculated by applying a two-layer model.
5) The turbulence intensity and the stability class in the year 2002 are determined.

Because these steps are quite general the method can be applied to any region in the world. As an example a map of the mean wind speed, and distributions of wind speed average and standard deviation, turbulence intensity and stability class at 60 meter above sea level are presented. The 99% confidence interval for the measured wind speed ranges from (U_{map} – 0.5) m/s to (U_{map} + 0.2) m/s, where U_{map} is the wind speed according to the map.

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ECN
P.O. Box 1,
1755 ZG Petten
The Netherlands

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Motivation

- The Netherlands has a target to develop 6000 MW offshore wind energy in the Dutch part of the North Sea
- Maps with the wind speed above the North Sea lacked accuracy and detail

Offshore wind atlas

- Mean wind speed at heights between 60 and 150 meter
- Distributions of wind speed, wind direction, turbulence and stability
- Cdrom with maps and distributions
- http://www.ecn.nl/wind/other/offshorewindatlas

Relevance of wind data

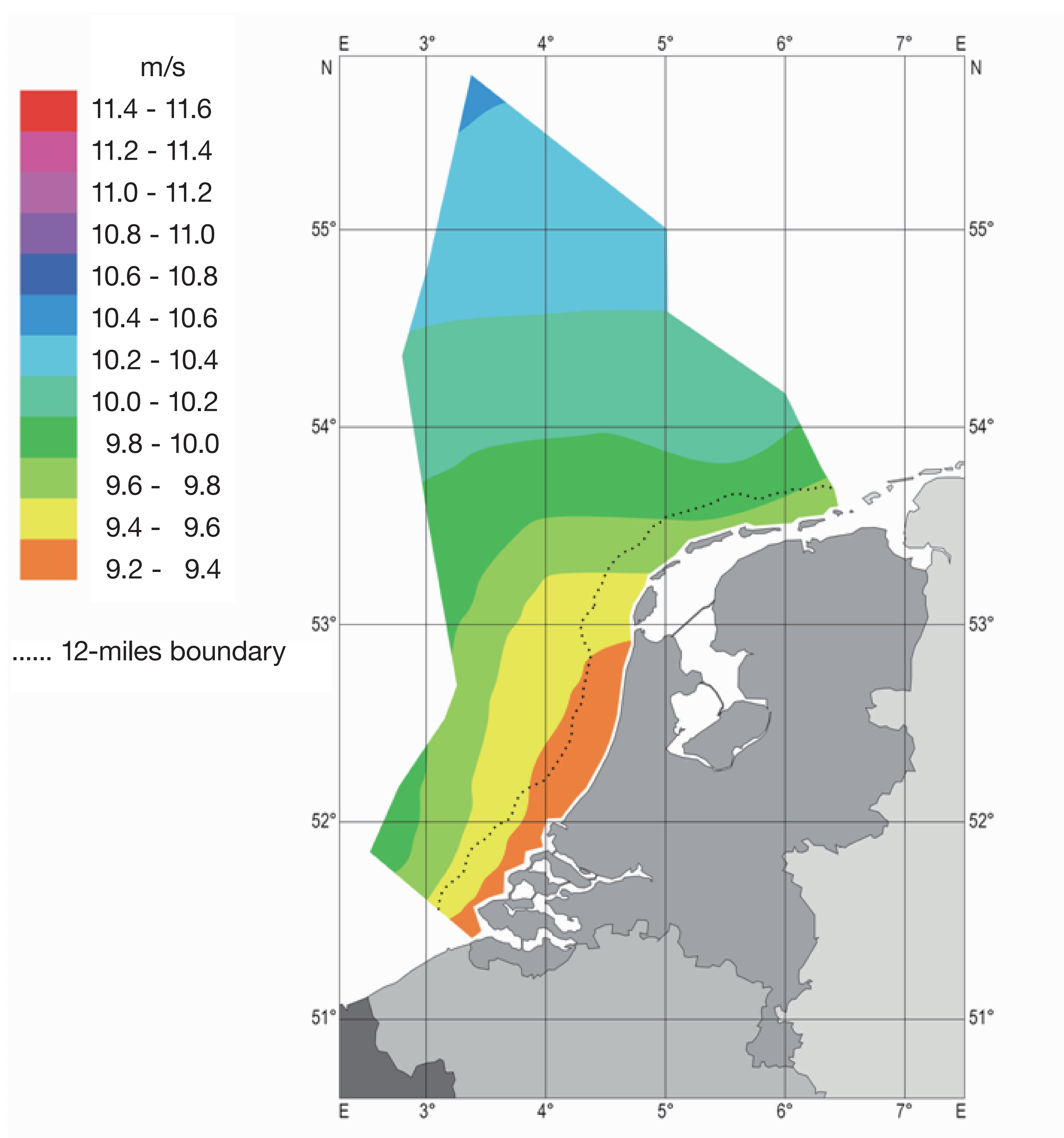
- Mean wind speed overview: Rapid estimate of electricity production
- Wind rose: Better estimate of electricity production
- Prevailing wind direction: Wind farm design
- Turbulence and stability: Estimate of mechanical loading of wind turbines

Approach

- Numerical wind atlas method
- Atmospheric model data from HiRLAM
- Validation on basis of measured data
- Applicable to any region in the world

Mean Wind Speed at the Netherlands' Exclusive Economic Zone (NEEZ)

Period: 1997 - 2002
Height: 60 m above mean sea level



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