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Europe's onshore and offshore wind energy potential

An assessment of environmental and economic constraints

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Executive summary

Wind power — a fast growing renewable energy

The European Union has ambitious targets in the field of environment and energy policy. The new 'climate-energy legislative package' sets mandatory national target corresponding to a 20 % share of renewable energies in overall Community energy consumption by 2020 and a mandatory 10 % minimum target to be achieved by all Member States for the share of renewable energy in transport consumption by 2020.

As a proven source of clean, affordable energy, wind resources clearly have a vital role to play in realising these goals. It is little surprise, therefore, that the wind power sector has grown exponentially in recent years. At the end of 2008, there were 65 GW of wind power capacity installed in the EU-27 producing 142 TWh hours of electricity, and meeting 4.2 % of EU electricity demand (EWEA, 2008a).

European Wind Energy Association (EWEA) projections suggest that the wind power sector will continue to expand fast. But determining where capacity can be developed most cost-effectively, the likely competitiveness of wind energy relative to average energy costs, and the role of wind power in the future energy mix calls for detailed, land use based analysis.

This report responds to that need, providing a Europe-wide resource assessment of onshore and offshore wind potential in a geographically explicit manner. In addition to calculating raw wind resource potential, this study also introduces and quantitatively analyses the environmental and social constraints on wind sector development. Concerns addressed include the noise and visual impact of wind power, as well as the deaths of birds and bats that fly into rotor blades. The report also evaluates the future costs of wind energy production across Europe in order to gauge the potential output at competitive rates.

Methodology

This report commences with an analysis of local wind resources across Europe, primarily based on wind speed data. Those findings are then used along with projections of wind turbine technology development to calculate the maximum amount of wind energy that could be generated (the technical potential) in 2020 and 2030.

Evidently, raw potential is only part of the story. Policymakers need to know how much wind energy is feasible in practical terms and that calls for the integration of other factors into the analysis. For that reason, the subsequent analysis uses various proxies to convey both the (socially and environmentally) 'constrained potential' for wind energy development and the 'economically competitive potential'.

To calculate 'constrained potential', Natura 2000 and other protected areas are excluded from the calculations of wind energy potential. Although it is not illegal to site wind farms on Natura 2000 sites they provide a useful proxy for the restrictions implied by biodiversity protection. Offshore, constrained potential accounts for public opposition to having wind farms visible from the coast and the limitations imposed by other uses such as shipping routes, military areas, oil and gas exploration, and tourist zones.

'Economically competitive potential' is calculated based on the forecasted costs of developing and running wind farms in 2020 and 2030, relative to projected average energy generation costs derived from the Commission's baseline scenario (EC, 2008a). This scenario is based on the CO_2 price of 22 EUR/t CO_2 in 2020 and 24 EUR/t CO_2 in 2030 and on oil prices of 55 USD/bbl in 2005 rising to 63 USD/bbl in 2030. It does not include policies to reduce greenhouse gases in view of the Kyoto and possible post-Kyoto commitments.

Key findings

This study confirms that wind energy can play a major role in achieving the European renewable energy targets. As Table ES.1 makes apparent, the extent of wind energy resources in Europe is very considerable.

- 1 Leaving aside some of the environmental, social and economic considerations, Europe's

Table ES.1 Projected technical, constrained and economically competitive potential for wind energy development in 2020 and 2030

		Year	TWh	Share of 2020 and 2030 demand (a)
Technical potential	Onshore	2020	45 000	11–13
		2030	45 000	10–11
	Offshore	2020	25 000	6–7
		2030	30 000	7
	Total	2020	70 000	17–20
		2030	75 000	17–18
Constrained potential	Onshore	2020	39 000	10–11
		2030	39 000	9
	Offshore	2020	2 800	0.7–0.8
		2030	3 500	0.8
	Total	2020	41 800	10–12
		2030	42 500	10
Economically competitive potential	Onshore (b)	2020	9 600	2–3
		2030	27 000	6
	Offshore	2020	2600	0.6–0.7
		2030	3400	0.8–0.8
	Total	2020	12 200	3
		2030	30 400	7

Note: (a) European Commission projections for energy demand in 2020 and 2030 (EC, 2008a, b) are based on two scenarios: 'business as usual' (4 078 TWh in 2020–4 408 TWh in 2030) and 'EC Proposal with RES trading' (3 537 TWh in 2020–4 279 TWh in 2030). The figures here represent the wind capacity relative to these two scenarios. E.g. onshore capacity of 45 000 TWh in 2020 is 11–12.7 times the size of projected demand.

(b) These figures do not exclude Natura 2000 areas

Source: EEA, 2008.

raw wind energy potential is huge. Turbine technology projections suggest that it may be equivalent to almost 20 times energy demand in 2020.

- Onshore wind energy potential is concentrated in agricultural and industrial areas of north-western Europe. Likewise, the largest offshore potential can be found in low depth areas in the North Sea, the Baltic Seas and the Atlantic Ocean, with some local opportunities in areas of the Mediterranean and Black Seas. The deep offshore potential is even larger but costs mean that it is unlikely to contribute in any significant way to the energy mix within the time horizon of this study.
- Onshore, the environmental constraints considered appear to have limited impact on wind energy potential. When Natura 2000 and other designated areas are excluded, onshore technical potential decreased by just 13.7 % to 39 000 TWh. However, social constraints, particularly concerns regarding the visual impact of wind farms, may further limit the onshore wind energy development.
- Offshore, the environmental and social constraints applied have a larger impact on potential. Using only 4 % of the offshore area within 10 km from the coast and accounting for the restrictions imposed by shipping lane, gas and oil platforms, military areas, Natura 2000 areas etc. reduces the potential by more than 90 % (to 2 800 TWh in 2020 and 3 500 in 2030).
- When production costs are compared to the PRIMES baseline average electricity generation cost, the onshore potential for wind decreases to 9 600 TWh in 2020, whereas offshore wind potential decreases to 2 600 TWh. Despite being a small proportion of the total technical potential, the economically competitive wind energy potential still amounts to more than three times projected demand in 2020. However, high penetration levels of wind power will require major changes to the grid system i.e. at higher penetration levels additional extensions or upgrades both for the transmission and the distribution grid might be required to avoid congestion of the

existing grid. Moreover, power flow needs to be continuously balanced between generation and consumption. The total requirement depends on the applied interconnection, geographical dispersion and forecasting techniques of wind power. Economically competitive potential figures do not include these aspects and the relevant costs.

- The fact that the competitive potential even in a relative short time horizon is much bigger than the electricity demand means that the key need for policy makers should be on facilitating the integration of wind energy into the energy system via research and development. Field testing of integration strategies along with initiatives aimed at making demand more responsive to fluctuations in supply is needed. A higher penetration of electric vehicles could potentially be one such application, albeit not one that is analysed in this report.
- The average power production costs to determine the competitive potential are dependent on the fossil fuel and carbon prices. These will vary depending on developments in the global economy as well as developments in scale and cost of greenhouse gas mitigation efforts. The assumptions used here as deemed rather conservative. Thus, the economically competitive wind potential can be higher than presented. On the other hand applying a single average production cost disregards the regional price differences among different regions (i.e availability of hydro in Northern Europe) and its impact on the electricity price. Due to time constraints those possible impacts are not assessed within this study.

Uncertainties and future challenges

This report confirms that, alongside other renewable sources such as biomass, wind energy can play a major role in achieving Europe's renewable energy targets. While that message is quite clear, the results of the analysis are subject to uncertainties, particularly at the country level as Europe-wide data on meteorology, land cover, sea depth and wind turbine technology and their costs are applied. The result of this study can be used as benchmark for the evaluation of the potential role of wind energy at European scale. More detailed assessments at regional, national or local scale are needed for decisions developing wind farms.

1 Introduction

1.1 Background

The exploitation of renewable energy sources can help the European Union meet many of its environmental and energy policy goals, including its obligation to reduce greenhouse gases under the Kyoto Protocol (EC, 2002a) and the aim of securing its energy supply (EC, 2002b; EC, 2005).

As early as 1997, the European Union set an ambitious 2010 indicative target of 12 % for the contribution of renewable energy sources to EU-15 gross inland energy consumption (EC, 1997). In 2001, the EU adopted the Directive on the promotion of electricity produced from renewable energy sources in the internal electricity market, which included a 22.1 % indicative target for the share of EU-15 electricity consumption produced from renewable energy sources by 2010 (EC, 2001).

In January 2008 the European Commission published proposals for a climate change and energy package. In December 2008 the European Parliament and Council reached an agreement on the package that retained the main elements of the Commission's original proposal. The final version of the package adopted by the Council includes national targets to increase the EU average share of renewables to 20 % of final energy consumption by 2020, with at least 10 % of transport energy consumption in each Member State deriving from renewable sources.

According to the EEA (2008a), the production of energy and electricity from renewable energy sources grew steadily between 1992 and 2006, with particularly large increases in wind and solar electricity. In 2006 renewable energy accounted for 9.3 % of total energy consumption and 14.5 % of gross electricity consumption in the EU-27. Clearly, a significant further expansion will be needed to meet the EU-27 target of generating at least 20 % of final energy consumption from renewable sources by 2020.

Wind energy currently meets 3.7 % of EU electricity demand. The European Commission's goal of increasing that share to 12 % by 2020 is regarded as achievable by EWEA (2008a). In fact, EWEA predicts for the EU-27 to have 80 GW installed capacity, including 3.5 GW offshore by 2010 and set target of 180 GW installed capacity, including 35 GW offshore by 2020, which is equivalent to approximately 5 % of total power supply in 2010 and 11.6 % and 14.3 % in 2020, depending on the electricity demand. In its Renewable Energy Roadmap, the European Renewable Energy Council estimates that wind energy will reach 477 TWh by 2020 (EREC, 2008). Greenpeace and the Global Wind Energy Council predict wind power growth in Europe from about 41 GW in 1990 to 385 GW by 2020 in their most optimistic scenario (Greenpeace and GWEC, 2006). That target is based on market growth and technological progress rather than wind resource availability.

Most literature that considers wind resources focuses on the EU-15 countries. As their methodologies vary, the studies' results differ quite significantly. For instance, Hoogwijk *et al.* (2004) estimate that western European onshore technical wind potential is 14 400 PJ/year (4 000 TWh) where they include sites with wind speed above 4 m/s at 10 m. Hoogwijk *et al.* further estimate that half of this potential can be produced at less than USD 0.10 per kWh.

Another assessment carried out by the World Energy Council (1994) is based on the assumption that 4 % of the area with wind speeds higher than 5.1 m/s at 10 m height is suitable for wind power generation. This study also excludes areas more than 50 km from the existing grid. As a consequence, the technical potential is calculated to be approximately 4 680 PJ/year (1 300 TWh).

For offshore wind, EWEA and Greenpeace (2003) restrict the offshore area to a water depth of 20 m and estimate potential at approximately 1 500 PJ/year (417 TWh). All above-mentioned estimations consider a time frame until 2050.

The German Advisory Council on Global Change (WBGU, 2003) arrives at a global technical potential for energy production from both onshore and offshore wind installations of 278 000 TWh. The report then assumes that only 10–15 % of this potential could be produced in a sustainable fashion, bearing in mind that urban areas and natural areas would not be used. The figure estimation of long-term wind energy output is approximately 39 000 TWh per year.

The present report estimates onshore and offshore wind energy potential for the EEA countries considered in this report (EU-27 and Norway, Switzerland and Turkey), using a consistent methodology and presenting findings specific to geographic regions. It also quantitatively analyses the environmental, legislative, social and economic constraints that further reduce actual wind energy potential.

1.2 Approach and definitions

Wind energy resources in Europe offer power that is renewable and clean. Establishing realistic medium-term wind energy targets necessitates robust estimates of wind energy potential in Europe. Mapping areas with high probability of significant wind resources could also be particularly helpful for those European countries where wind energy is in its infancy. This report therefore aims to identify EEA member countries' ([1]) wind energy potential in a geographically explicit manner.

In this study, 'technical potential' refers to the highest potential level of wind energy generation, based on overall resource availability and the maximum likely deployment density of turbines, using existing technology or practices.

'Constraint potential' refers to the amount of the total technical potential that can be produced once issues such as biodiversity protection, regulatory limitation and social preferences have been taken into consideration. Likewise, 'economically competitive potential' describes the proportion of technical potential that can be realised cost-effectively in the light of projected average energy costs in the future.

1.3 Report structure

This project has the following main objectives:

- 1 to develop and apply a methodology to assess the technical potential of onshore and offshore wind energy in Europe in a consistent and geographically explicit manner;
- 1 to introduce various constraints related to biodiversity protection, visual impacts of wind farm development and regulatory issues, in order to derive environmentally and socially restricted potential;
- 1 to introduce economic factors in order to estimate economic potential.

Chapter 2 describes the methodology applied in this study for determining the technical potential. It presents the load hours calculated and uncertainties concerning terrain.

Chapter 3 presents the technical potential results for both on shore and offshore wind energy.

In Chapter 4 the wind data projections are tested against empirical observations to reveal uncertainties.

Chapter 5 analyses 'constrained potential' where environmental and social constraints are taken into account.

Chapter 6 evaluates the economics of future wind turbine technology. This chapter further analyses the economically competitive potential that can be realised cost-effectively in the light of the projected average energy costs in the future.

Current wind energy penetration levels in Denmark and the Netherlands are demonstrated in Chapter 7 to reach a 'feasible penetration level' that may be used as a proxy to reflect social constraints on land.

Chapter 8 presents the uncertainties and future challenges.

([1]) Iceland and Liechtenstein are not included in this assessment.

2 Methodology for determining technical potential

2.1 Approach

This report aims to identify the most suitable locations to generate wind energy at particular costs. The primary data source used to derive wind speeds in Europe is the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (described in more detail in Section 2.2.1 below) (²).

Since meteorological conditions vary from year to year, average wind speeds for the period 2000–2005 are used. Those data are reprocessed to reflect surface roughness for different land cover types using the Corine Land Cover database (CLC) described in Section 2.2.2.

As the ECMWF data provide wind speeds at 10 m height, they are recalculated to generate the expected wind speed at assumed wind turbine hub heights for the period up to 2020 and 2030.

Energy potential is calculated assuming the use of 2 MW wind turbines onshore up to 2030. Offshore wind turbines are assumed to be larger, with a capacity of 8 MW up to 2020 and 10 MW in the period 2020–2030. Expected hub heights are determined as 80 m onshore and 120 m offshore.

Regarding average wind energy production potential per square kilometre, it is considered that five 2 MW wind turbines can be sited per square kilometre onshore. Offshore, the 8 MW wind turbines are sited at 1.25 per square kilometre in 2020, while wind turbines rated power is assumed to be 10 MW in 2030.

2.2 Data handling

2.2.1 *Wind data*

Depending on the purpose of a study, different sources of wind data with varying levels of details and accuracy can be employed. Global wind resource assessments normally apply reanalysis data, whereas national and regional wind resource assessments use synoptic data. On-site wind measurements, on the other hand, are often used to predict the power production of a single wind turbine or wind farm or to establish the power curve of a wind turbine (Monahan, 2006; Petersen *et al.*, 1997).

As this study focuses on a European scale assessment, reanalysis data sets have been used. There are two large sets of reanalysis data, one produced by ECMWF called ERA-40 (³) and one produced by the United States of America's National Centre for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR) (⁴).

The ERA-40 data set initially covered the period 1958–2001 but has been recently expanded. By 2008 it had been extended to 2005 and in 2009 it is expected to reach 2008. Thereafter it will continue to be produced with a small time lag. The NCEP-NCAR reanalysis data are available from 1948 onwards (Larsson, 2006). This study uses the ECMWF's ERA-40 reanalysis data at 10 m height as the primary resource.

Actual meteorological surface layer parameter data for the years 2000–2005 were extracted from the ECMWF Meteorological Archival and Retrieval System (MARS) (⁵). Specifications of the data extracted, including the MARS parameter code references, are presented in Box 2.1.

(²) ECMWF is an international organization supported by eighteen European states and with cooperation agreements with several other European states, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the World Meteorological Organization (WMO). It is responsible for producing operational global data analyses and medium-range forecasts for its member states, and undertakes a comprehensive programme of research to ensure the continued development and improvement of its products.

(³) More information on ERA-40 is available at: www.ecmwf.int/research/era.

(⁴) More information on the NCEP-NCAR reanalysis data is available at: www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html

(⁵) MARS is the main repository of meteorological data at ECMWF from which registered users can freely extract archived data. It contains terabytes of a wide variety of operational and research meteorological data as well as data from special projects.

Box 2.1 Specifications of the ECMWF MARS data extracted (⁶)

Spatial grid resolution	0.25 x 0.25 degrees latitude/longitude (approximately 15 x 20 km)				
Geographic window	Lower left corner 34 x –42 degrees latitude/longitude; upper right corner 72 x 59.5 degrees latitude/longitude (i.e. covering the Europe-wide study area).				
Years	2000–2005				
Time resolution	Monthly mean, 6-hour averages (00:00, 06:00, 12:00, 18:00)				
Parameters	Name	Remark	Abbrev.	Units	Code (Table 128)
	10 m wind U	(W → E)	10U	$m.s^{-1}$	165
	10 m wind V	(N → S)	10V	$m.s^{-1}$	166

The wind speeds used in the calculations were derived from the 10 metre height wind speed in U (10U) and V (10V) direction with the magnitude $\sqrt{(10U)^2 + (10V)^2}$. The meteorological gridded data for the years 2000–2005 were transformed into the grid format used by ESRI (a firm specialising in geographic information software). Both the original six-hour and the daily/monthly meteorological parameter values were converted into annual averages at the given grid resolution. As ESRI's ArcGIS software has a limited calculation capacity, six-hour values were averaged to half-month values and daily values were averaged to two-month values. These intermediate average values were in turn used to derive annual averages.

The topography of the terrain was taken into consideration because it strongly influences wind close to the earth's surface. The 10 m wind speed values derived were subsequently recalculated to correspond to wind turbine hub heights of 80 m onshore and 120 m offshore.

The interaction between the wind and the surface takes places at a broad range of scales. In the field of boundary-layer meteorology, much effort has been devoted to separating this range of scales into a number of characteristic domains that can be systematically described, parameterised and/or modelled. For the purpose of wind power meteorology, which is primarily concerned with the wind from 10 to 200 m above the ground, the effects of the topography can be divided into two categories (Troen and Petersen, 1989):

- 1 Roughness: the collective effect of the terrain surface and its roughness elements, leading to an overall retardation of the wind near the ground, is referred to as the roughness of the terrain. The point of interest must be 'far away' from the individual roughness elements and normally much higher than them in order to avoid being affected by the roughness.
- 1 Orography: when the typical scale of the terrain features is much larger than the height of the point of interest it influences wind speeds. Near the summit or the crest of hills, cliffs, ridges and escarpments the wind will accelerate, while near the foot and in valleys it will decelerate.

2.2.2 *Corine Land Cover database and hub height conversion ratio*

As noted above, the wind speed at the hub height (assumed to be 80 m onshore and 120 m offshore is required rather than the 10 m ECMWF data. To derive this wind velocity at hub height the following formula was used:

$$V_H = V_{10}\left(\frac{\ln(H/z_0)}{\ln(10/z_0)}\right)$$

Where:

- 1 H stands for the hub height expressed in metres;
- 1 V_H is the wind speed at hub height expressed in metres per second;
- 1 V_{10} is the wind speed at 10 m height expressed in metres per second;
- 1 z_0 is the roughness length expressed in metres.

This is the logarithmic wind profile for neutral conditions, in which thermal effects have been discarded (Hoogwijk *et al.*, 2004).

(⁶) It should be noted that the 0.25 degrees spatial grid resolution is just below the current highest possible MARS grid resolution of 0.225 degrees (13.5 minutes) for extracting data through interpolation. A resolution below the maximum was used due to a typographic error in the extraction script discovered after finalisation of the extractions. It was decided not to repeat the extractions because the resolution loss is acceptably small and the extraction is costly in terms of time and resources.

The Corine Land Cover database 2000 (CLC) is used to account for the differences in surface roughness (at a 250 x 250 m resolution) of the various land cover types. Data in the CLC is aggregated into 15 CLC classes, which reflect similar land cover types with comparable roughness. Data from ECMWF (2007) for wind speed and Ecofys (Coelingh *et al.*, 2002) for roughness length (z_0) have been used to determine minimum and maximum z_0 values for each CLC class. The values are converted to a hub-height conversion ratio using the formula above for each CLC class. The average conversion ratio for each class is presented in Annex 1 to this report. A similar approach is used to determine the conversion ratio for offshore areas.

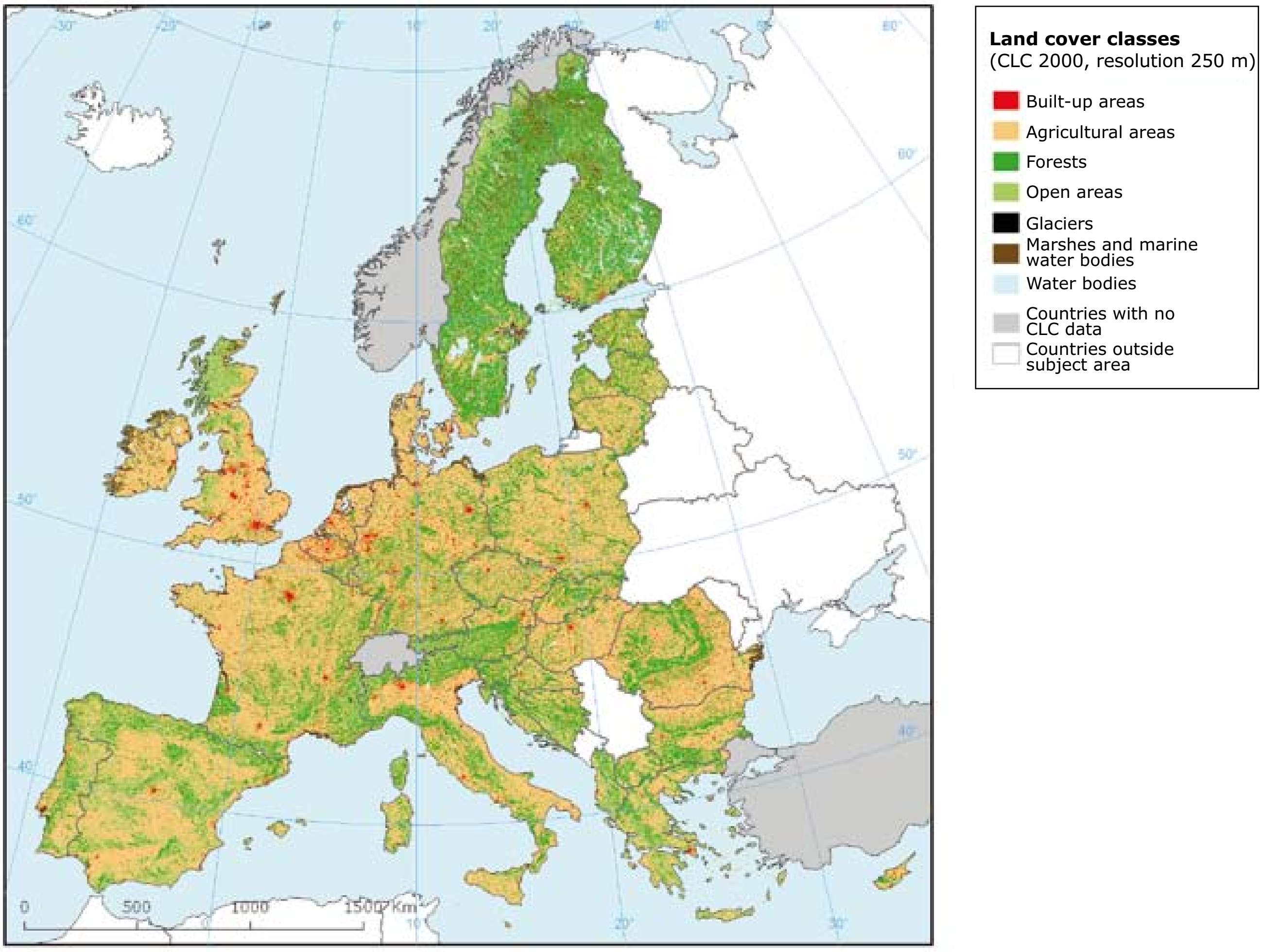
At the time of this preparing this report CLC data were not available for Norway, Switzerland and Turkey. For that reason, this study uses the Global Land Cover 2000 database of the Joint Research Centre of the European Commission (GLC, 2000) released in 2001 with a 0.6 km resolution grid. A conversion table between the Corine Land Cover classes and the Global Land Cover 2000 database is presented in Annex 1.

For presentation purposes the 15 CLC classes are aggregated to seven land cover classes.

2.2.3 *Uncertainty concerning terrain speed-up effects*

The low resolution of the ECMWF data can create uncertainty with respect to complex terrains. Although ECMWF data might indicate low wind speed for a particular grid cell, local effects can enhance the wind resource, making power generation possible. One example of such an occurrence exists around La Muela, on the edge of the Ebro river valley

Map 2.1 Spatial distribution of land cover



Note: At the time this report was prepared CLC data were not available for Norway, Switzerland and Turkey.

Source: EEA, 2008.

in Spain. The first map of wind potential produced according to above methodology designated that the area was not suitable for wind power installation, despite the fact that large scale wind power installations currently operate there.

Highly elevated areas are usually complex terrains. There are few high plains in Europe, so most of the area above 500 m is divided between mountain ranges and valleys. In the valleys, wind speeds are low, while on top of mountains wind speeds can increase by more than 70 %. This acceleration effect depends on the local slopes.

As noted above, the wind speed dataset used has a resolution of 0.25 x 0.25 deg. Preliminary results showed that when the value derived from the full wind power analysis (number of full load hours) falls below the economic minimum necessary for wind turbine erection, the whole grid cell is discarded. However, it is possible that in some areas of a grid local effects will increase wind resources to levels capable of sustaining a wind farm economically.

In order to deal with this uncertainty, the first set of calculations (preliminary results) are calibrated against the variation in wind speed around the grid average that would result in the same distribution of full load hours (details of the methodology can be found in Annex 2). The derived correction factor for wind speed is then used to calculate the full load hours in a straightforward manner that allows the differentiation in Corine Land Cover data to be preserved. The following correction factor is applied for heights above 50 m:

$$Vi = Vmean + 0.001508 \times (Hi-Hmean)^2$$

Where:

- 1 i indicates the various height of sub-cells within a certain ECMWF wind field cell;
- 1 Vmean indicates the mean wind speed (m/s).
- 1 Hi indicates the height of the sub-cells in various heights.
- 1 Hmean indicates the mean height.

Map 2.2 depicts wind speed in EEA countries at hub height, based on ECMWF data corrected for surface roughness.

2.2.4 *Offshore: sea depth and selection of economic zones*

The potential area for offshore wind energy generation is limited to sea depths less than 50 m using a global digital elevation model from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Centre (NGDC) including bathometric data (7).

The VLIZ Maritime Boundaries Geodatabase, which defines exclusive economic zones (EEZs) for every country, is used to attribute offshore areas to specific countries (see Map 2.3). Furthermore, the offshore area has been divided into different classes depending on the distance from the coastline, specifically areas less than 10 km from the coast, areas 10–30 km away, areas 30–50 km away and areas more than 50 km away.

The legal exclusive economic zone extends 200 nautical miles from the coastline. When the space between two countries is less than 400 nautical miles, the boundary should be the median line or prescribed in a multilateral treaty (8).

2.2.5 *Wind turbine technology*

When assessing wind energy potential in 2020 and 2030, it is necessary to make projections with respect to the technological and economic developments of wind turbines. These include factors such as rated power (9), hub height and turnkey investment costs (i.e. expenditures incurred before an investment is ready for use).

Turbine size

Wind turbine size has increased significantly, from an average rated power of less than 50 kW at the beginning of the 1980s to over 1 MW in 2005 (DWIA, 2006). The commercial size sold today is typically 750–2 500 kW (GWEA, 2006). In this study we assume that rated power will level off at 2 MW. That assumption is in accordance with the findings of various other studies (EWEA, 2006a; Greenpeace and EWEA, 2005; Greenpeace and GWEC, 2006).

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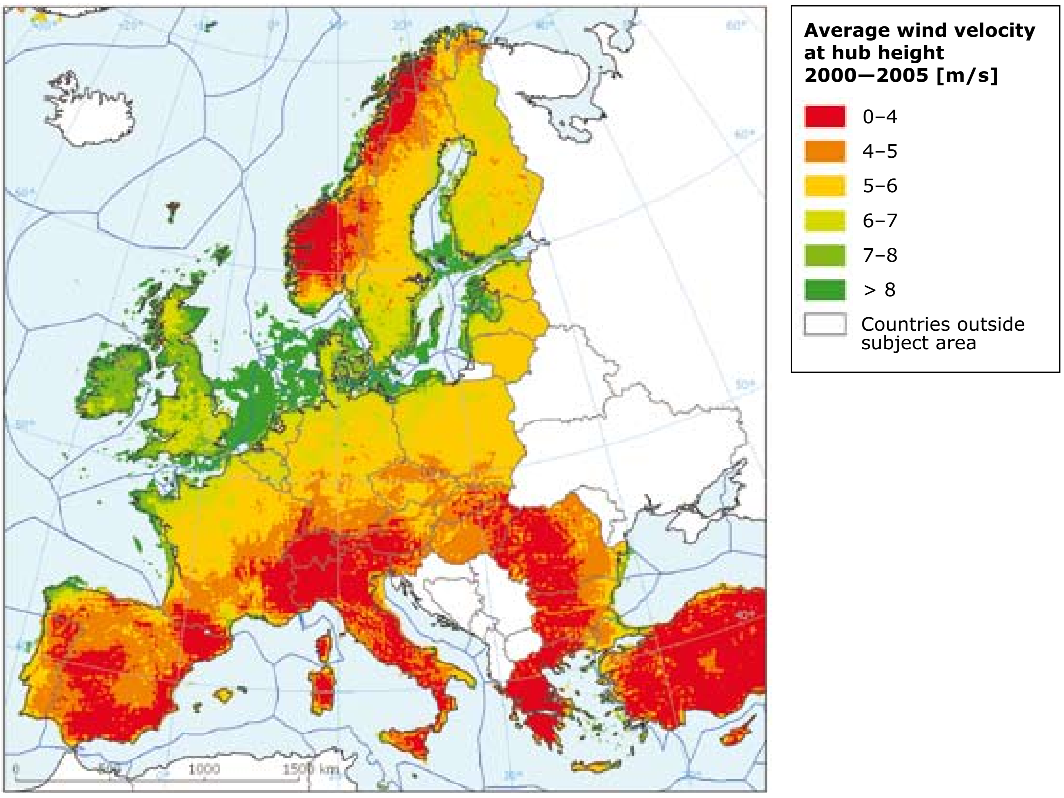
(7) 30 x 30 seconds (1 km) data, including Sandwell and Smith bathymetry and ETOPO5 in polar areas, is used for this purpose. (Spatial reference system: decimal degrees, GCS_Clarke_1866.)

(8) Multilateral treaties and documents describing the baselines of countries can be found on the website of the United Nations Convention on the Law of the Sea (UNCLOS).

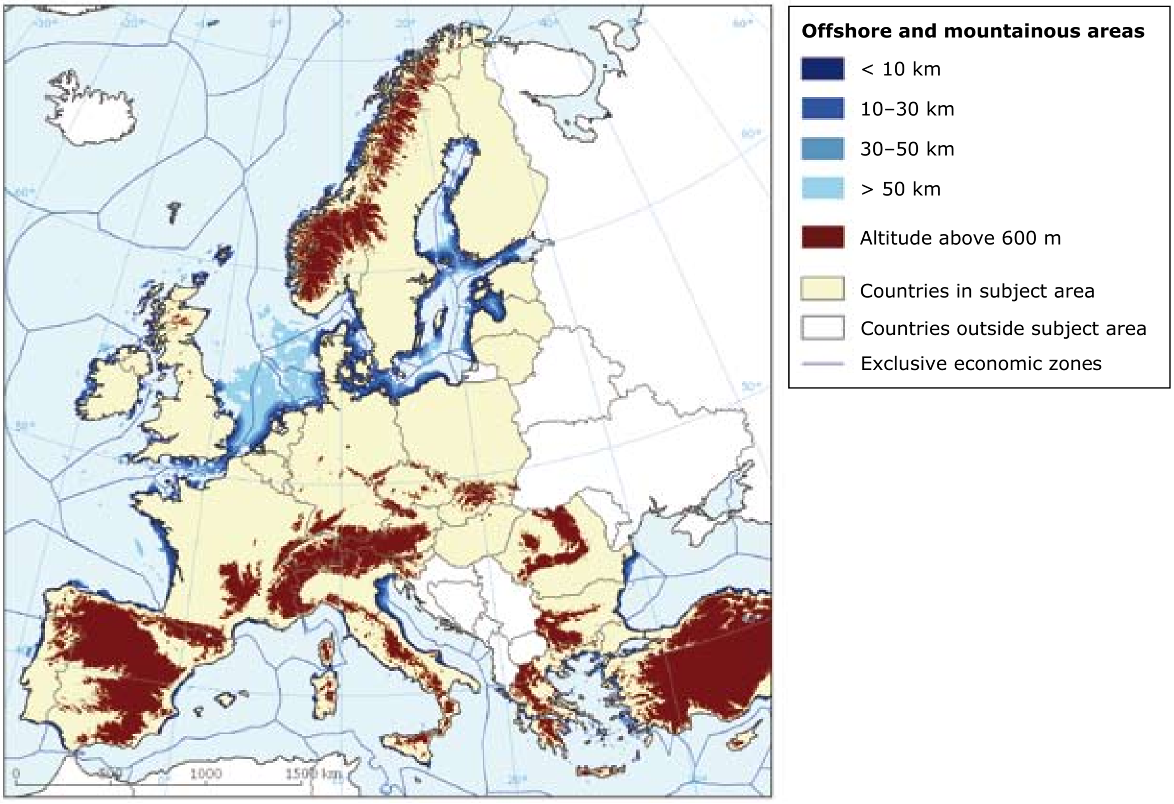
(9) Rated power is the windmill's performance under specific operating circumstance; here the energy per hour of operation when running at its maximum performance (i.e. at high wind levels).

Map 2.2 ECMFW wind field data after correction for orography and local roughness (80 m onshore, 120 m offshore)



Source: EEA, 2008.

Map 2.3 Offshore locations with a water depth of less then 50 m and mountainous areas (above 600 m) in Europe



Source: EEA, 2008.

Rotor diameter

Related to the turbine size, the rotor diameter has also increased from around 15 m in the 1980s to 60–80 m for current turbines with an average size of 1–1.5 MW (EWEA, 2003a). EWEA shows that there is a relationship between the rated power of turbines and the rotor diameter. Rated power increases as a power of the rotor diameter with an exponent of around two. This implies that a diameter of 100 m is related to a rated power of around 3 MW, whereas a 70 m turbine would have a rated power of approximately 1.5 MW (EWEA, 2003a). For the average turbine of 2 MW, the related rotor diameter would be 80 m. The historical development of rated power and rotor diameter is presented in Figure 2.1.

The hub height, however, is partly related to the rated power. There is a trade-off between increased power from wind at higher hub heights and the additional costs of larger turbines. EWEA (2003a) indicates that for larger onshore turbines, the hub height equals almost the rotor diameter. Thus, this study also assumes that the hub height equals the rotor diameter.

There is not much experience with offshore wind energy projects. Overviews of planned or installed wind farms within Europe were made by Van Hulle *et al.* (2004), the International Energy Agency (IEA, 2005), and Papalexandrou (2008). Most offshore wind turbines had a rated power of 2–3 MW, with the exception of DOWEC (Dutch Offshore Wind Energy Converter**)** in the Netherlands where the turbines had a rated power of 6 MW.

Assumptions on future wind turbine characteristics

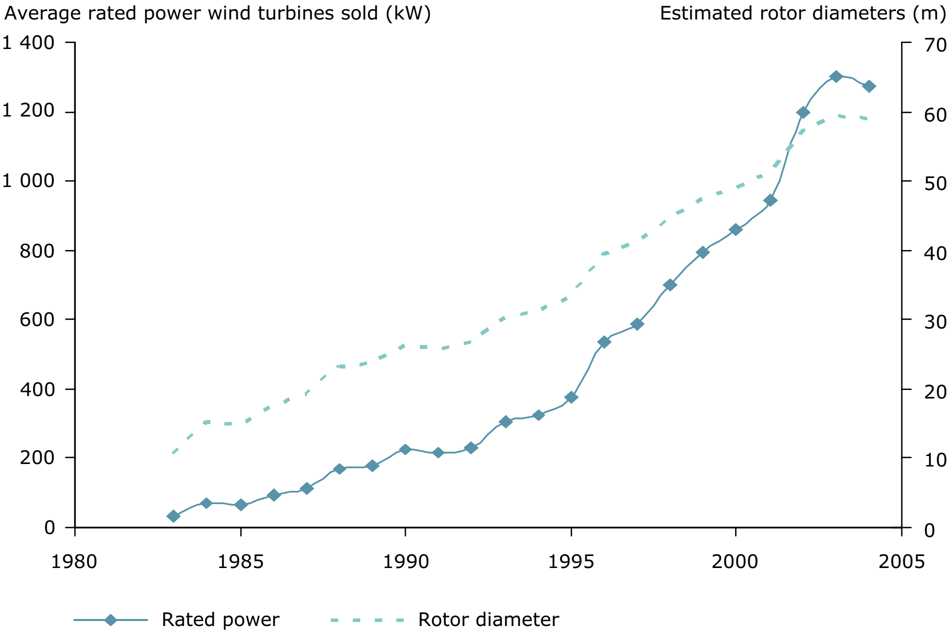
The assumptions applied on the wind turbine technology are summarised in Table 2.1.

Because of economies of scale, turbine sizes may increase further. For instance, EWEA assumes an average wind turbine size of 10 MW in its briefing paper 'No Fuel' (EWEA, 2006a). The rotor diameter of such large turbines would be around 150 m. However, as indicated earlier, rotor diameter also relates to hub height. It is expected that large offshore wind turbines will have a possible tower height less than equal to the rotor diameter because of reduced wind speed disturbance (low wind shear).

2.2.6 *Full load hours*

Depending on actual wind speed, a wind turbine will generate 0–100 % of its nominal power. Figure 2.2 depicts the power output of various existing wind turbine types at different average

Figure 2.1 Historical development of onshore wind turbine size, in rated power and estimated rotor diameter



Source: DWIA, 2006.

Table 2.1 Summary of assumptions on future characteristics of wind turbines

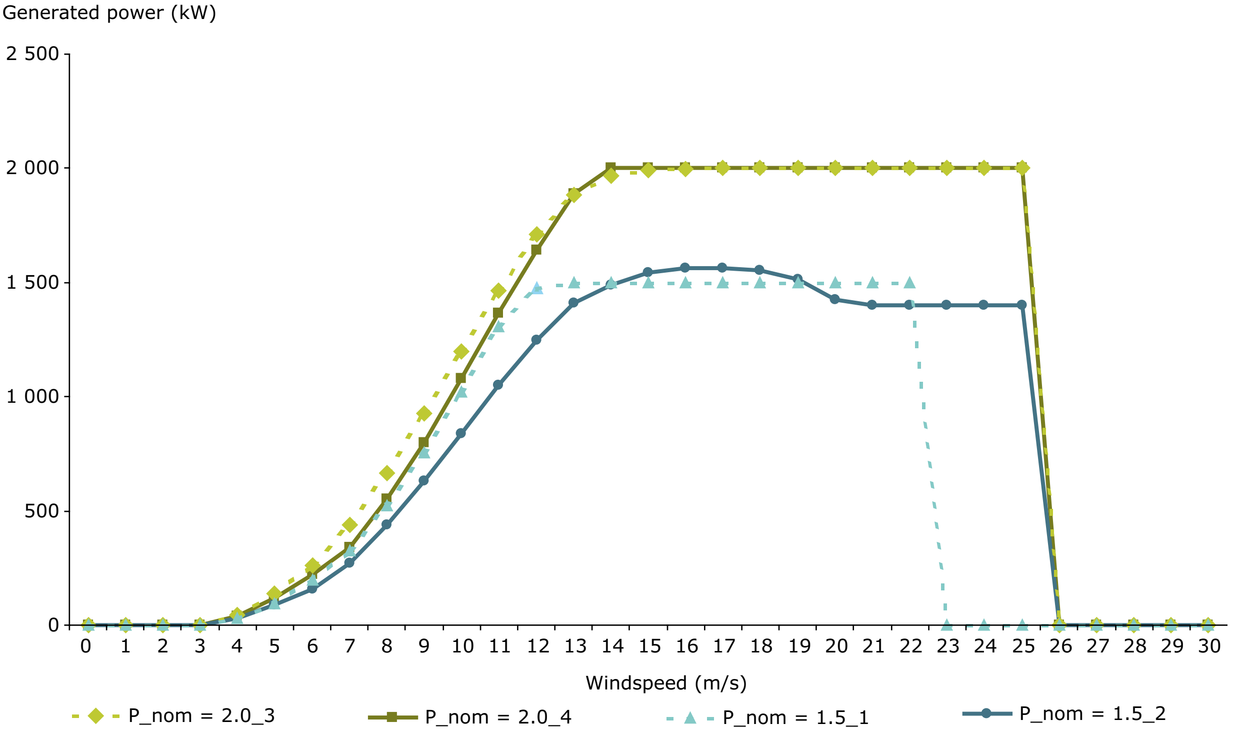
	Onshore			Offshore		
	Current average	Future		Current average	Future	
		2020	2030		2020	2030
Rated power (MW)	1.5	2	2	2–6	8	10
Rotor diameter (m)	60–80	80	80	80–129	140	150
Hub height (m)	80	80	80	100	120	120

wind speeds. Based on these output figures (kW) a Weibull distribution is calculated, with k = 2 (10), which describes the variation in wind speeds over the year. The amount of full load hours (11) as a function of the wind speeds is calculated from the outcomes, and general trend lines are plotted. From these trend lines, linear regression functions were derived to calculate full load hours from known wind speed at hub height.

The calculated full load hours of individual wind turbines are theoretical values. In practice, full load hours are lower because of two factors: 'array efficiency' and 'wind farm availability'. The array efficiency factor represents the efficiency of the total wind farm, which decreases with closer spacing due to the interference of turbines. In this study, an array efficiency of 0.925 for onshore wind farms and 0.90 for offshore wind farms is assumed taking into consideration the placing of the wind turbines with appropriate spacing.

The second efficiency factor, availability, refers to the fraction of the full load hours in a year that the turbine is available. Reasons that a wind turbine may not be available include maintenance and repair activities. The availability factor is set to 10 % for offshore and 3 % for onshore wind farms below 600 m height and 10 % for turbines above 600 m height (Hoogwijk, 2004).

Figure 2.2 Power-velocity curves of four existing wind turbines



Source: Hoogwijk, 2008.

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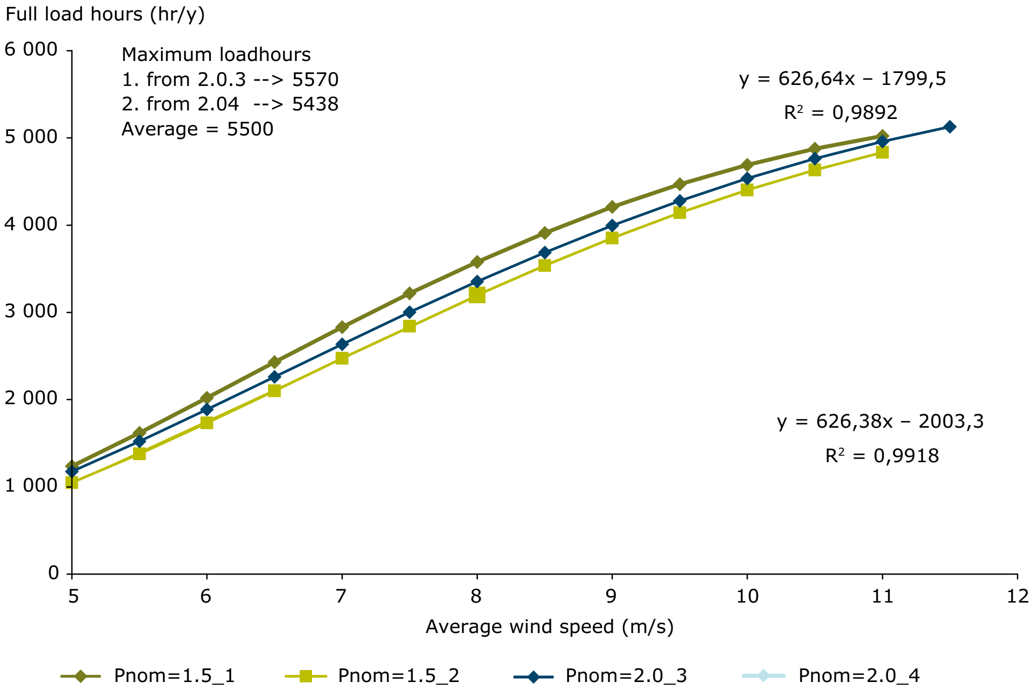
(10) k is the Weibull shape factor (generally ranging between 1 and 3). Sensitivity analysis showed that in the range k = 1.75–2.4 the results for annual wind speeds between 5 m/s and 11 m/s produce not more than 10 % variance in full load hour results.

(11) Full load hours are the number of hours a year that the wind turbine operates at rated power (kWh/y)/(kW).

Figure 2.3 Estimated full load hours based on power-velocity curves and Weibull distribution



Source: Hoogwijk, 2008.

In summary, theoretical full load hours need to be multiplied by 0.81 for offshore wind turbines and 0.83–0.90 for onshore wind turbines to derive practical full load hours.

Practical full load hours per grid cell are calculated in two steps:

1. Average wind speed at hub height = (average 00–05 wind speed data) x (scaling factor dependent on CLC type)
2. Practical full load hours are calculated in accordance with the linear relationship between average wind speed and full load hours (Figure 2.3):
   - practical full load hours grid onshore where H < 600 m = (average wind speed at hub height x 626.51 – 1 901) x 0.90;
   - practical full load hours grid onshore where H > 600 m = (average wind speed at hub height x 626.51 – 1 901) x 0.83;
   - practical full load hours grid offshore = (average wind speed at hub height x 626.51 – 1 901) x 0.81.

2.3 Summary

On the basis of the foregoing analysis, the main assumptions for future technological progress and technical limitations are presented in Table 2.2.

Table 2.2 Summary of future technological development of wind energy

		2005			2020			2030		
	Unit	**Offshore**	**Onshore**	**Mount.([a])**	**Offshore**	**Onshore**	**Mount. ([a])**	**Offshore**	**Onshore**	**Mount. ([a])**
Rated power	MW	3	2	2	8	2	2	10	2	2
Power density	MW/km^2	10	8	4	12	8	4	15	8	4
Array efficiency	%	90	92.5	92.5	90	92.5	92.5	90	92.5	92.5
Availability	%	90	97	90	90	97	90	90	97	90
Load hour losses	%	19	10	17	19	10	17	19	10	17

Note: ([a]) Mount. = Mountenous areas.

3 Technical potential

3.1 Onshore areas available for wind energy

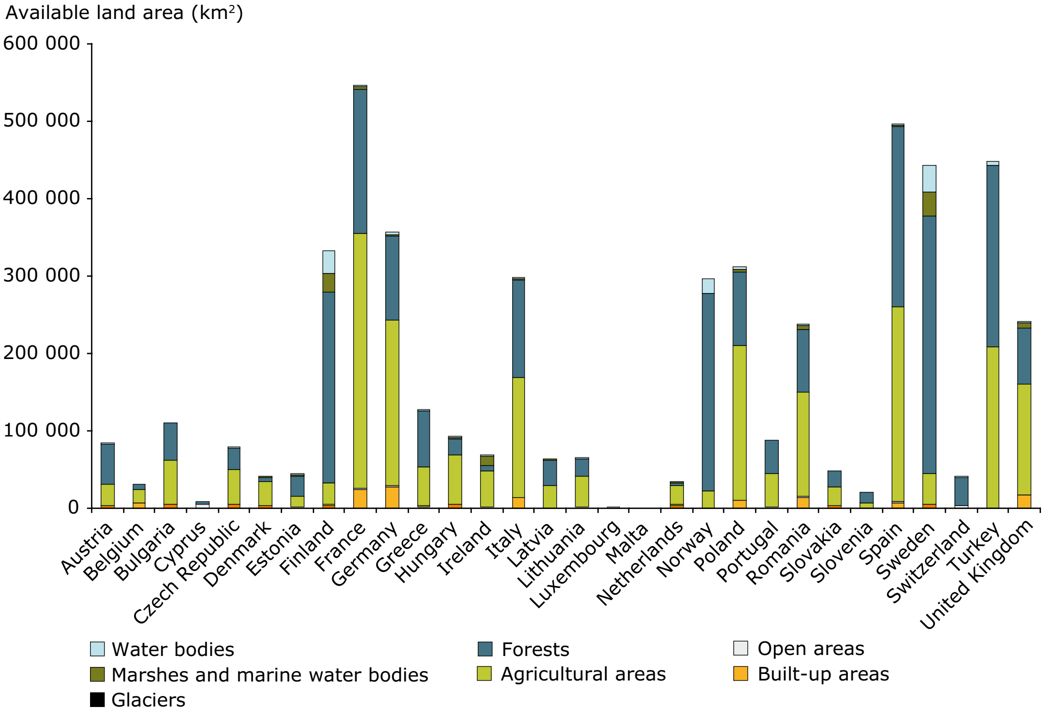
As previously stated, the unrestricted technical potential estimation for wind potential on land is based on wind power density and wind turbine technology development per type of land cover. All types of land are included, independent of their suitability for wind turbine development.

Figure 3.1 describes the available area onshore, aggregating the 15 Corine Land Cover classes into 7 classes. The total land area totals 5.4 million km^2 in all EEA countries. The aggregated class 'forests' (CLC classes 8 to 11), and the aggregated class 'agricultural land' (CLC classes 4 to 7) cover about 90 % of total land available.

France, and Spain have the largest agricultural land area and Sweden, Finland, Turkey and Norway have the largest forest area. The feasible penetration of wind turbines on agricultural land (CLC-4, CLC-6 and CLC-7) is higher compared to the average feasible penetration on all land cover types. In fact, in countries where wind energy deployment is quite high (i.e. Denmark, Germany and the Netherlands), agricultural land area has been most attractive for wind energy deployment. Installation of wind turbines on agricultural land can be very well combined with other uses such as vegetable production or keeping cattle (Pimentel *et al.*, 1994). Besides, agricultural land has relatively few obstacles, which implies a low roughness. In such areas, wind farms can be designed in an optimal way and do not need to be decreased in size or have a different layout or sub-optimal spacing.

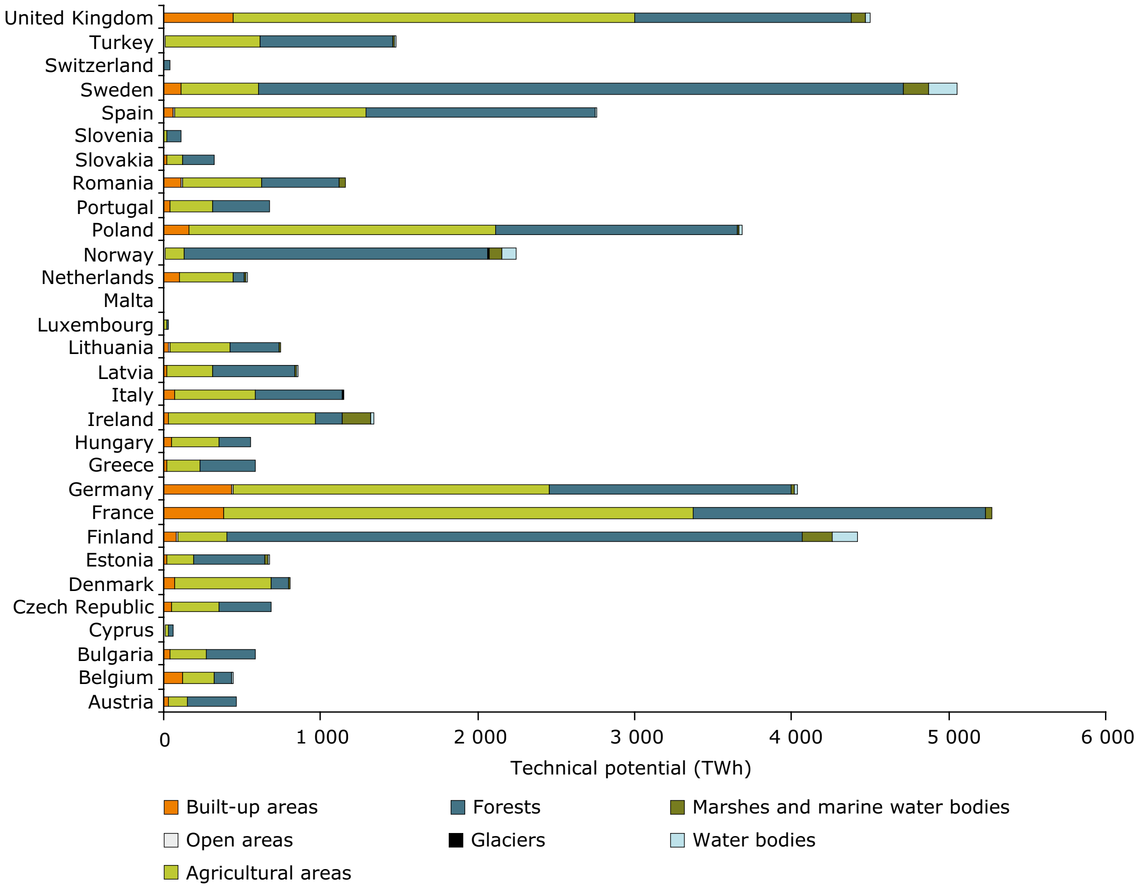
For each of the seven aggregated land cover classes, the technical potential for onshore wind has been calculated on a country basis. Figure 3.2 sets out the results of this analysis. The estimated technical potential for wind energy on land is calculated to be around 45 000 TWh in all EEA countries together in 2030. More than half of the technical potential is generated in classes with average wind speeds of 5.4 m/s and 5.7 m/s.

Figure 3.1 Area available per type of aggregated land cover class (km^2)



Source: EEA, 2008.

Figure 3.2 **Unrestricted technical potential for onshore wind energy up to 2030, based on estimated 80 m average wind speeds 2000–2005**



Source: EEA, 2008.

3.1.1 *Wind energy potential in mountainous areas*

Only a limited number of wind farms are installed in mountainous areas. In mid-2004, for instance, 1.5 % of turbine capacity was installed in mountainous countries in Austria, France, Italy, Slovenia and Switzerland (Winkelmeier and Geistlinger, 2004). Lower accessibility of mountainous areas and the limited roads and grid connections result in less favourable conditions for wind farms. However, there are wind turbines at high altitudes. For instance, the highest large-scale wind park was situated at 2330 m in Switzerland in 2004.

Because of the limited wind farms at high altitudes there is not much extended research on the impact of the lower accessibility. Only one EU research project has been identified that considered the impact of wind farms in alpine area: Alpine Windharvest (see Winkelmeier and Geistlinger, 2004).

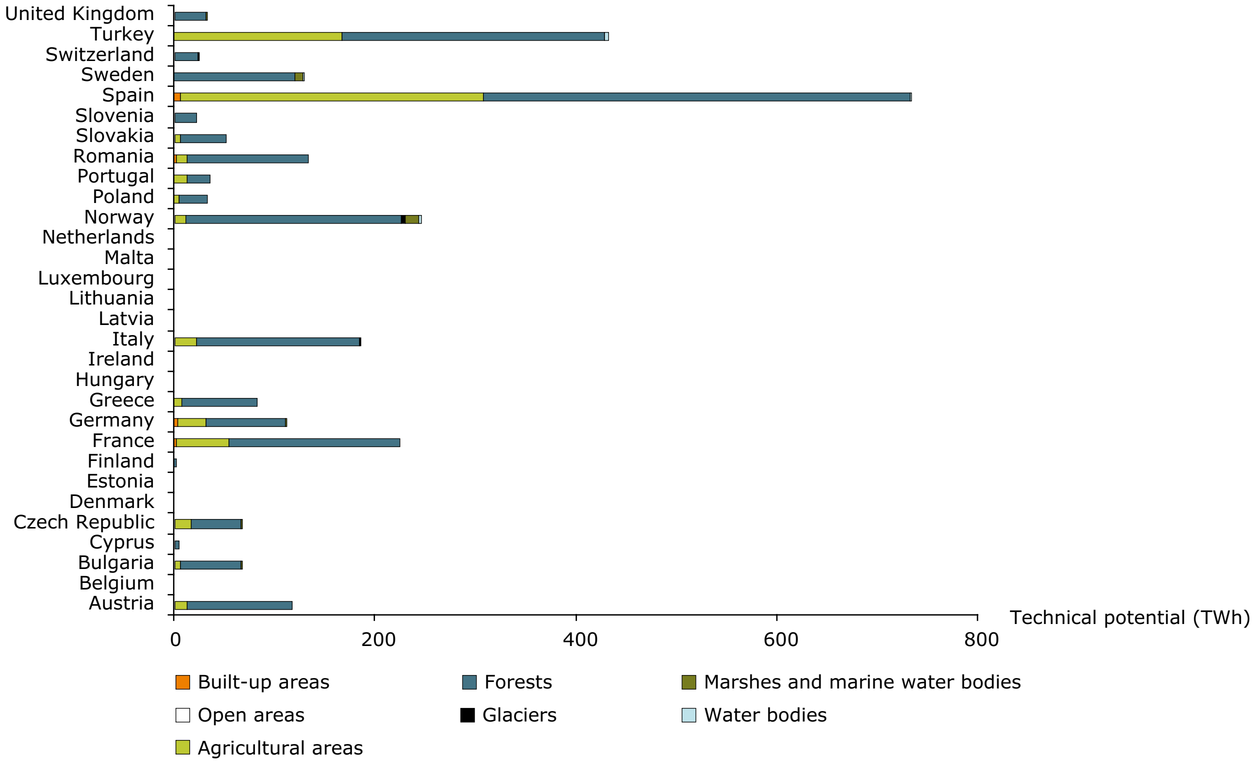
The assumptions applied for the mountainous areas are as follows:

- 1 wind farms should be sited below 2 000 m above sea level;
- 1 power density is reduced at sites more than 600 m above sea level.

It is assumed that access to roads and grid connections above 2 000 m is quite restricted and therefore there is very limited area suitable for wind energy. The value of 2 000 m is somewhat arbitrary as the highest large-scale wind farm is installed at 2 330 m (see above). All other current large-scale wind farms are below 2 000 m, however.

It is assumed that between 600 and 2 000 m some areas might be more isolated as the terrain is more complex for large wind farms. Because wind turbines have to be connected to low-voltage grids, the scale of the wind farms at areas between 600 and 2 000 m (and therefore the maximum power density) is assumed to be lower. To avoid overestimation, the power density for wind farms in mountainous areas between 600 and 2 000 m is reduced by 50 % relative to those below 600 m. For this study it implies that

Figure 3.3 Potential for wind energy in mountainous areas in 2030 (TWh)



Source: EEA, 2008.

the power density of 8 MW/km^2 applied to all types of land uses is set to 4 MW/km^2 for mountainous areas (12) This assumption on power density in mountainous areas is in line with an Italian study that analysed the power density of a sample area in the Apennine Mountains. The power density at heights of 800–1 000 m averaged 4.2 MW/km^2 (CESI, 2003).

Reduction of output at higher altitudes

The weather conditions at high altitude are more extreme. This can result in increased shutdown as well as productivity reduction due to ice build-up. Nonetheless, the available literature indicates that on average the shutdown due to extreme weather conditions is not higher compared to non-mountainous areas. Only two cases mention a shutdown of more than 10 days. Productivity reduction due to ice build-up is mostly put at below 10 % or even below 2 %.

When mountainous areas are defined as areas above 600 metres, 33 % of the total land area in EEA countries falls in this category. Switzerland, Turkey, Austria and Spain have the largest shares of mountainous areas as a proportion of their land area. In Switzerland, 74 % of the total land area is mountainous. For Turkey, Austria and Spain it is 71 %, 59 % and 57 %, respectively. The technical potential for wind in mountainous areas where we assume a lower power density of 4 MW/km^2 totals just over 2 500 TWh in all EEA countries. The wind energy potential in mountainous areas is shown in Figure 3.3.

3.2 Offshore

As explained above, Economic Exclusive Zones have been used to determine the national jurisdictions of different countries over offshore areas. Unsurprisingly, the United Kingdom (114 000 km^2) and Norway (88 000 km^2) comprise the largest share of available offshore area for wind energy generation. In order to clarify the relationship between wind energy potential and distance to the shore, offshore areas are split into categories according to the distance to the coast: 0–10 km; 10–30 km; 30–50 km; and > 50 km. The potential in each category is presented in Figure 3.4.

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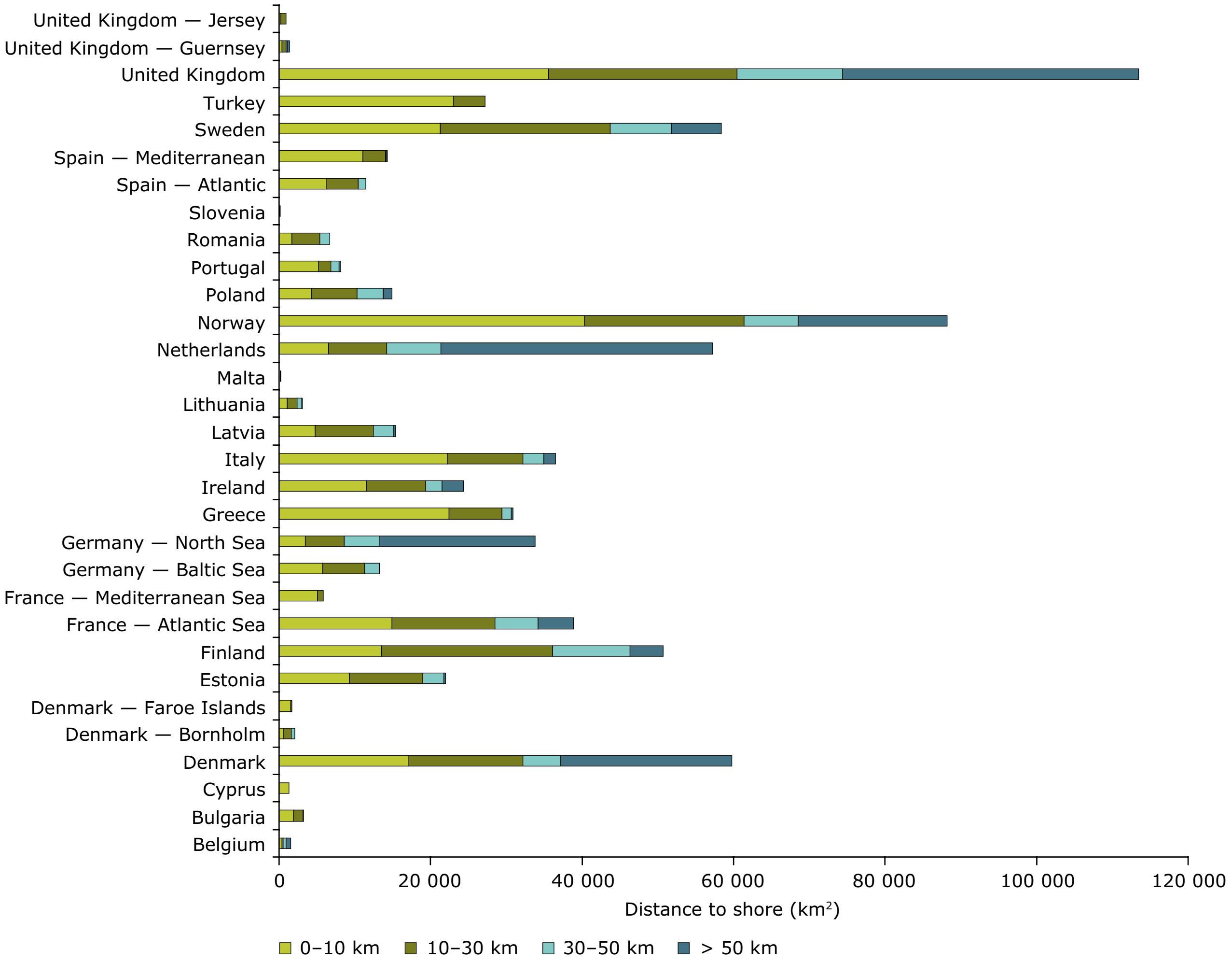
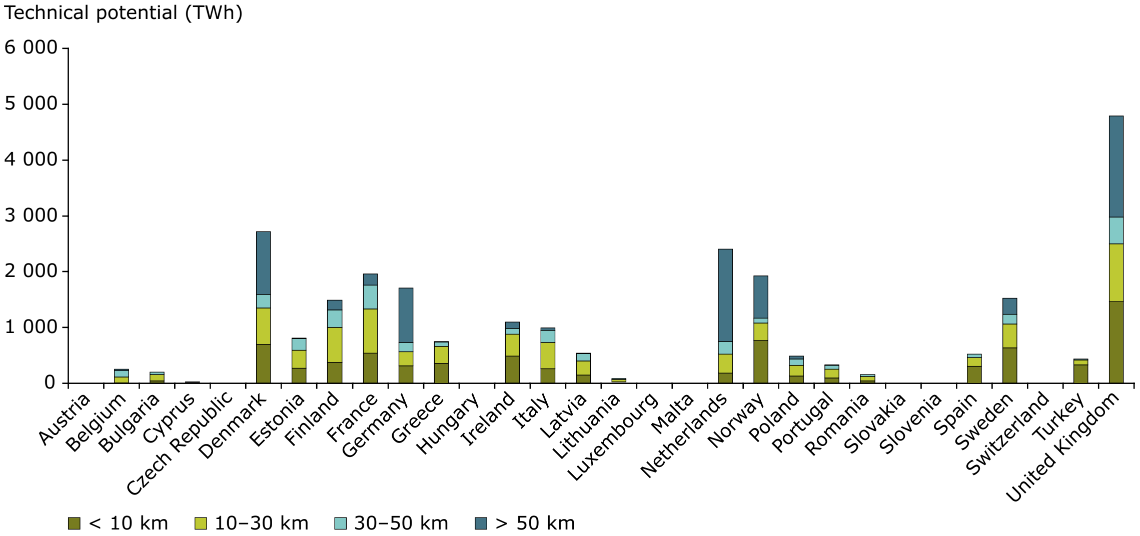
(12) Norway has reported that there are several licensing applications pending in Norway concerning locations higher than 600 m above sea level.

Figure 3.4 **Available offshore area (km²) for wind energy farms within national jurisdictions**



Source: EEA, 2008.

Figure 3.5 **Unrestricted technical potential for offshore wind energy in 2030 based on average wind speed data**



Note: A recent Norwegian study (NVE, 2008) estimates Norwegian offshore wind power capacity to be around 55 300 MW (at maximum depths of 50 m and minimum distances to the coast of 1 km).

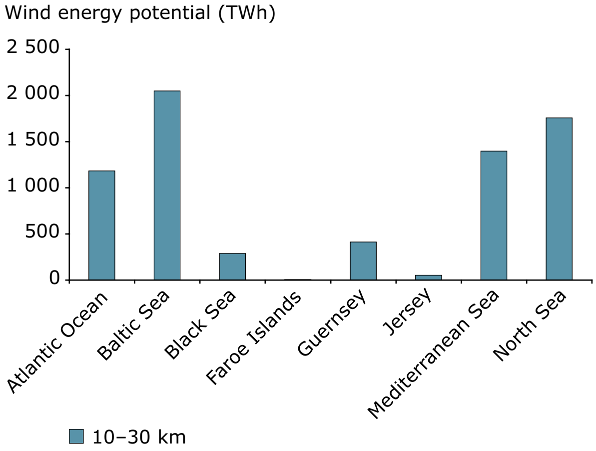
Source: EEA, 2008.

Current and anticipated technology limits the potential for offshore wind energy generation. First, no wind speed data have been collected for offshore areas with a depth of more than 50 metres. Second, wind turbine developments in such deep waters are within this study considered not to happen within the limits of current technology. Therefore, these areas are excluded from the technical potential estimates. Currently wind farms are with a few exceptions, placed in shallow waters, with depths up to about 25 metres.

The offshore technical potential in 2030 is estimated at 30 000 TWh for all EEA countries (Figure 3.5). This figure is two-thirds of the onshore (unrestricted) technical potential (45 000 TWh). This study includes 5 000 000 km^2 land area and 750 000 km^2 sea area, which explains the lower offshore (unrestricted) potential. As mentioned above, 2000–2005 average wind speeds have been used as the primary data.

As a sensitivity analysis wind potential was recalculated using the 2003 and 2004 wind speed data separately. The results show that there is a large inter-annual variability in estimates: the 2004 data produce an estimated potential 11 % higher than the results using 2003 data due to large differences in wind speed in those two years. Some individual countries show inter-annual variability of almost 30 %, e.g. Denmark (North Sea) and Germany (the Baltic and North Sea).

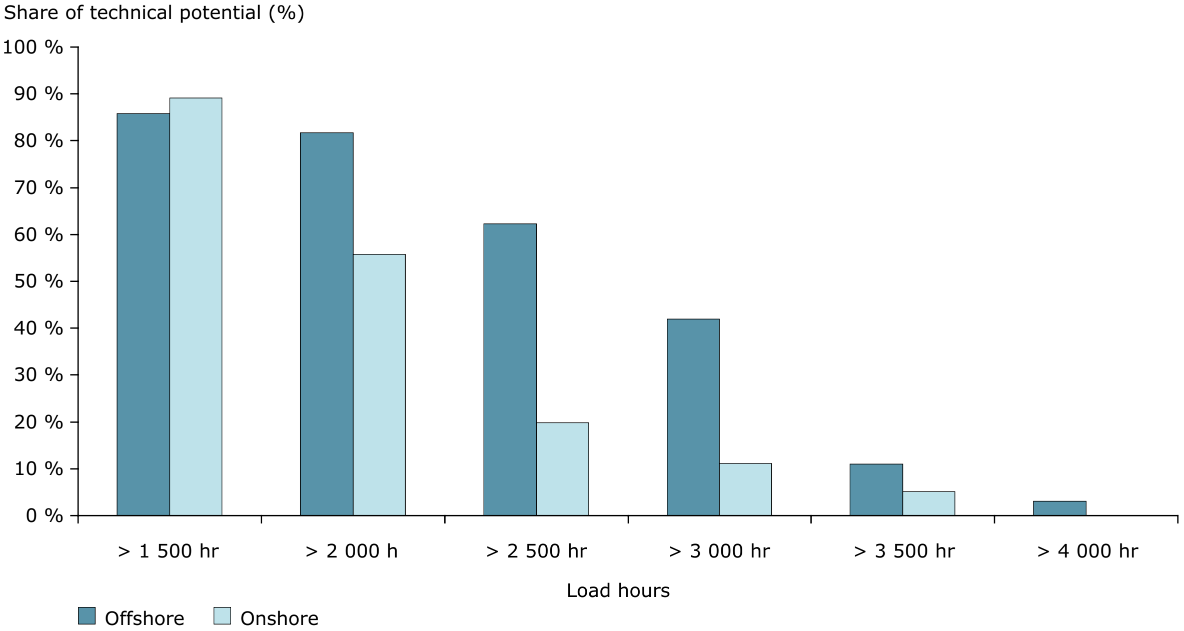
Figure 3.6 **Unrestricted technical offshore wind potential in offshore areas 10–30 kilometres from the coast**



Source: EEA, 2008.

Figure 3.6 shows that the offshore wind energy potential between 10 and 30 kilometres from the coast is concentrated in the Baltic, the North Sea (including the English Channel) and the

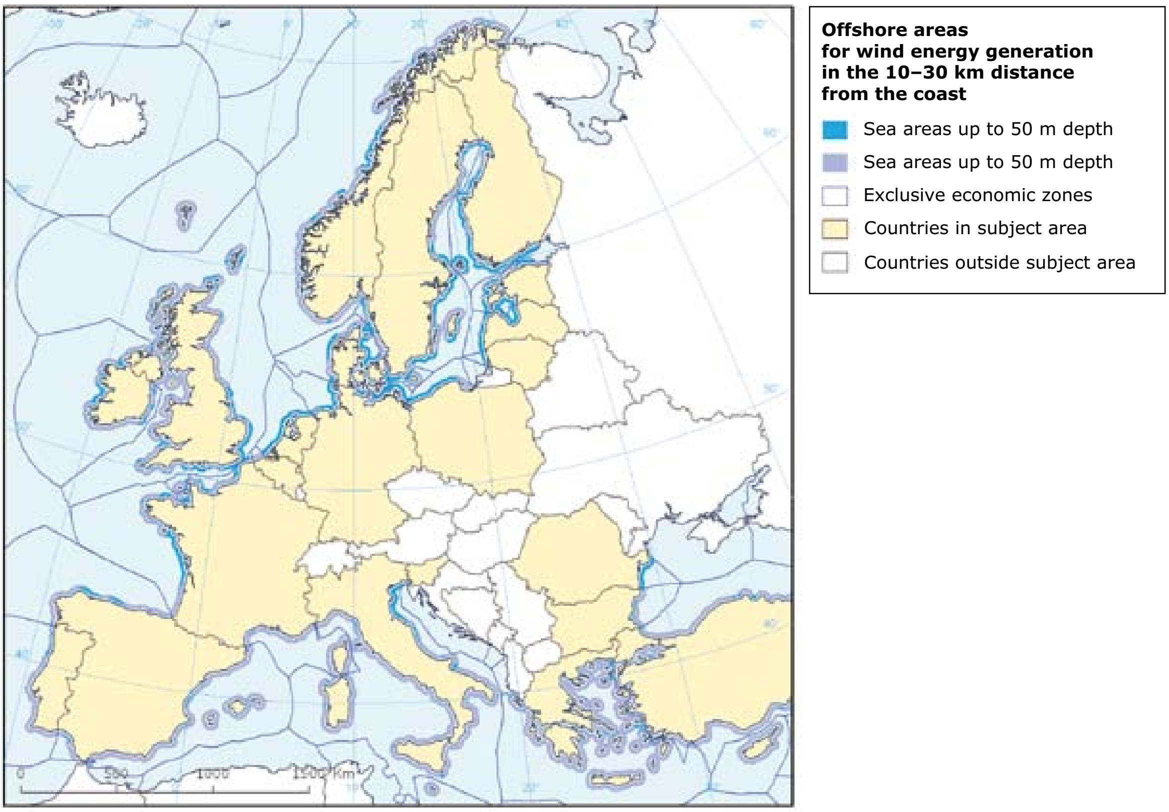
Figure 3.7 **Share of the technical potential realised in different full load-hour classes**



Note: 'Offshore' here includes all classes of distance from shore (0–50 km).

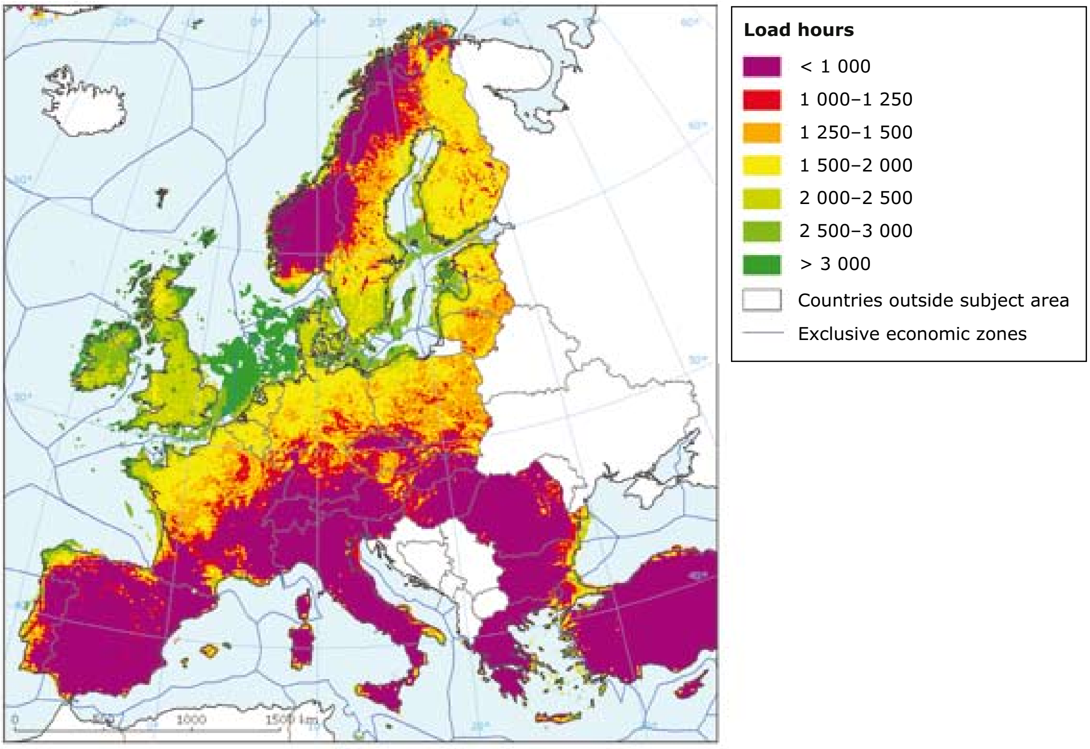
Source: EEA, 2008.

Map 3.1 **Offshore areas for wind energy generation at a distance of 10–30 km from the coast**



Source: EEA, 2008.

Map 3.2 **Distribution of full load hours in Europe (80 m hub height onshore, 120 m hub height offshore)**



Source: EEA, 2008.

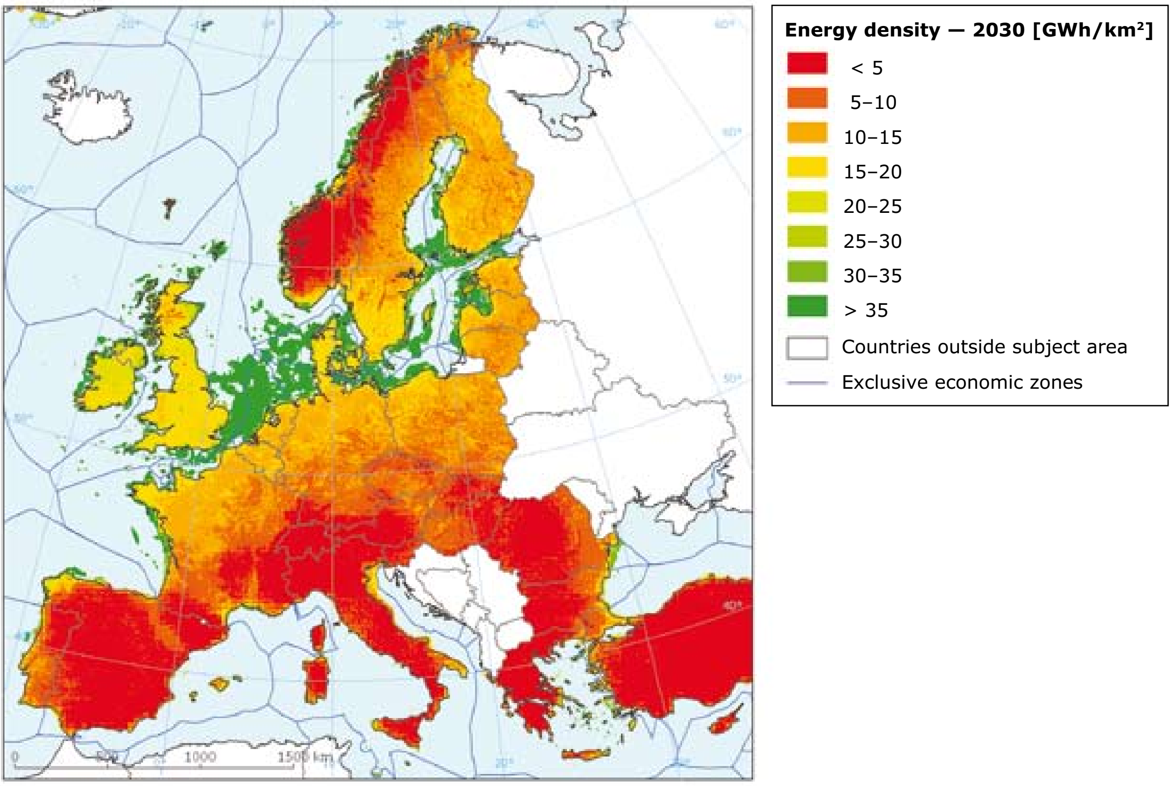
Mediterranean. Respectively, 29 %, 25 % and 20 % of the projected total offshore wind potential at 10 to 30 kilometres from the coast (7 100 TWh) in 2030 can be found in these areas. Map 3.1, however, illustrates that some offshore areas in this distance class have sea depths greater than 50 metres and are therefore not suitable for wind energy development.

Further out at sea, at 30 to 50 kilometres from the coast, the Baltic, the North Sea (including the English Channel) and the Mediterranean respectively account for 30 %, 30 % and 20 % of total wind potential. The total potential for this distance class is estimated as 3 300 TWh in 2030.

3.2.1 Distribution of wind energy potential

As water has less surface roughness than land (especially deeper waters), offshore wind speeds are considerably higher than onshore. Thus, offshore wind resources are characterised by higher load hours. Figure 3.7 illustrates this point. On land only 5 % of technical potential is realised in areas with over 3 000 full load hours, while at sea this percentage is over 40 %. Very windy onshore areas are mainly located in parts of Ireland and the United Kingdom (see Maps 3.2 and 3.3). No onshore areas have resource potentials exceeding 4 000 full load hours.

Map 3.3 Distribution of wind energy density (GWh/km²) in Europe for 2030 (80 m hub height onshore, 120 m hub height offshore)



Source: EEA, 2008.

4 Model calibration — annual wind speeds in Europe

4.1 Approach

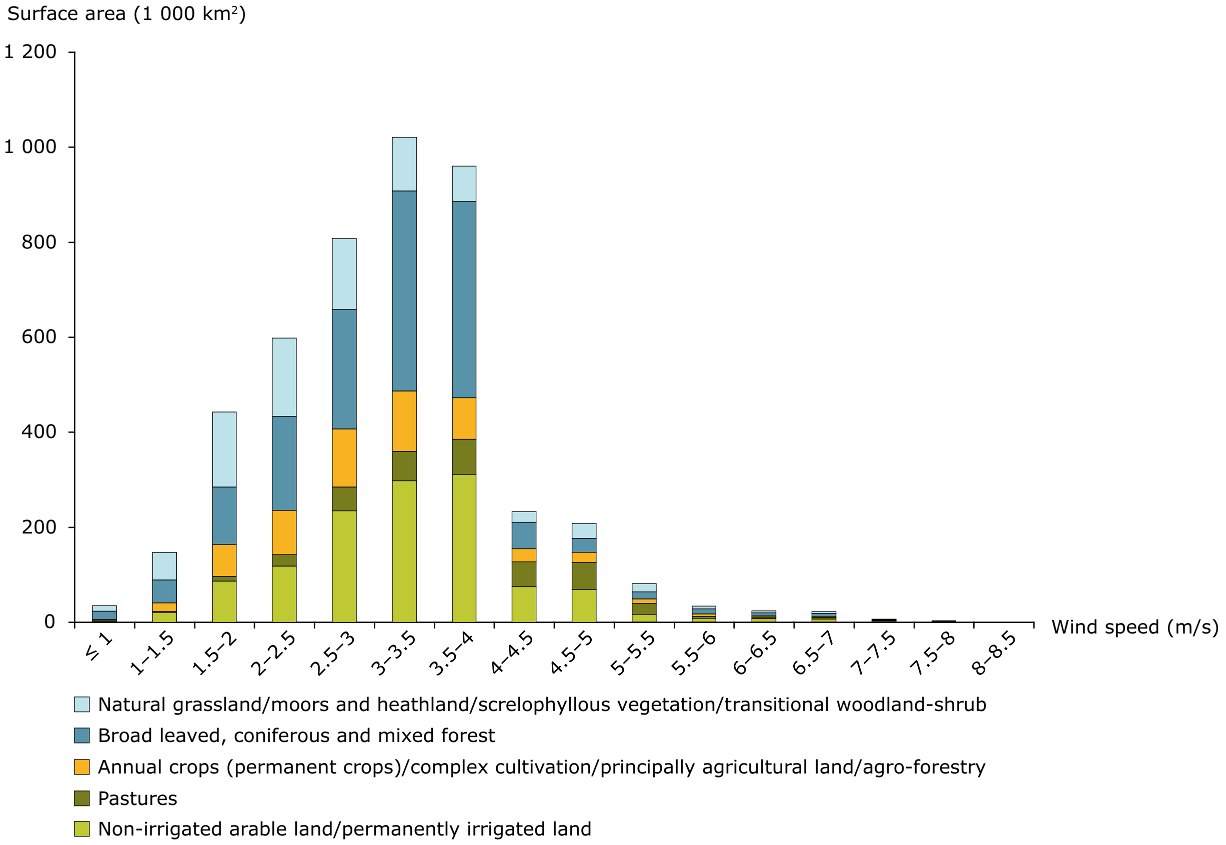
As the assessment of wind energy potential relies heavily on reanalysis of wind data, it contains a key uncertainty in terms of how well the results reflect the actual observed values. In the following sections the performance of the model are validated against observations of surface wind speed made at meteorological stations throughout Europe.

The wind speed value of 4 m/s is of particular interest for this study since it is typically only at wind speeds above this threshold that turbines can operate effectively. Model calculations (ECMWF, 2007) show that surface (10 m above ground level) wind speeds across most of Europe average less than 4 m/s. Annual mean wind speeds greater than 4 m/s are expected across 13.5 % of the European land surface area.

Figure 4.1 shows that there is a significant drop off in surface area between the wind speed bands, 3.5–4 m/s and 4–4.5 m/s. Figure 4.1 also reflects the most important Corine land classifications for Europe, in terms of area, these are:

- 1 Non-irrigated arable land, permanently irrigated land and rice fields (CL-4);
- 1 Pastures (CL-6);
- 1 Annual crops associated with permanent crops, complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation and agro-forestry (CL-7);
- 1 Broad-leaved, coniferous and mixed forests (CL-8);
- 1 Natural grasslands, moors and heathland, sclerephyllous vegetation and transitional woodland shrub (CL-9).

Figure 4.1 **Land surface area, distributed between different Corine land classifications, plotted against modelled surface wind speeds for 2001**



Source: EEA, 2008.

The method used in this study generates gridded information on wind velocities, based on spatially averaged ECMWF data.

Annual mean daily surface wind speeds were calculated for European meteorological stations using the National Climatic Data Centre (NCDC), Global Surface Summary of the Day dataset (NCDC, 2007). Surface wind speed observations in this dataset are reported at approximately 10 m above ground level.

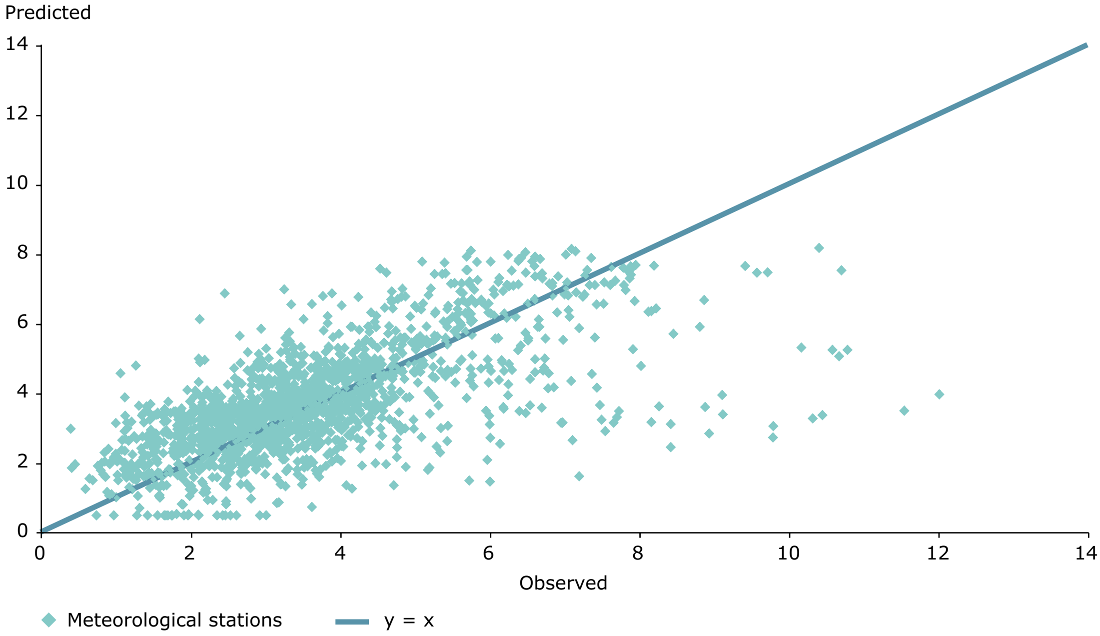
To validate the performance of the GIS calculations, the annual mean observed wind speeds were then compared against wind speeds calculated at 10 m above ground level for each meteorological station location and elevation. Due to the time constraints of downloading the information from the NCDC web portal, annual data was only obtained for the year 2001 and the evaluation is therefore based on that year.

4.2 Europe-wide comparison

The mean wind speed across all European meteorological stations, for which wind speed observations were made, on average more than twice per day and for more than 75 % of year, was 3.63 m/s in 2001 with a standard deviation, σ, of 1.66. Mean wind speeds for 2001, predicted using the GIS methodology across these stations, come to 3.74 m/s (σ = 1.51).

Figure 4.2 illustrates that for wind speeds less than 5 m/s the model shows reasonable agreement with surface observations. The coefficient of determination, r^2, for the entire population suggests that 12 % of the variability in predicted wind speeds can be associated with variability in the observations (13), taking y = x as the regression line. The standard error of prediction, the standard distance of the prediction from the y = x line, is 1.35 m/s. However, there are a number of locations,

Figure 4.2 Relationship between observed and predicted 2001 mean daily wind speeds for all European meteorological stations



Source: EEA; AEAT, 2008.

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(13) r^2 here refers to the proportion of the variability in the predictions that can be explained by comparing regression with observations, in this case in the regression line y = x. If we have an r^2 value of 0.4 then we can say that the variability of the prediction values around the line y = x is 1–0.4 times the original variance. Alternatively, the r^2 allows the line y = x to explain 40 % of the original variability, leaving 60 % residual variability. Ideally, the GIS methodology would perfectly predict the wind speed at meteorological stations, in which case the line y = x would explain all the original variability. The r^2 value is an indicator of how well the model fits the data, where r^2 = 1.0 indicates that the model accounts for all the variability with the variables specified in the model.

Table 4.1 Predicted and observed wind speed statistics across four geographical regions of Europe

Region	Annual mean wind speed (m/s)				Error (m/s)		Coefficient of determination, r^2 (for y = x)	Standard error of prediction (m/s)
	Observed		Predicted					
	Mean	σ	Mean	Σ	Mean	σ		
A: Denmark, Germany and Netherlands	4.460	1.495	4.573	1.336	0.114	0.798	0.636	0.812
B: Finland, Norway and Sweden	3.832	1.881	3.839	1.878	0.007	1.450	0.999	1.455
C: France, Portugal and Spain	3.825	1.437	3.637	1.307	– 0.189	1.309	N/A	1.329
D: Austria and Switzerland	2.538	1.594	2.081	0.995	– 0.456	1.451	N/A	1.534

particularly for larger observed annual wind speeds, at which the model under-predicts by significantly more than this value. Since high wind speed locations are of interest for generating electrical energy, it is important that this divergence be analysed further.

4.3 Geographical differences

Topography and meteorology vary significantly across Europe. It is therefore important to consider whether there are any differences in the relationship between predicted and observed wind speeds. Table 4.1 shows several statistics for meteorological stations in four different European country blocks. In region A (Denmark, Germany and Netherlands), the mean model-predicted wind speed is 2.5 % greater than the observation mean. The mean error is 0.11 m/s for the whole population, with a standard deviation of 0.798 m/s. A plot of the model-predicted wind speed against observations at meteorological stations in region A shows very good agreement (Figure 4.3). Nearly two-thirds of the variability in model predictions can be explained by the variability in the observations and the standard distance of predictions from the regression line y = x is 0.812 m/s.

The model compares well also for region B (Finland, Norway and Sweden), with mean predicted wind speeds less than 1 % greater than mean observed wind speeds. According to the statistics, nearly 100 % of the variability of model predictions is explained by variability of the observations. However, it can be seen from the regression plots and the standard deviation of the error, that there is substantial scatter.

In region C (France, Portugal and Spain), mean predicted wind speeds are around 5 % lower than observed. For regions B and C, the standard error of prediction is 1.46 m/s and 1.33 m/s respectively.

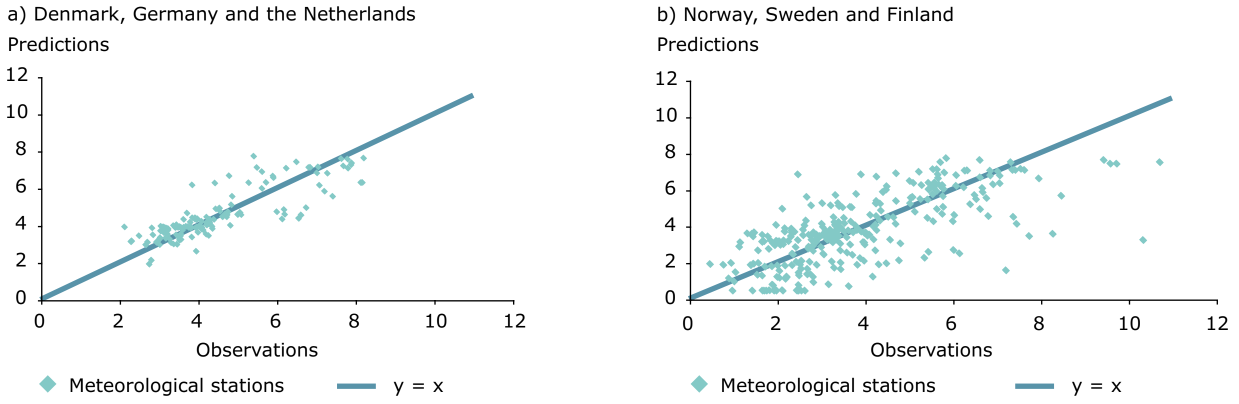
The differences become even greater between the modelled wind speeds and observations for region D (Austria and Switzerland). The mean predicted wind speed is 18 % below the observed mean whilst the mean error between the two populations is – 0.46 m/s, the standard deviation of this error is similar to that for region B (1.45 m/s). As Figure 4.3d makes plain, the relationship between observed and predicted wind speeds lies some way from the y = x regression line, particularly for higher observed wind speeds.

Both Austria and Switzerland are situated in the Alps and therefore contain some very mountainous terrain. As discussed in Chapter 2, the model predicted wind speeds are derived from ECMWF analyses with a resolution of 0.25 ° x 0.25 °. The ECMWF analysis presents spatially averaged values and therefore encompasses some error against point locations. In mountainous areas, there is significant variation in topography and the elevation of mountain peaks is not captured by the ECMWF spatially averaged topography.

Some meteorological stations within mountainous areas are sited on mountain tops where wind speeds are typically high since wind speeds generally increase with altitude in the lower atmosphere. As a result, the model predicted wind speeds, based on ECMWF spatial mean values, under-predict the wind speeds at these point locations. By way of illustration, Figure 4.4 shows the ratio of predicted and observed wind speeds at meteorological stations with annual mean wind speed greater than 5 m/s, plotted against the elevation of the station.

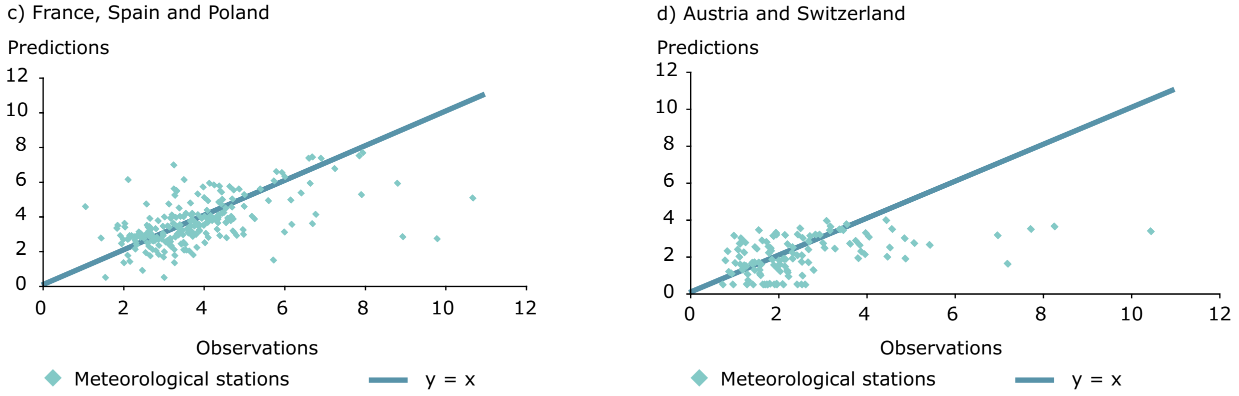
Below approximately 250 m elevation, there is a cluster of points between the ratio values of

Figure 4.3 Relationship between observed and modelled 2001 mean daily wind speeds for the four geographical regions listed in Table 4.1



a) Denmark, Germany and the Netherlands

b) Norway, Sweden and Finland

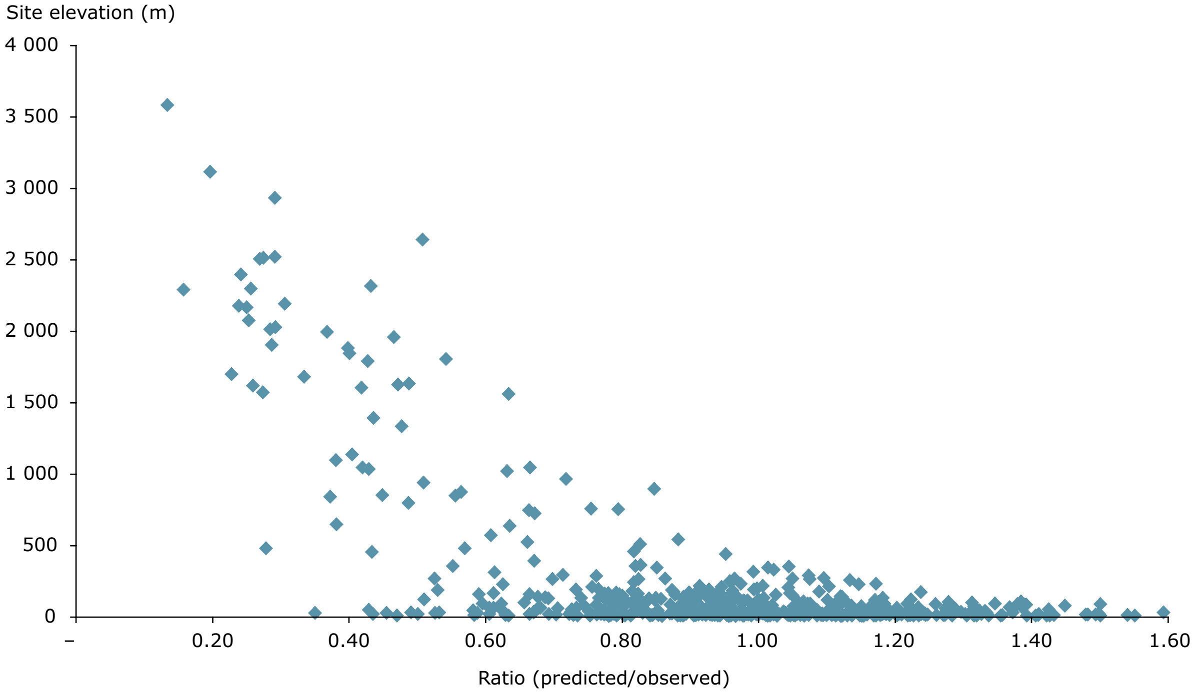


c) France, Spain and Poland

d) Austria and Switzerland

Source: EEA; AEAT, 2008.

Figure 4.4 Ratio of predicted to observed wind speeds plotted against station elevation



Source: EEA; AEAT, 2008.

0.6 and 1.4. However, as station elevation increases, the ratio declines to values between 0.2 and 0.4, showing some under-prediction of wind speeds by the model at relevant stations.

Figure 4.5 shows the relationship between observed and GIS-calculated wind speeds for meteorological stations in the two most extensive Corine land classifications in Europe: CL-4 (non-irrigated arable land, permanently irrigated land and rice fields) and CL-8 (broad-leaved, coniferous and mixed forests). It is clear from Figure 4.6 that there is much better correlation between predicted and observed wind speeds at meteorological stations situated in CL-4 areas, with 33 % of the variability in the prediction error associated with variability of observed wind speeds at those stations. In contrast, for those stations within CL-8 areas, the distribution of predicted and observed wind speeds is much wider.

Again, the model performance in these different land-type areas is likely to result from the spatially averaged surface wind speeds used to derive the predicted values at the meteorological station locations in combination with the representativeness of those mean quantities for each point location. In areas where surface roughness, and hence turbulence, is low, spatially averaged values typically give a good representation of point locations within that area. This is true for Corine land classification CL-4, which has a surface roughness of 0.03–0.17 m. The surface roughness range for land classification CL-8, however, is 0.75–1.0 m. Therefore, for surface measurements at meteorological stations in forested areas (CL-8), there is a greater likelihood of an observed wind speed lying further from the area mean.

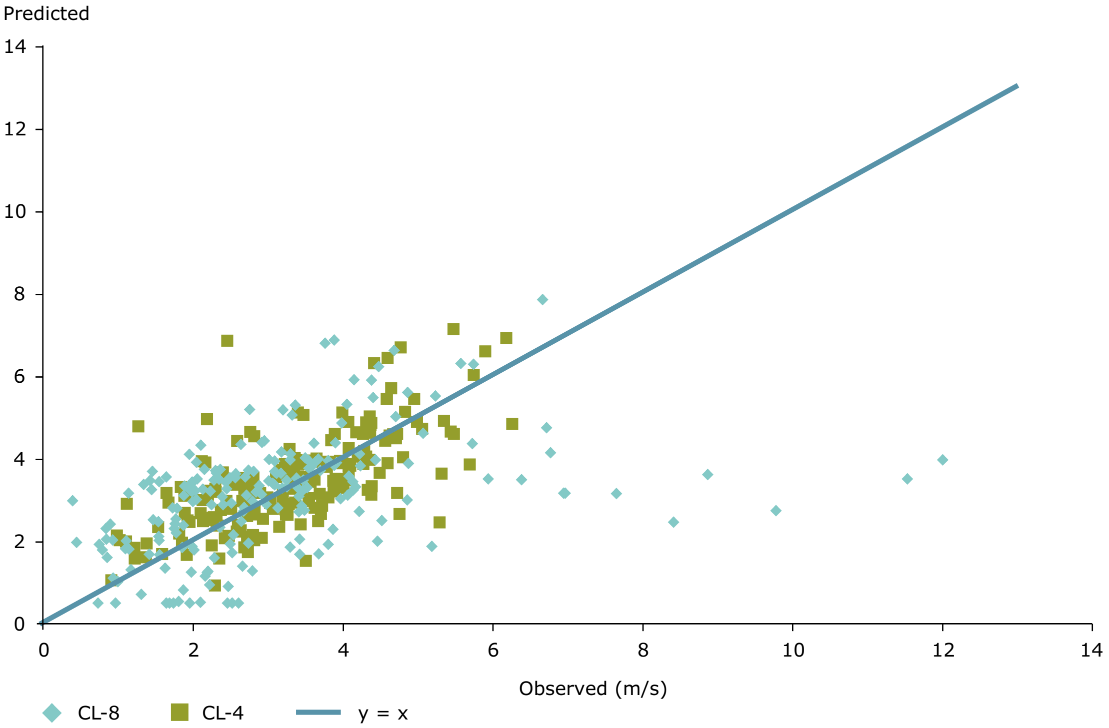
4.4 Evaluation of errors

While previous sections have analysed the general model agreement with observed wind speeds, this section aims to evaluate levels of uncertainty in the model that might affect the calculation of wind energy potential across Europe.

4.4.1 High and low wind speeds

One potential area of uncertainty is model over-prediction of wind speeds, where observed winds are low and another is under-prediction, where observed winds are high. This concept is illustrated in Figure 4.6. Taking 4 m/s as the threshold wind

Figure 4.5 Relationship between observed and predicted 2001 mean daily wind speeds for met stations within Corine land classification areas CL-4 and CL-8



Source: EEA; AEAT, 2008.

speed for energy generation, how many stations with an observed wind speed of less than 4 m/s are predicted by the model to have a wind speed of greater than 4 m/s (shaded region of Figure 4.6a. This is reversed for stations with an observed wind speed greater than 4 m/s (shaded region of Figure 4.6b).

As a percentage of all the European meteorological stations for the total population considered here, 11 % of stations with observed wind speed below 4 m/s are predicted to have a wind speed above the threshold, whereas 9 % of stations with an observed wind speed above the threshold are predicted below that value. To some extent these two prediction errors should counteract each other so that the mean wind predictions across Europe are reasonable. However, another effect of these errors is to reduce the range of the predicted wind speeds compared to observations, resulting in a greater extent of Europe in estimated wind speeds at the centre of the wind speed distribution and less area assigned to low or high values.

4.4.2 *Upper and lower wind speed intervals and full load hour implications*

Figure 4.7 shows the relationship between predicted and observed wind speeds for meteorological stations in CL-4 areas and also the upper and lower limits for wind speed predictions based on the standard error prediction against the regression line y = x. The standard error for these stations is 0.95 m/s, which leads to a 95 % confidence interval of ±1.88 m/s. The significance of this error margin grows when it is scaled to a load hour error; for the CL-4 example, the wind speed error of 1.89 m/s translates to ± 1 120 full load hours. Since the error is linear, as expressed as a percentage, the error margin narrows with rising predicted wind speed.

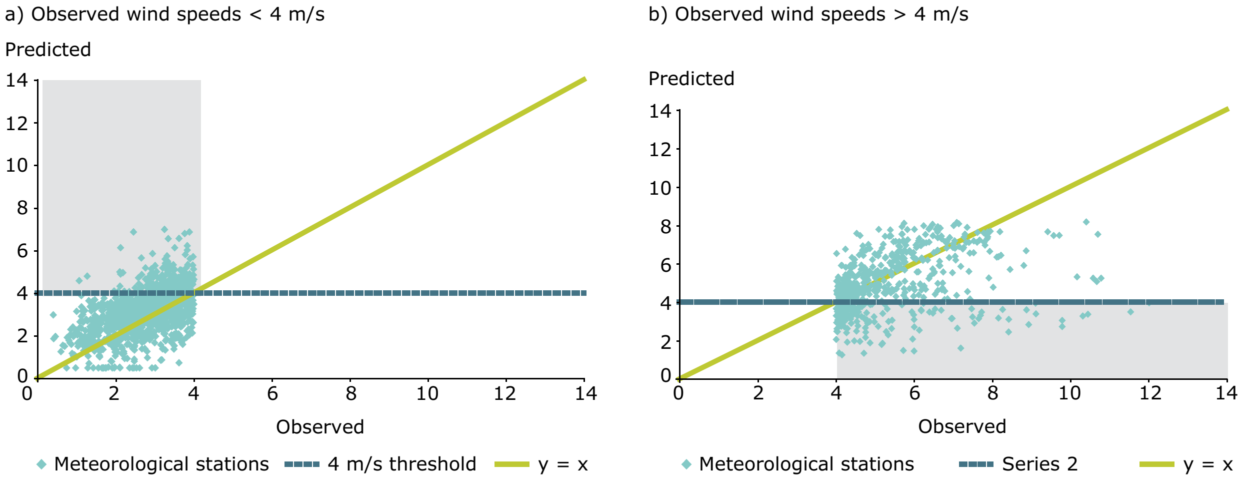
The load hour error calculated from meteorological stations within CL-8 areas is much greater than for CL-4 zones, suggesting greater uncertainty in model predicted wind energy within such regions. However, it should be noted here that the methodology for calculating full load hours takes into account the surface roughness when calculating wind speeds at 80 m above the surface. Better correlation might be expected between predicted and observed wind speeds at this height, which is possibly above boundary layer turbulence associated with surface roughness. Further validation of the model at this height above ground level would be an informative avenue for a future study and might involve the use of measurements from towers or from radiosonde.

4.5 Conclusions

This chapter has established that wind speeds predicted using the methodology employed in this study generally correlated with surface wind speed observations at European meteorological stations. Good correlation between observed and predicted values was found in relatively flat geographical regions with low surface roughness, such as Denmark, Germany and the Netherlands.

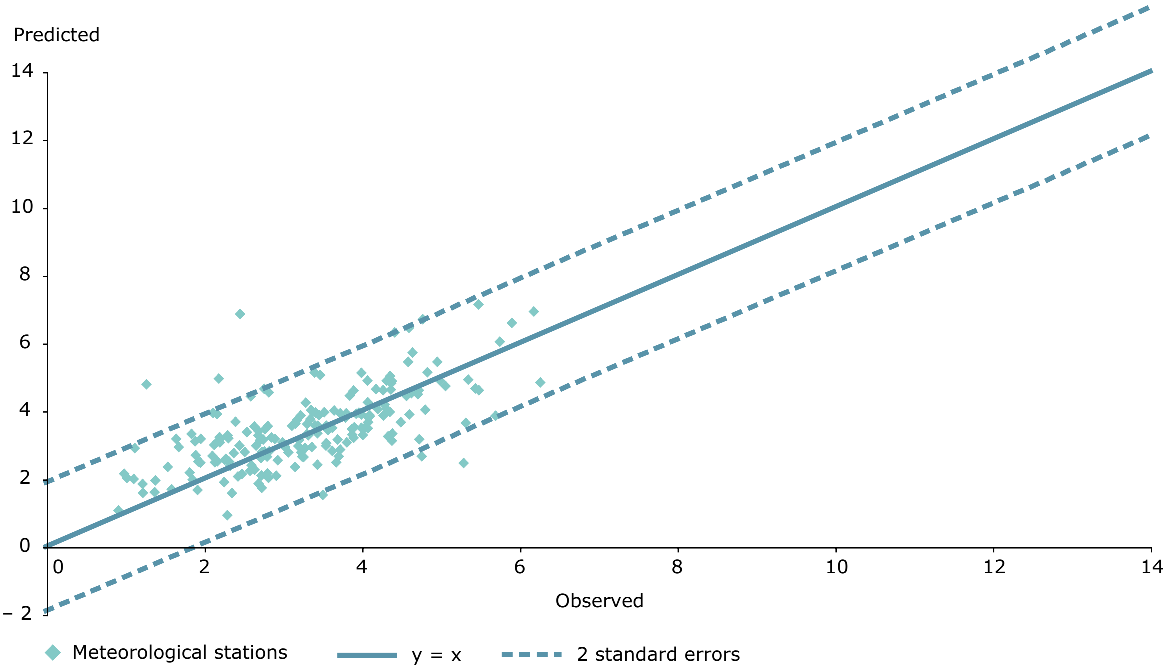
At the surface level, somewhat better agreement was found for CL-4 areas (agricultural lands) than

Figure 4.6 Illustrations of over- and under-prediction (grey areas) of wind speeds in the model at low and high observed wind speeds



Source: EEA; AEAT, 2008.

Figure 4.7 **Relationship between observed and modelled 2001 mean daily wind speeds for met stations in Corine land classification CL-4**



Source: EEA; AEAT, 2008.

CL-8 areas (forests). This is probably due to the low surface roughness of CL-4 land, which means that the spatially averaged winds used to derive the model predictions provide a reasonably good representation of the wind speed at point locations within that area. The uncertainty associated with CL-4 values was evaluated to 95 % confidence intervals of ± 1.88 m/s.

The modelled wind speeds show poor correlation at meteorological stations that are not representative of the 15 km by 20 km grid average value provided by the ECMWF data that underpin the model, for example, in forested areas (CL-8) and mountainous regions. Clearly, much larger uncertainty is associated with surface wind speed predictions in such areas as compared with CL-4 areas. However, better correlation might be possible at the 80 m hub height than for surface readings and further analysis of this uncertainty should be included in any future investigation using this methodology.

On balance, the uncertainties have been found to be smallest for areas that are generally most suitable for establishing of wind farms, namely relatively flat low-lying areas. The uncertainties are larger for mountainous areas and other areas with larger surface roughness. In many cases, these areas are less suitable for wind energy turbines because of landscape, biodiversity and other concerns (see the following chapters), even if they offer high wind speeds.

For future studies, it may be possible to construct a model of the statistical error in predicted wind speeds, taking into account the model over-prediction at low wind speeds, the under-prediction at high wind speeds and errors associated with elevation to evaluate wind speed-dependent uncertainty. This analysis could be used either to modify wind speeds predicted using the methodology, or to provide an estimate of uncertainty when converting these wind speeds to energy generation potentials.

5 Constrained potential

This chapter provides a brief quantitative analysis of the extent to which environmental (biodiversity) factors and social preferences may limit wind energy potential in Europe. To evaluate onshore environmental constraints, wind potential is calculated excluding Natura 2000 and Common Database on Designated Areas (CDDA) sites. Unfortunately, the slow implementation of Natura 2000 means that comprehensive mapping of sensitive offshore areas across Europe is currently unavailable. Offshore wind energy constraints have been evaluated, however, in the light of spatial planning and visibility concerns that may limit the marine areas available for wind energy development.

Annex 3 to this report provides additional information on the environmental and social constraints to wind farm development and possible ways to minimise adverse effects on both humans and wildlife. The analysis set out there could point the way for more detailed analysis of these issues in subsequent studies.

5.1 Onshore

Poorly sited wind farms can have significant negative impacts on certain species, in particular birds and bats. As a starting point to analysing the issue, wind energy potential is recalculated excluding Natura 2000 areas and other designated areas. Although the legislation does not preclude such developments, and indeed there are examples of projects which have been integrated in such areas, they are sensitive areas demanding careful stewardship. As such, they serve as a useful proxy in order to evaluate environmental constraints on wind energy potential.

In total, Natura 2000 and CDDA areas in Europe comprise 12.5 % of the total area in Europe by 2006. As a proportion of the area exceeding the minimum average wind speed (4 m/s), the share increases to 13.7 %. However, in some regions designated areas have much higher wind speeds. In Romania, for example, 96 % of designated areas have wind speed above 4 m/s indicating that a complete exclusion of wind energy development in protected areas would severely affect wind energy development.

Map 5.1 depicts Natura 2000 areas and CDDA areas in two regions of Europe and locations where they overlap. A relatively large area where Natura 2000 and CDDA overlap is along the coast of the Netherlands, Germany and Denmark. In Map 5.2 the same areas are mapped together with full load hour information.

When the aggregated Natura 2000 and CDDA areas are shielded from wind energy developments the available land decreases by 13.7 %. If we assume that the protected areas are spread equally over all land cover classes the technical potential decreases to 39 000 TWh.

5.2 Offshore

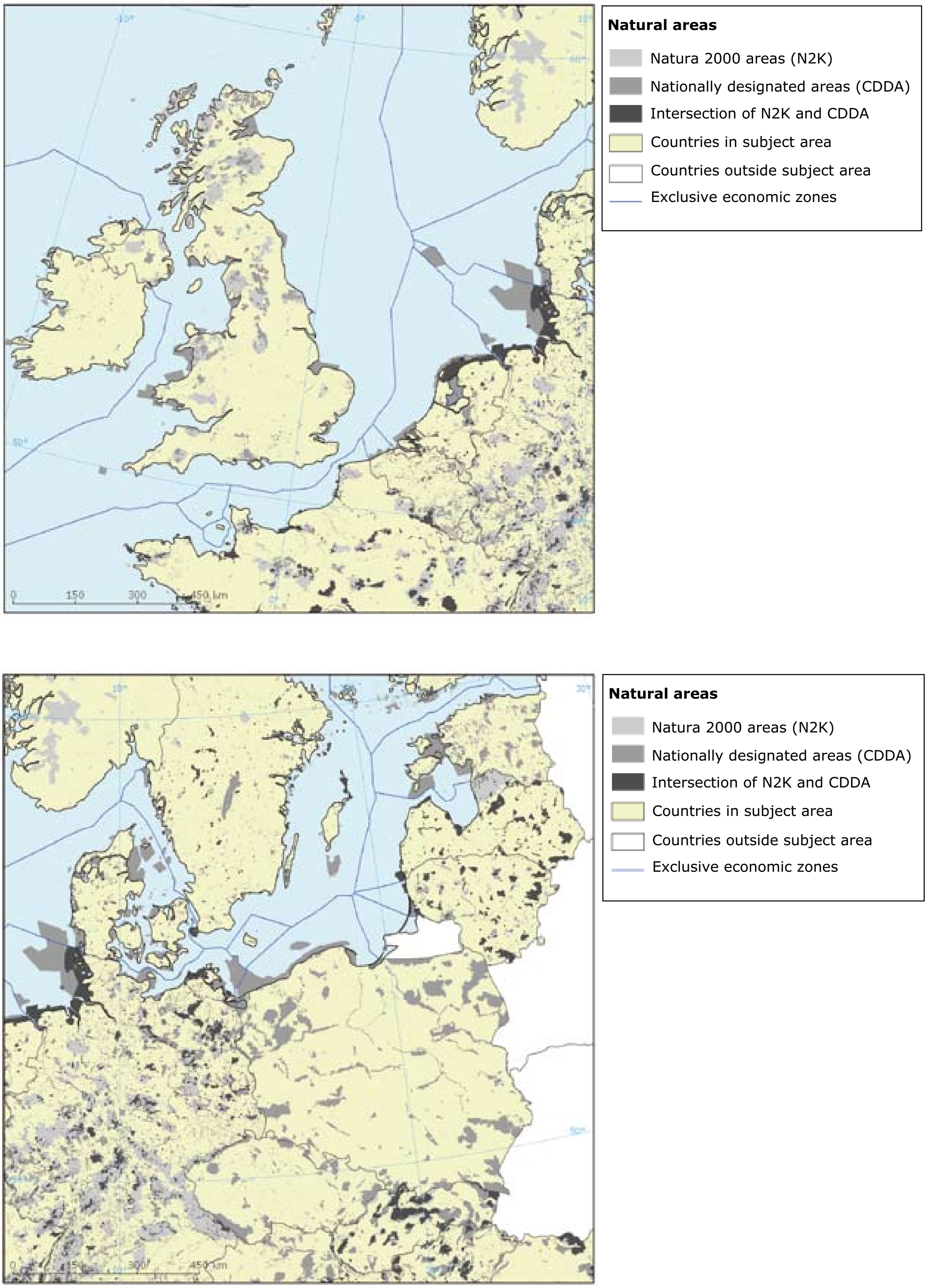
The technical potential for offshore wind does not account for the fact that other uses of the sea area may limit the potential for offshore wind developments. Such uses comprise, for example, shipping routes, military use of offshore areas, oil and gas exploration, and tourist zones.

Spatial planning policy is very important to guide proper use of the available sea area. Relatively new functions of the sea, such as wind farms, are an integral part of spatial planning policies.

For the area up to 10 kilometres from the coast, the visual impact of wind turbines is significant, as the wind farms can be seen from the coast. In some countries, such as the Netherlands, it is prohibited to build wind farms within 12 nautical miles of the coast (about 22 km), mainly due to the visual impacts. In the United Kingdom too, the strategic environmental assessment for the third round of tenders for wind farms published in January 2009 (UK, 2008) proposes to give preference to locations beyond the 12-mile zone.

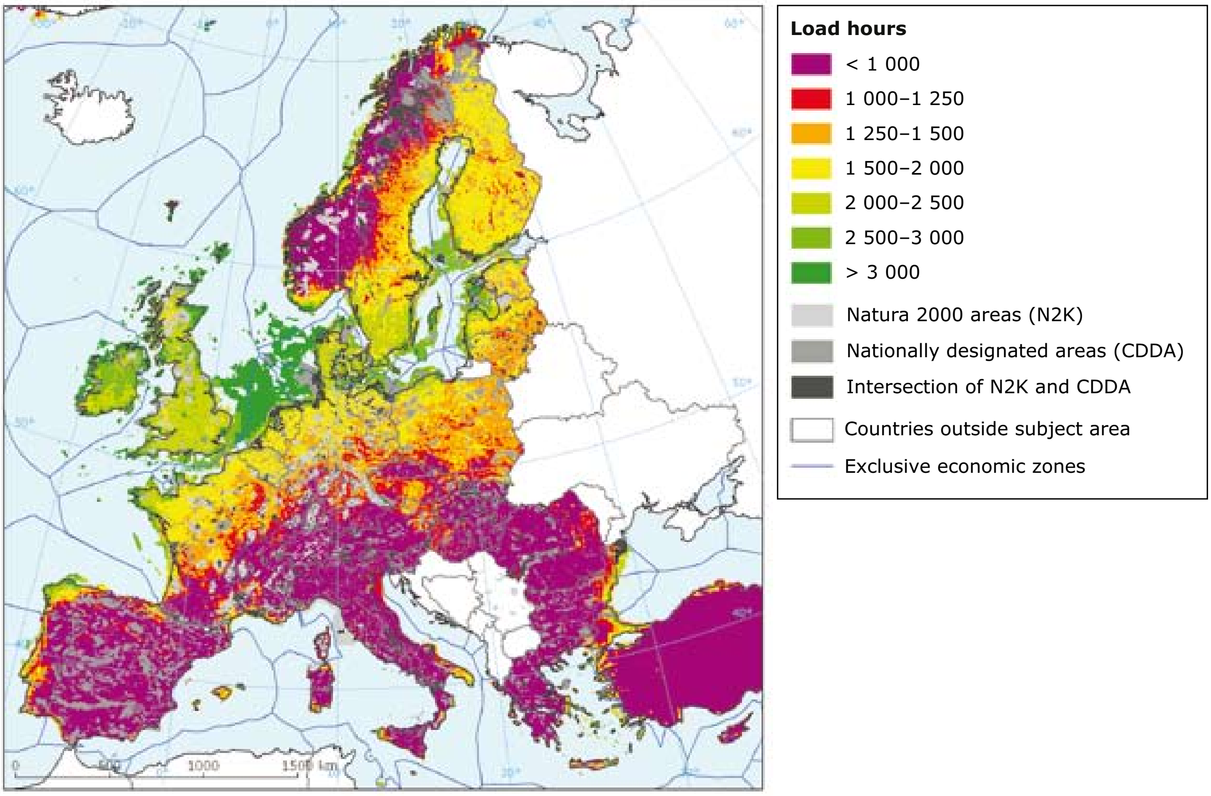
On the basis of these considerations, it is assumed that in practice only 4 % of the offshore area in the 0–10 km class might be available for developing wind farms. Because the spatial planning and social limitations will be relatively smaller, it is assumed that 10 % of the areas 10–30 km and 30–50 km from the coast can be used for wind farms. For distances to the coast above 50 km a larger share could be utilised

Map 5.1 Natural 2000 and CDDA sites in north-west and north-east Europe



Source: EEA, 2008.

Map 5.2 Natura 2000 and CDDA areas in Europe, and full load-hour potential

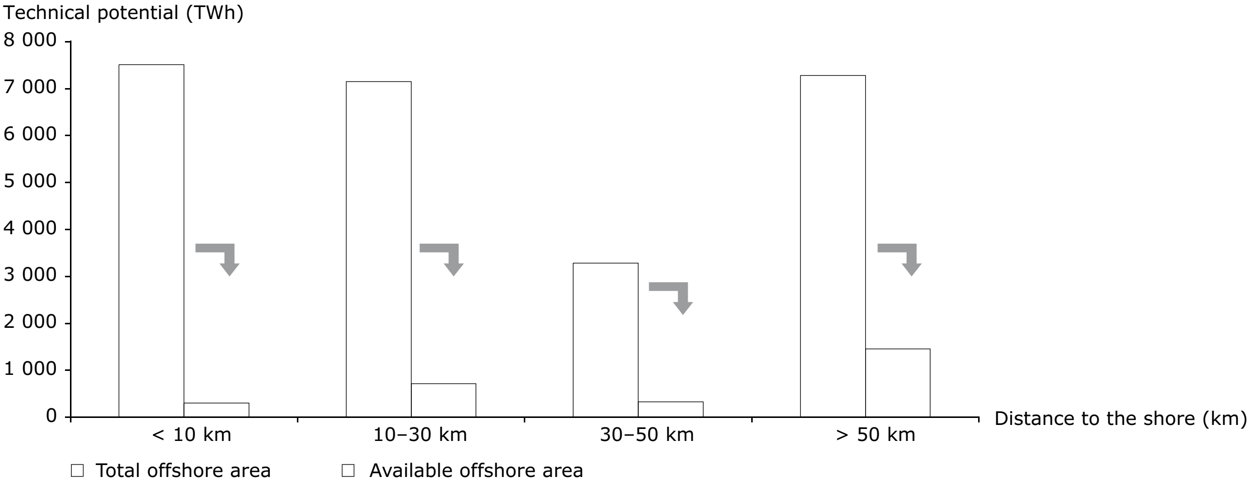


Source: EEA, 2008.

because this area is relatively large and other functions such as shipping are less concentrated. Therefore it is assumed that 25 % of the areas above 50 km are used for wind farms.

If these restrictions are applied the unrestricted technical potential for offshore wind drops from 30 000 TWh to 3 500 TWh in the years to 2030 (see Figure 5.1). To put this figure in perspective, this amount of electricity from wind would be sufficient to fulfil about 78 % of the projected electricity demand in Europe in 2030 (5 100 TWh). The constrained offshore potential in 2020 is calculated as 2 800 TWh.

Figure 5.1 Estimated technical potential of offshore wind in Europe with restricted offshore areas available (sea depth < 50 m)



Source: EEA, 2008.

6 Competitiveness of wind energy

6.1 Cost development of wind energy

The main parameters determining the cost of wind energy are investment costs (i.e. turbine costs, foundations, electrical installations, connections to the electrical grid, consultancy fees, land costs, financing, security and road construction) and operation and maintenance costs (O&M). As costs depend on various factors, they also vary significantly between different countries. In this project, investment and O&M costs are mainly derived from studies with an international scope.

6.1.1 Historical and current investment costs

Current turnkey wind energy costs are estimated to be around 1 000 EUR/kW for onshore and 1 200–2 000 EUR/kW for offshore wind farms (Junginger, 2005; ECN 2004). Table 6.1 presents an overview of cost estimates for onshore and offshore derived from various studies. It is evident that onshore wind energy costs are dominated by turbine costs. For offshore wind, the costs of foundation and grid connection can make up a significant share of investment costs. Investment costs for offshore wind are currently significantly higher and have increased considerably over recent years due high steel prices and shortage of offshore wind turbines. In this study we assume that current high prices for wind turbines are short-term increases and that the market will adjust to price levels that better represent real costs. The situation may improve already in 2010 when new manufacturers enter the market (Papalexandrou, 2008).

Wind turbine costs are the major part of onshore wind energy investment costs, thus, the main focus is given to those costs. Figure 6.1 indicates the steep decrease in average wind turbine prices. The largest historical factor behind these reductions has been increased turbine size (Junginger, 2005; Coulomb and Neuhoff, 2006). At the turn of the century wind turbine costs were reported to be between 750–1 000 EUR/kW (Junginger, 2005; Neij *et al.*, 2005).

6.1.2 Future investment costs

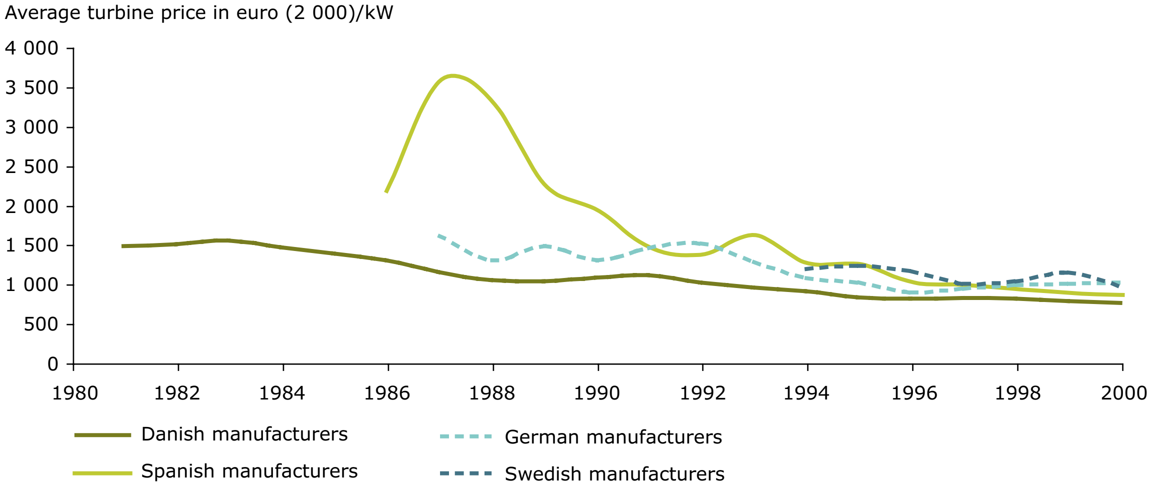
Wind turbine investment costs are expected to decrease further over time. As a rule of thumb, turbine manufacturers expect the production costs of wind power to decline by 3–5 % for each new generation of wind turbines (EWEA, 2003a). Another, more conservative estimate, applied by Garrad Hassan in their global wind energy

Table 6.1 Overview of cost estimates for onshore and offshore wind farms

	Onshore (a)	Onshore (a)	Offshore (b)
	Share of total investment costs (%)	Typical share of other costs (%)	Share of total investment costs (%)
Turbine	74–82		30–50
Foundation	1–6	20–25	15–25
Installation	1–9	10–15	0–30
Grid connection	2–9	35–45	15–30
Consultancy	1–3	5–10	
Land	1–3	5–10	
Financial costs	1–5	5–10	
Road construction	1–5	5–10	
Others			8
Total turnkey investment costs	800–1 100 EUR/kW (b)		1 200–2 000 EUR/kW (b,c)

Note: (a) EWEA, 2003b Based on data from Germany, Denmark, Spain and the United Kingdom for 2001/2002 for a typical medium-sized wind turbine (850 kW–1 500 kW).
(b) Junginger, 2005.
(c) ECN, 2004.

Figure 6.1 Historical development of wind turbine investment costs in various countries



Source: Neij *et al.*, 2005.

potential study, is a decrease of investment costs of 1–2.2 % per year (Fellows, 2000).

Whereas past reductions in wind energy generation costs derived mainly from scaling up turbine capacity, future cost reductions are expected to come from mass production and improved design (Junginger, 2005; EWEA, 2003a). Growing experience and mass production are expected to also reduce other costs, such as those relating to grid connections, foundations and planning. These costs have already decreased significantly over the past few years (EWEA, 2003a).

Learning or experience curves provide a method for understanding and conceptualising declining per unit production costs as output expands (e.g. EWEA, 2003a; Junginger, 2005; Neij *et al.*, 2005). Such a decline arises from accumulated learning on the part of workers, and (in the case of experience curves) other experience-related improvements such as labour efficiency, standardisation and specialisation, improved technology, and redesigns based on research and development. Typical progress ratios (14) for wind turbines are 80–95 % (Junginger, 2005; Neij *et al.*, 2005) meaning that wind turbine costs decrease by 5–20 % when total installed wind capacity doubles.

Several studies indicate that analysis of the future costs of wind energy or wind turbines using learning or experience curves is most effective when considered at the global scale. The wind turbine market is an international market dominated by a few wind turbine manufacturers (Coulomb and Neuhoff, 2006; Junginger, 2005). We therefore consider future wind energy developments globally rather than focusing on wind energy penetration in Europe.

Table 6.2 presents an overview of wind energy capacity in three global energy scenarios for the target years 2020 and 2030. In addition, the number of time that the capacity has doubled (cumulative installed capacity for these targets years) is indicated. Using a progress ratio of 80–95 %, the cost drops 5–20 % for each doubling. The highest cost reduction ranges are regarded as theoretical. For the purpose of this study, moderate cost reduction estimates of 25 % for 2020 and 40 % for 2030 are applied. This study assumed a progress ratio of 89 % and a growth of capacity (assuming a gradually decrease in growth to 12 % a year by 2020 and beyond) globally to 630 GW in 2020 (2.4 doublings compared to 2007) and 2 000 GW in 2030 (4.0 doublings compared to 2007) for onshore.

As discussed previously, wind turbine costs are around 80 % of the total turnkey investment costs of onshore wind farms. The other costs can also be expected to decrease as experience increases. Due to lack of data, the same relative cost reductions for the other costs are assumed as for the turbine costs. In addition, the share of turbine costs is assumed to remain constant over time.

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(14) The progress ratio is a measure of the relative investment cost reduction per unit of capacity when doubling production.

Table 6.2 Overview of the contribution of wind energy capacity in various global energy scenarios

		Cumulative installed capacity (GW)					Number of doublings	
Reference	**Scenario name**	**Current (a)**	**2010**	**2015**	**2020**	**2030**	**2020**	**2030**
Greenpeace and GWEA, 2006	Reference	59			231	364	2	2.5
	Moderate	59			560	1 129	3.2	4.3
	Advanced	59			1 073	2 107	4.2	5.2
IEA, 2006	Reference	48		168		430	1.8 (2015)	3.2
	Alternative policy	48		174		538	1.9 (2015)	3.5
Greenpeace, EWEA, 2004		51	198		1245		4.6	

Note: (a) 'Current' means between 2003 and 2005.

For offshore scenarios, no experience curve can be constructed as there is insufficient data. Junginger (2005) estimates cost reductions for the year 2020 based on projected costs of separate parts of the wind farm (e.g. foundation, grid connection, cable, installation) and concludes that the cost of electricity from offshore wind farms could be reduced by almost 40 % by 2020. Assuming average turnkey costs of 1 800 EUR/kW at present, this results in 1 080 EUR/kW by 2020. For the period to 2030, a conservative estimate of 1 % cost reduction per year is used, resulting in turnkey costs of about 975 EUR/kW. Thus, progress ratio of 91 % and a capacity growth to 63 GW in 2020 (4.8 doubling compared to 2008) and 164 GW in 2030 (6.2 doublings compared to 2008) are applied in this study for offshore wind energy. This implies an annual growth of 19 %–15 % till 2020 and 9 % thereafter.

6.1.3 *Operation and maintenance costs*

Based on experiences from Denmark, Germany, Spain and the United Kingdom, EWEA (2003b) reports that O&M costs are, in general, estimated to be approximately 0.012–0.015 EUR/kWh of produced wind power over the total lifetime of a wind farm. O&M costs thus correspond to 2–3 % of total turnkey investment costs in the early years of the farm and around 5 % at the end of the lifetime (EWEA, 2003b). O&M costs for offshore wind farms are estimated to be 2–4.4 % of turnkey investment costs (Junginger, 2005). We assume lifetime average O&M costs at 4 % for both onshore and offshore wind farms. Due to lack of data, these relative O&M costs are assumed to remain a constant proportion of investment costs. As such, they decrease in absolute terms over time at the same rate as wind turbine costs.

6.1.4 *Estimation of investment costs of offshore wind as a function of water depth and distance to coast*

The literature review clearly shows that offshore investment costs are dominated by turbine (30– 50 %), grid connection (15–30 %) and foundation cost (15–25 %). Current high price levels of wind turbines create a different picture on the split between the different cost elements. The construction of offshore wind parks at locations further from the shore often implies placement in deeper waters and changed weather conditions. This section investigates how investment costs of offshore wind parks might change when the distance to shore and water depth increase. The base scenario comprises a 200 MW wind farm using 2 MW turbines, 5 km from shore in water depths of 15 metres.

Of the cost items listed, installation and grid connection costs are those most affected when offshore wind parks are located further from the shore. At larger distances installation costs increase because of the greater travelling time needed from the holding port to the site. In addition, weather conditions usually worsen further offshore making installation more difficult. 'Weather downtime' — a concept used to represent the additional time needed to install offshore — is usually 20–30 %. The effect on installation costs is minimal for wind turbines and foundations because the cost share of the travelling to site is low compared to total installation costs. The costs most affected by the distance to shore are the cable installation costs within the total electrical installation costs. Herman *et al.* (2003) analysed the influence of distance to the shore on transport and installation costs. A cost relation was derived based on the

Table 6.3 Increase in offshore investment cost as function of distance to the coast

		Distance to coast (km)							
		0–10	10–20	20–30	30–40	40–50	50–100	100–200	> 200
Cost (EUR/kW)	**Turbine**	772	772	772	772	772	772	772	772
	Foundation	352	352	352	352	352	352	352	352
	Installation	465	476	488	500	511	607	816	964
	Grid connection	133	159	185	211	236	314	507	702
	Others	79	81	82	84	85	87	88	89
	Total cost (EUR/kW)	1 800	1 839	1 878	1 918	1 956	2 131	2 534	2 878
	Scale factor	1	1.022	1.043	1.065	1.086	1.183	1.408	1.598

Source: EEA, 2008.

scheduled cycle time for installations performed with the vessel 'Svanen'. This cost relation shows that installation cost almost double when the distance to the onshore grid connection point goes from zero to 60 kilometres.

Another cost affected when the distance to the shore increases is the export cable, which connects the wind farm to a suitable connection point on land. The factors influencing cable costs are cable size, sea bed conditions and the possible need for transformer stations. Experts estimate costs of offshore cables (excluding transformation stations) at between 500 000 and 1 million euro per kilometre (International Association of Engineering Insurers, 2006). Another study estimates costs of supply and installation of export cable at 1 million euro per kilometre of offshore cable (Papalexandrou, 2008). The share of grid connection cost in total investment cost decreases as wind farm size increases.

Investment cost for offshore wind farms are also influenced by the onshore distance to the grid. According to (Papalexandrou, 2008) onshore cable cost is equal to EUR 0.65 million per offshore cable used (export cable) per km of onshore cable.

Based on the above information it is assumed that:

- 1 weather downtime (15) is 25 %;
- 1 export cable costs 1 million euros per km including installation and that the relationship between distance from shore and grid connection cost is linear;
- 1 installation costs are linear.

Based on these assumptions the overall cost increase of investment costs is indicated in Table 6.3. It shows that offshore investment cost might increase from 1 800 to 2 878 EUR/kW as the distance to the coast.

The distance to the shore affects water depth, which is treated as an independent factor in this analysis. As we move to deeper water the foundation costs of wind turbines tend to increase. According to Nikolaos (2004) foundations may account for up to 30 % of total cost in deeper waters. In a report published by Greenpeace (2000) the relationship between water depth and foundation cost is derived. For offshore wind turbines with capacities between 1 and 1.5 MW the foundation costs are estimated to increase from EUR 317 000 at eight metres depth to EUR 352 000 at 16 metres depth; a cost increase of 11 %. Finally, according to Papalexandrou (2008) foundation supply costs can differ from 300 000 EUR/MW at 15 metres to 1 000 000 EUR/MW at 40 metres, using monopiles.

Currently, offshore wind farms have not been built in waters with depths above 30 metres but in the future this will change. Design and cost restrictions necessitate new designs other than monopiles for water depths above 30–35 metres. Tripods, quatropods, jacket and floating structures are under consideration. The cost of these structures remains uncertain. Installation costs will increase because of the need for vessels capable of installing wind turbines in greater water depths and larger turbines and blades.

Based on the information above it is assumed that the estimation of foundation supply costs as a function of water depth follows the cost

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(15) The weather downtime is a factor that reflects the percentage of the time in which the weather conditions do not allow the vessel to operate safely. In other words it is an additional factor acquainting the real time needed to install offshore (Papalexandrou, 2008).

Table 6.4 Increase in offshore installation costs as a function water depth

		Water depth (m)			
		10–20	20–30	30–40	40–50
Cost (EUR/kW)	**Turbine**	772	772	772	772
	Foundation	352	466	625	900
	Installation	465	465	605	605
	Grid connection	133	133	133	133
	Others	79	85	92	105
	Total cost (EUR/kw)	1 800	1 920	2 227	2 514
	Scale factor	1.000	1.067	1.237	1.396

Table 6.5 Scale factors for cost increases as a function of water depth and distance to coast

		Distance to coast (km)							
		0–10	10–20	20–30	30–40	40–50	50–100	100–200	> 200
Depth (m)	**10–20**	1	1.022	1.043	1.065	1.086	1.183	1.408	1.598
	20–30	1.067	1.090	1.113	1.136	1.159	1.262	1.501	1.705
	30–40	1.237	1.264	1.290	1.317	1.344	1.464	1.741	1.977
	40–50	1.396	1.427	1.457	1.487	1.517	1.653	1.966	2.232

Source: EEA, 2008.

relationship set out in Papalexandrou (2008). The relationship for foundation supply costs is expected to be exponential. On that basis, Table 6.4 presents the offshore installation costs as a function of water depth, based on the reference cost of 1800 EUR/kW in the shallowest waters.

Thus, installation cost increase both due to increasing distance to the coast and water depth. Further statistical analysis is needed to find out how these parameters are correlated and what their combined effect is on the investment costs. As a first approximate we have used the scale factors set out in Tables 6.4 and 6.5 to derive offshore investment costs as a function of both distance to the coast and water depth. The combined scale factors are set out in Table 6.5. Based on the combination of scaling costs for distance to shore and the depth the current offshore investment costs can vary between 1 800–4 000 EUR/kW. They can further decrease to 890–2 200 EUR/kW by 2030.

6.2 Implications of high wind energy penetration for the grid

Recent European studies have concluded that high penetration of wind power can be achieved in several countries, even up to levels of 40 % of the total electricity demand. Technical limitations do not appear to play any significant role (EWEA, 2006b). However, for such high penetration levels of wind power, major changes to the grid system are required (for upgrading and/or extending the grid) and there are additional costs for system balancing.

Although the additional costs can be categorised in many ways, we describe two types of additional costs here:

- 1 upgrade and extension of the distribution and transmission grids;
- 1 system balancing and additional reserve capacity for system balancing.

When focusing only on these aspects, the costs for discarded wind electricity (overproduction of wind due to a mismatch between demand and supply) are neglected. This assumption is reasonable for this study as, first, it is expected that this will not occur widely in the time frame we are considering and second, additional grid extensions will be implemented first and will further reduce the risk of discarded wind electricity.

6.2.1 Grid upgrade and extension

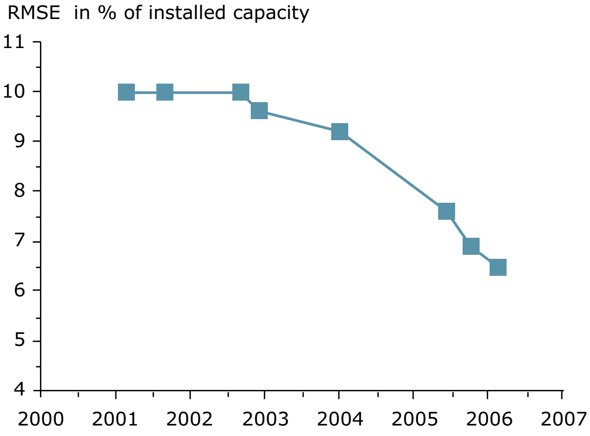
Wind turbines are often installed in distant regions far from major electricity consumption.

Large portions of the electricity produced must therefore be transported over large distances to load centres (16). This could lead to congestion of existing infrastructure. Therefore, at higher penetration levels both the transmission and the distribution grid might require additional extensions or upgrades. These upgrades can also be on a cross-border level. The 'Wind Energy — The Facts' publication (17) reviewed several country-specific studies and concluded that (both onshore and offshore) the grid extension and/or reinforcement costs caused by additional wind generation are in the range of 0.1–5 EUR/MWh for penetration levels up to 30 %. Other sources mention costs for grid extension of 1–10 eurocents/kWh , or 0–5 eurocents/kWh for various countries and at different levels of wind energy penetration (GreenNet, 2004).

6.2.2 *System balancing*

Power flow needs to be continuously balanced between generation and consumption. This balancing takes place at a level of seconds and various types of reserve capacity are used. Estimates for extra reserve requirements due to wind power are in the order of 2–8 % of installed wind power capacity at 10 % penetration of gross consumption. The total requirement depends on the applied interconnection, geographical dispersion and forecasting techniques of wind power. At higher wind energy penetration levels, higher shares of reserves are required.

Figure 6.2 Reduction in wind power forecasting prediction error in the period 2000–2006



Source: Lange *et al.*, 2006.

Related costs for this additional reserve are estimated at a level of 2–4 eurocents/kWh, assuming proper use of forecasting techniques (EWEA, 2006c). The most important factors determining these costs are wind penetration, forecasting technique, interconnection, geographical distribution and generation system. Lange *et al.* (2006) show the improvement and current state-of-the-art in country wide forecasting for Germany. As Figure 6.2 illustrates, root mean square error (RMSE) in forecasting decreased from about 10 % in 2001 to about 6 % in 2006, with more improvements in the pipeline.

The other aspects influencing systems balancing costs vary significantly between countries. Interconnection in Europe is expected to increase over time, which would improve the grid's capacity to accommodate larger proportions of wind energy without additional costs.

6.3 Allocation of costs at high penetration levels

The previous section presented some indications of additional costs related to higher wind energy penetration levels. In summary, depending on wind penetration, geographical distribution and forecasting techniques, the additional costs for grid extension are estimated to be 0–10 eurocents/kWh and for additional reserve capacity 2–4 eurocents/kWh.

However, it is questionable whether all grid extension and reserve capacity costs should be allocated to wind power when the benefits accrue to the entire electricity system. In the debate, these are often referred to as 'deep' or 'shallow' grid connection costs (Auer *et al.*, 2007). In this report we limited ourselves to the costs of wind turbine construction.

6.4 Additional cost for wind farms in mountainous areas

In addition to having fewer suitable areas, costs of wind farms in mountainous areas are expected to be quite high. There is, however, limited research

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(16) A load centre is a large switch with smaller switches serving as circuit breakers. These protect the wires and equipment from potential short circuits or overloads.

(17) See www.wind-energy-the-facts.org/en/part-2-grid-integration/chapter-7-economic-aspects-integration-costs-and-benefits/additional-balancing-and-network-costs/additional-network-costs.html.

on costs. The data presented below are based on a survey of project developers of wind farms in alpine areas reported in the project 'Alpine Windharvest', (Winkelmeier and Geistlinger, 2004). Higher costs in mountainous arise from:

- investment costs of turbines and foundations;
- construction costs;
- operation and maintenance costs.

6.4.1 Increased investment costs of turbines and foundations

The turbine costs increase as measures to limit the formation of ice on blades, the nacelle or monitoring equipment such as the anemometer can be costly. Furthermore, foundation and grid connection costs can rise due to the roughness of the terrain. Not all farms require additional investments for all factors mentioned above. However, it can be expected that wind farms require at least one of the additional measures listed above. Winkelmeier and Geistlinger (2004) did not quantify the additional costs.

6.4.2 Increased construction costs

Construction costs can increase because new or extended roads, or special vehicles are required. From the thirteen project developers included in the survey (Winkelmeier and Geistlinger, 2004) six reported moderate to extraordinary additional construction costs. Further quantification is not presented.

6.4.3 Increased costs of operation and maintenance

Due to the extreme conditions, many turbines are not accessible during all seasons unless special vehicles are used. Further additional measures are required to guarantee the safety of the specialists responsible for maintenance. No quantification of the additional costs is given.

As explained above, there is limited literature on average wind farms cost increases in mountainous areas and most of the data derive from one wind farm in Austria (Tauern park). Based on this survey, it can be expected that the cost increase is moderate. The figures mentioned are all less than 10 % of investment costs. As the factors may accumulate, a total investment cost increase of 10 % is estimated. O&M costs are expected to increase by only 1 %. For the offshore investment costs used in this study it means an increase from 1 800 EUR/MW to 1 980 EUR/kW.

6.5 Analysis of future competitiveness of wind energy

On the basis of the analysis in the preceding sections, Table 6.6 sets out the main cost

Table 6.6 Main assumptions regarding future costs of wind energy

		2005			2020			2030		
	Unit	**Offshr.**	**Onshr.**	**Mount.**	**Offshr.**	**Onshr.**	**Mount.**	**Offshr**	**Onshr.**	**Mount.**
Turnkey costs	EUR/kW	1 800 ([a])	1 000	1 100	1080	720	792	975	576	632
O&M costs	%	4	4	5	4	4	5	4	4	5
Share of private capital (at 15 %)	%	50	20	20	40	20	20	30	20	20
Share of loans (at 6 %)	%	50	80	80	60	80	80	70	80	80
Average interest	%	10.5	7.8	7.8	9.6	7.8	7.8	8.7	7.8	7.8
1600 load hrs	EUR/kWh	0.175	0.097	0.12	0.10	0.07	0.082	0.099	0.056	0.065
2500 load hrs	EUR/kWh	0.112	0.062	0.077	0.065	0.045	0.052	0.063	0.036	0.042
$F_{distance}$	Cost scale factor relative to the distance to the coast: 0.00285 x distance (km) + 0.972									
F_{depth}	Cost scale factor 15–50m depth: – 0.0125 x Fd +0.812 (i.e depth as negative number – 25 m)									

Note: 'Offshr.' denotes 'offshore'; 'Onshr.' denotes 'onshore'; 'Mount.' denotes 'mountain areas'.
([a]) Cost within 10 km of the coast and at water depths of less then 15 m. See the last two rows of the table for cost increases as a function of distance to coast and water depths.

Source: EEA, 2008.

development assumptions used in the analysis of economic potential. The average costs per kWh produced are presented at a level of 1 600 loadhours (benchmark for onshore locations) and at a level of 2 500 load hours (benchmark offshore locations). The costs are derived from the average turnkey costs and the average O&M costs and the costs of financing the necessary investments, in two variants. In the variat of private investment, the cost is split in assumed return on investment on private capital < 15 %) and the price of loans (6 %). In time it is assumed that the share of private capital versus loan will change for offshore and banks are willing to cover a larger portion of the required capital (from 50 % to 70 % by 2030). The benchmark costs for offshore wind energy has to be multiplied by a distance factor from the coast and the average assumed depth at the location. I.e. at 30 km from the coast and 20 m depth the turnkey costs are assumed to increase from 1 800 EUR/kW to 2 020 EUR/kW.

Based on the data presented in Table 6.6 wind energy generation costs are calculated across Europe in 2020 and 2030. Low wind speeds at hub height (< 4 m/s for onshore and < 5 m/s offshore) were excluded from the analysis as electricity generation from low wind speed classes is assumed to be not economically exploitable.

The second variant reflects public investment against financing costs of 4 %. Map 6.1 shows the spatial distribution of the energy costs for the years 2020 and 2030. A low cost production area stretches from Vigo (Portugal) to Gdansk (Poland) at one side and Tallin (Estonia) to Aberdeen (Scotland) at the other side.

Figure 6.3a shows the electricity production costs with a uniform 4 % interest rate while Figure 6.3b shows the costs when the (higher) private interest rate is applied. At average electricity production cost of 5.9 eurocent/kWh in 2005 ([18]), onshore wind energy starts to compete at 2 300 full load hours, while for offshore wind this needs 3 700 full load hours. When higher discount rates are applied, onshore wind energy starts to compete at 2800 full load hours while offshore wind energy requires higher than 4500 full load hours.

Comparing 2030 with 2005 we can see from the figure that this 'break-even' point is reduced by approximately 1 000 load hours. In 2030 production costs for offshore wind are almost at the same level of 2005 costs for onshore wind.

The projected cost figures for wind energy generation were then compared to European Commission electricity price forecasts (EC, 2008a) to identify the profitable wind energy generation potential up to 2030.

Table 6.7 presents the forecasted average electricity generation costs used in this study, derived from a European Commission baseline study (EC, 2008a). In 2020, the average electricity generation cost is projected to be 6.3 eurocents/kWh (at constant 2005 prices) and 6.5 eurocents/kWh in 2030. The baseline scenario is based on below assumptions

The CO_2 prices in the ETS sectors increase from 20 euro (2005)/t CO_2 in 2010 to 22 EUR/t CO_2 in 2020 and 24 EUR/t CO_2 in 2030.

- 1 The energy projections are based on a high oil price environment with oil prices of 55 USD/bbl in 2005 rising to 63 USD/bbl in 2030.
- 1 Effects related to global warming or the geopolitical risks affecting security of energy supply are assumed to be neglected.
- 1 It does not include policies to reduce greenhouse gases in view of the Kyoto and possible post-Kyoto commitments.

The average power production costs in the future are strongly dependent on above factors. These

Table 6.7 Projected average electricity tariffs and average production costs used in the calculations of market potential for wind energy

	2005	2020	2030
	eurocents (2005 prices)/kWh	eurocents (2005 prices)/kWh	eurocents (2005 prices)/kWh
Average production costs	5.9	6.3	6.5

Source: EC, 2008a.

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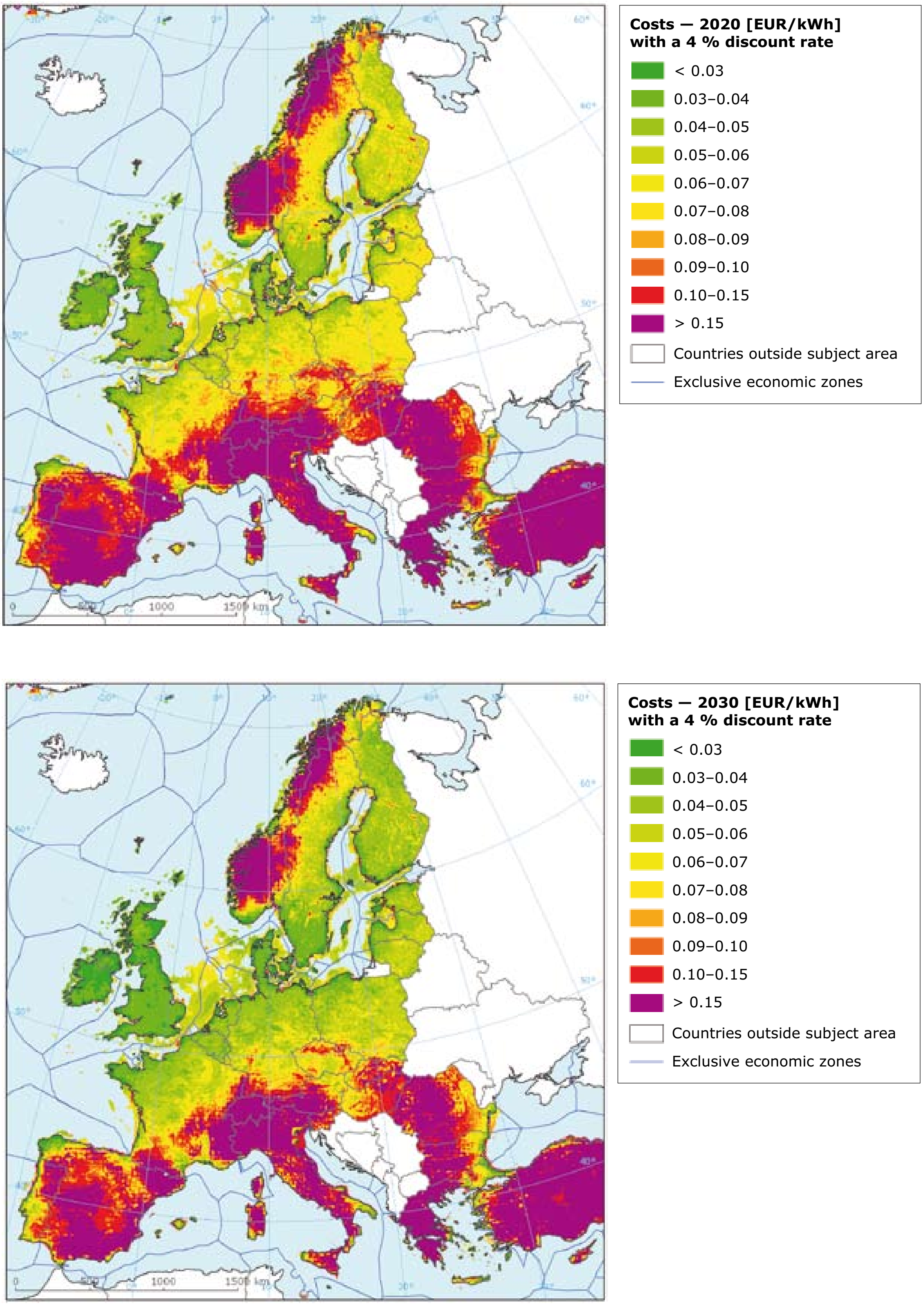
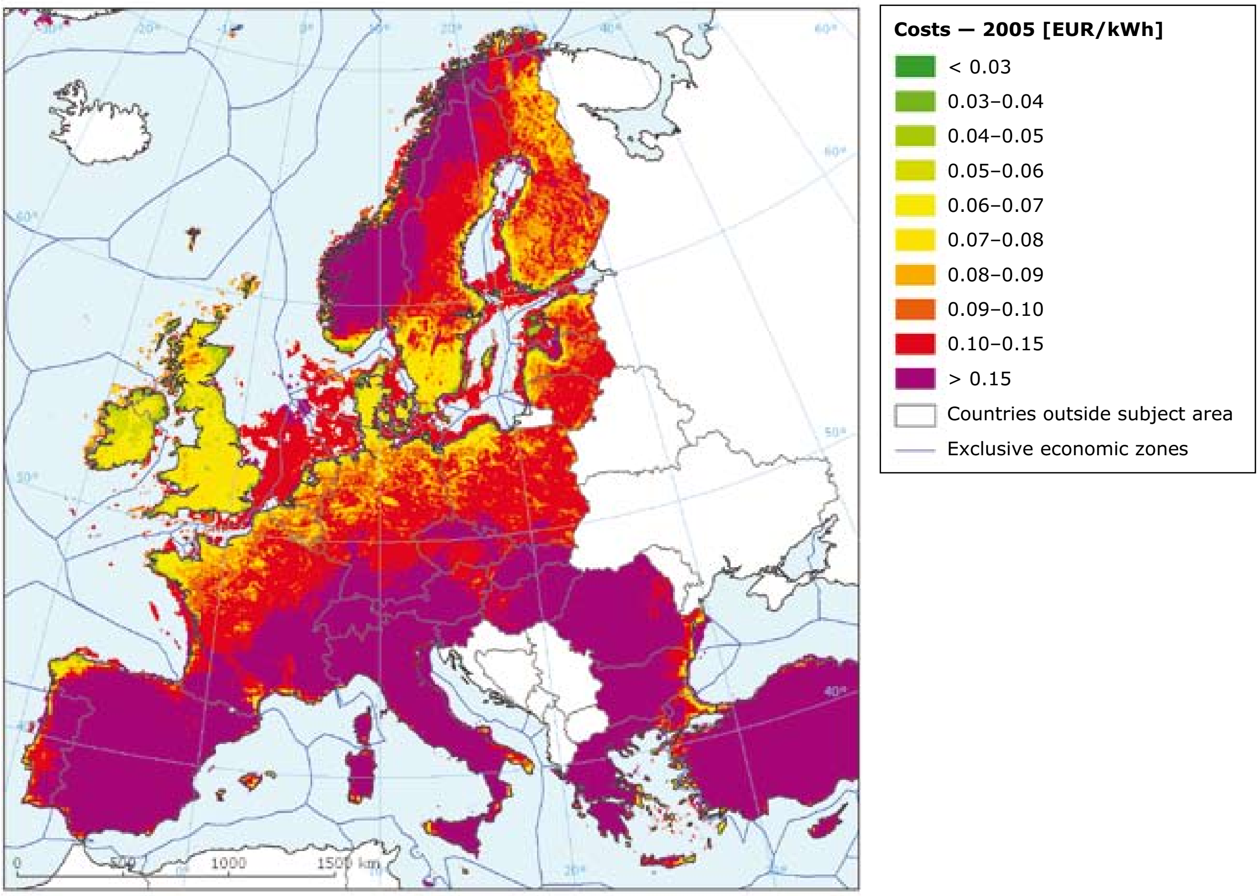
[18] EC (2008a) indicates the 2005 average generation cost to be 5.9 eurocents/kWh.

Map 6.1 Generation cost for wind energy in Europe (top 2020, bottom 2030), 4 % interest rate (variant reflecting public investment against financing costs of 4 %)



Map 6.2 Generation costs for wind energy in Europe, 2005



Source: EEA, 2008.

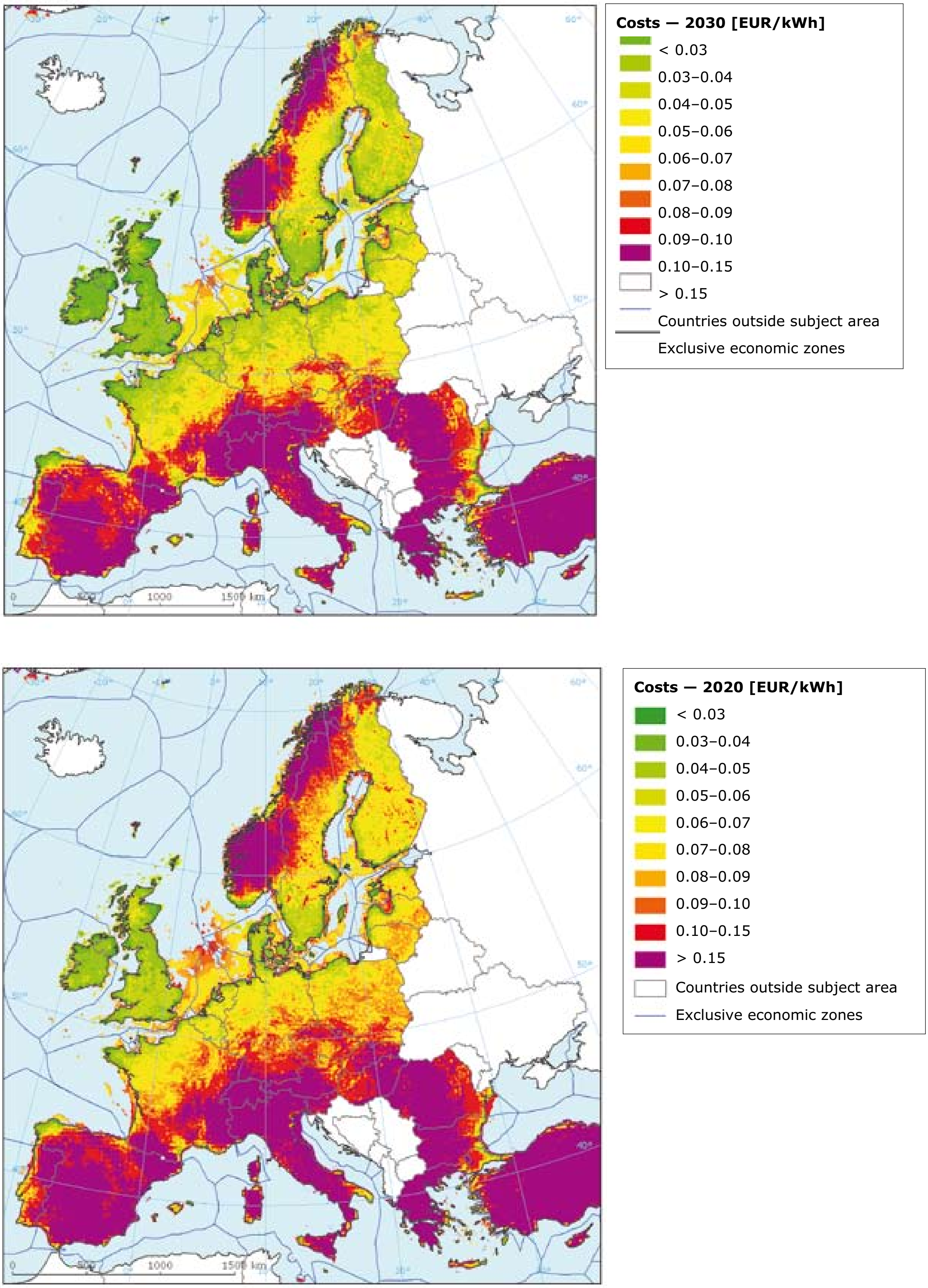
will vary depending on developments in the global economy as well as developments in scale and cost of greenhouse gas mitigation efforts. The assumptions used here as deemed rather conservative. Thus, the economically competitive wind potential presented in the next sections can be higher than presented. Even a modest increase in energy and carbon prices could lead to a doubling of the economically competitive wind energy potential. On the other hand applying a single average production cost disregards the regional price differences among different regions (i.e availability of hydro in Northern Europe) and its impact on the electricity price. Due to time constraints those possible impacts are not assessed within this study.

As illustrated in Map 6.2, in 2005 there were hardly any wind resource areas with generation costs below 10 eurocents/kWh. However, decreasing costs of wind turbine technology will mean lower wind energy costs in 2020 and 2030, as represented in Map 6.3. The red coloured area, which represents electricity generation costs above 10 eurocents/kWh shrinks significantly between 2005 and 2030. Countries in southern Europe, where relatively low wind speeds prevail, still have generation costs in the highest category (above 10 eurocents/kWh) in 2030.

6.5.1 Onshore potential

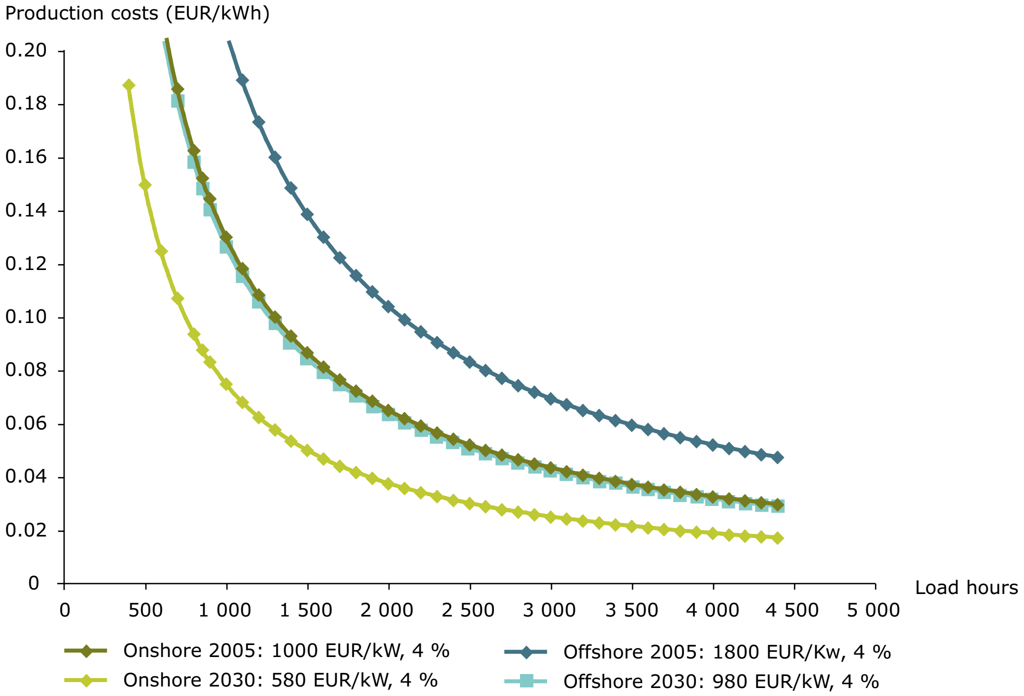
The wind energy potential is defined in different cost classes depending on the production cost figures. 'Competitive' class includes wind energy potential that will be generated with a cost below 5.5 eurocents (2005 prices)/kWh in 2020, whereas 'mostly likely competitive' class includes potentials with a production cost in the range of 5.5–6.7 eurocents (2005 prices)/kWh (average 6.3 eurocents (2005 prices)/kWh). The wind energy potential that is generated at average costs above 6.7 eurocents (2005 prices)/kWh and higher will not be competitive and classified as 'not competitive'.

Map 6.3 **Generation costs for wind energy in Europe (left 2030, right 2020)**



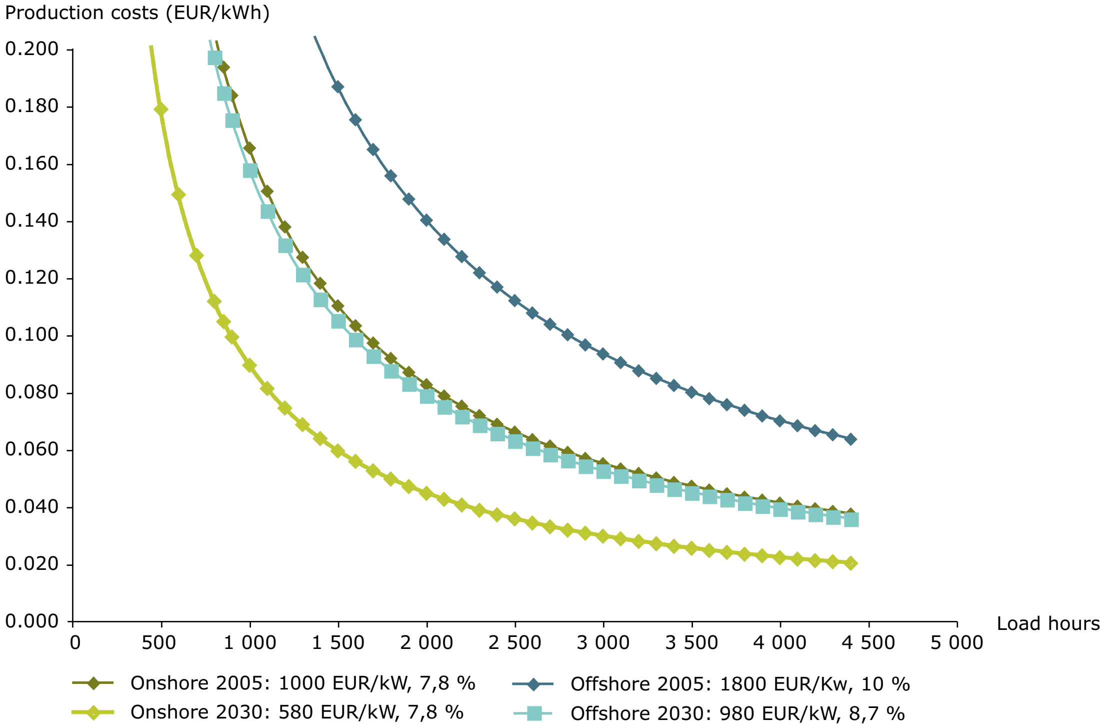
Source: EEA, 2008.

Figure 6.3a **Electricity generation costs for onshore and offshore wind in 2005 and 2030, interest rate of 4 % (public investment against financing costs of 4 %)**



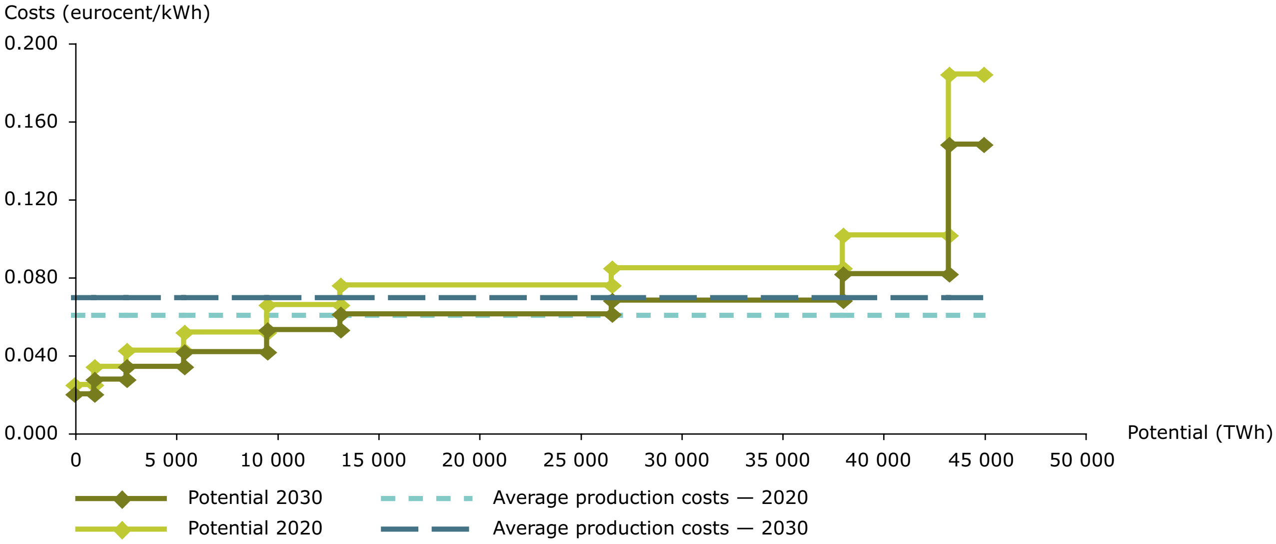
Source: EEA, 2008.

Figure 6.3b **Electricity generation costs for onshore and offshore wind in 2005 and 2030, private interest rates**



Source: EEA, 2008.

Figure 6.4 Projected supply curves for European onshore wind energy in 2020 and 2030

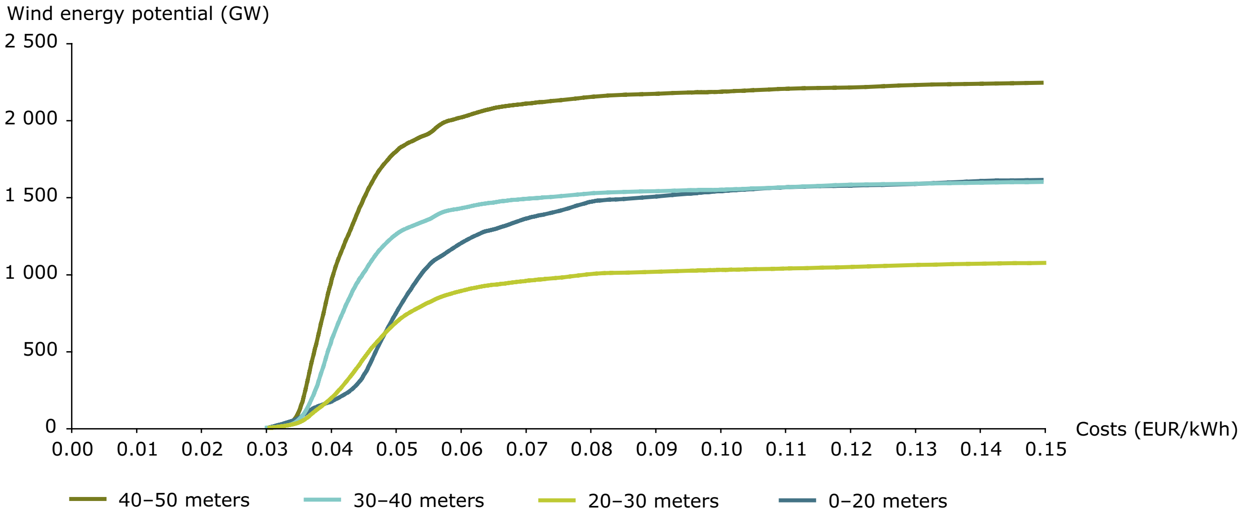


Source: EEA and EC, 2008a.

Table 6.8 indicates that the competitive potential in 2020 will be around 9 600 TWh, which is 20 % of the unrestricted technical potential. Up to 2030, the competitive potential for onshore wind will increase to over 27 000 TWh. This corresponds to almost 60 % of the total unrestricted potential. To put these figures into perspective, EU-27 wind energy production (both onshore and offshore) was around 82 TWh in 2006 (Eurostat, 2009) with an installed capacity of 48 GW. This capacity reached to 56 GW in 2007. According to the calculation results Czech Republic, Hungary, Austria and Slovakia are stated as having no competitive wind energy potential when the competitive production cost figure is set as 6 eurocents (2005 prices)/kWh.

The most remarkable development is in the EU-10 countries, where the economic competitive potential increases more than 10-fold (400 to 4 400 TWh) between 2020 and 2030. The EU-15 see an almost 250 % increase (8 500 to

Figure 6.5 Potential for wind energy at different water depths in 2030



Source: EEA, 2008.

Table 6.8 Generation potential of wind energy on land in different cost classes, TWh

TWh	Current electricity production (a)	Not competitive (b)	Most likely competitive (c)	Competitive (d)	Not competitive	Most likely competitive	Competitive	Total
	2006	**2020**	**2020**	**2020**	**2030**	**2030**	**2030**	**2030**
Austria	1.72 (e)	463	3	(f)	199	211	56	466
Belgium	0.36	371	53	12	0	12	425	436
Bulgaria	0.02	540	14	34	309	167	112	587
Cyprus	Data not available	48	8	4	20	14	25	59
Czech Republic	0.05	687	1	0	169	434	85	687
Denmark	6.11	0	65	687	0	0	751	751
Estonia	0.08	419	111	142	0	75	597	672
Finland	0.16	4 016	204	198	7	1 052	3 359	4 418
France	2.15	3 951	733	576	736	1 409	3 115	5 260
Germany	30.71	3 376	384	258	344	1 206	2 467	4 017
Greece	1.7	261	54	251	123	71	372	566
Hungary	0.04	557	0	0	343	213	1	557
Ireland	1.62	0	7	1 308	0	0	1 315	1 315
Italy	2.97	983	57	112	571	247	334	1 152
Latvia	0.05	614	154	85	0	260	593	853
Lithuania	0.01	703	13	30	0	305	442	746
Luxembourg	0.06	30	0	0	0	20	10	30
Malta	0	0	0	7	0	0	7	7
Netherlands	2.73	217	158	158	0	0	533	533
Norway (g)	0.67	1 517	191	528	616	527	1 094	2 236
Poland	0.26	3 437	134	112	39	1 035	2 609	3 682
Portugal	2.93	601	13	63	209	316	152	677
Romania	0.001	1 103	19	38	690	371	99	1 160
Slovakia	0.006	323	0	0	184	128	11	323
Slovenia	Data not available	106	0	0	87	17	2	106
Spain	23.02	2 316	170	263	1 050	1 018	682	2 749
Sweden	0.99	3 900	528	620	487	2 021	2 539	5 048
Switzerland	0.02	42	0	0	39	3	1	42
Turkey (h)	0.13	1 264	89	123	757	296	421	1 475
United Kingdom	4.23	0	447	3961	0	0	4 409	4 409
EU-27	82	29 022	3 330	8 919	5 567	10 602	25 102	41 266
Total	82	31 845	3 610	9 570	6 979	11 428	26 618	41 266

Note:
(a) Eurostat data.
(b) 'not competitive' are cost classes with average production costs higher than 6.7 cent/kWh).
(c) 'most likely competitive' is cost class with average production cost 6.3 cent/kWh (range 5.5–6.7).
(d) 'competitive' is cost class with average production cost lower than 5.5 cent/kWh.
(e) The current installed capacity in Austria is around 995 MW, delivering 2.1 TWh electricity (December 2008).
(f) The feasible wind power capacity for 2020 is mentioned as 3500 MW delivering 7.3 TWh electricity (Austrian Wind Energy Agency, 2008).
(g) The Norwegian Water Resources and Energy Directorate 'relevant publications indicate the production potential to be around 1 100 TWh, conditional economic wind power potential to be around 250 TWh (calculations were based on the assumptions: 15 MW/km^2 density and average wind speed > 6m/s, with 2 MW wind turbines). For offshore calculated potential of the Norwegian coast is estimated to be 55 300 MW (max. depth 50 m and minimum coast distance 1 km) (NVE report 2008).
(h) according to the potential assessment study carried out by Turkish officials, Turkey can produce 147 TWh electricity from wind.

21 000 TWh) of the economically competitive potential.

Figure 6.4 presents the supply curve for onshore wind energy in 2020 and 2030 derived from the data in Table 3.2.

6.5.2 *Offshore potential*

The market potential for offshore wind is, like land-based wind, estimated by comparing the generation cost forecasts for offshore wind to projected electricity tariffs and average production costs of electricity in 2020 and 2030. The lower limit of wind speed at hub height has been set to 5.0 m/s. At wind speeds of 5.0 m/s or below, the number of full load hours decrease to below 1 000, which are not considered economically viable.

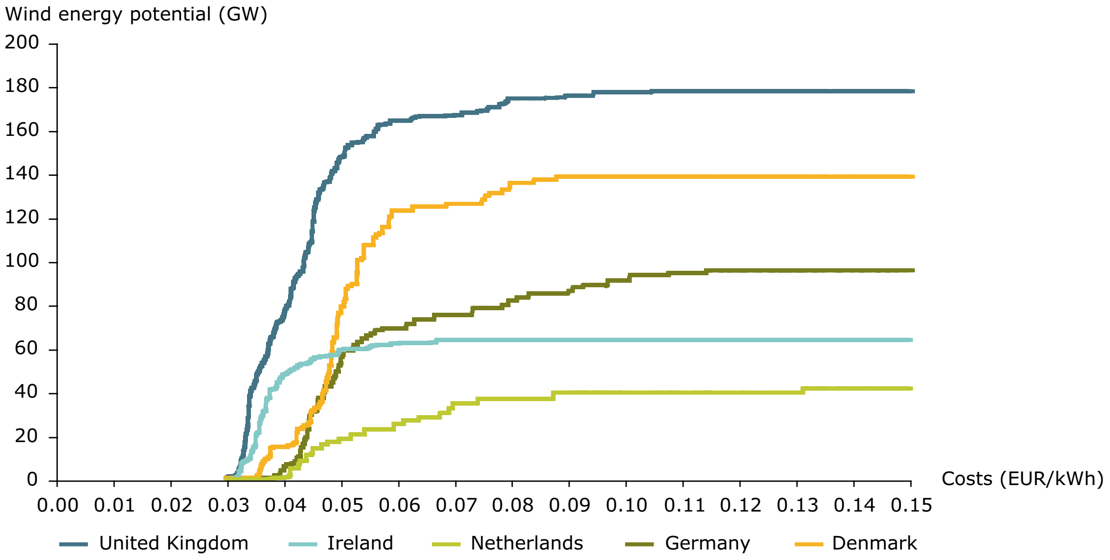
Production costs for offshore wind are calculated as a function of water depth and distance to the coast according to the methodology explained above. The potential for wind energy developments in the different water depth classes is presented in Figure 6.5. At average production cost of 6.9 eurocents (2005 prices)/kWh in 2030 5800 GW of offshore wind could be developed. This figure however corresponds to the unrestricted potential. For comparison, EWEA (2009) put the installed wind turbine capacity in 2008 at 1.4 GW. Deep seas at 40–50 metres have the highest potential of 2 100 GW, followed by 1 500 GW at 30–40 metres, 950 GW at 20–30 metres and 1 300 GW at 0–20 metres. With the production cost of 5.0 eurocents (2005 prices)/kWh areas with a depth up to 20 metres produce more potential than areas at depths of 20–30 metres.

Looking at operational offshore wind farms, it is apparent that only one wind farm in Scotland has a sea depth greater than 40 m. Current practice is generally limited to a maximum depth of 15 m. The exceptions are primarily new constructions in Denmark (Horns Rev II with 10–18 m water depth), the United Kingdom (Barrow with > 15 m and Beatrice with > 40 m), Belgium (Thorntonbank, 12–28 m) and the Netherlands (Egmons with 17–23 m and Q7 with 19–24 m).

Optimal wind locations in waters up to 20 m deep can be found in the United Kingdom and Ireland (see Figure 6.6). Competitive offshore wind capacity in the United Kingdom is estimated at about 165 GW at average production costs of 6.9 eurocents (2005 prices)/kWh in 2030. In Ireland most of the potential can be developed at production costs in the range of 3.0–5.0 eurocents (2005 prices)/kWh.

On the other hand when the assumptions applied for the constrained potential are considered, the competitive potential for offshore decreases to 2 600 TWh (630 GW) in 2020 and 3 400 TWh (820 GW) in 2030. 38 % of this potential can be harnessed within the distance 10–50 km from the shore.

Figure 6.6 Wind energy potential in the North Sea area at 0–20 m depth



Source: EEA, 2008.

7 Analysis of current penetration levels in Denmark and the Netherlands

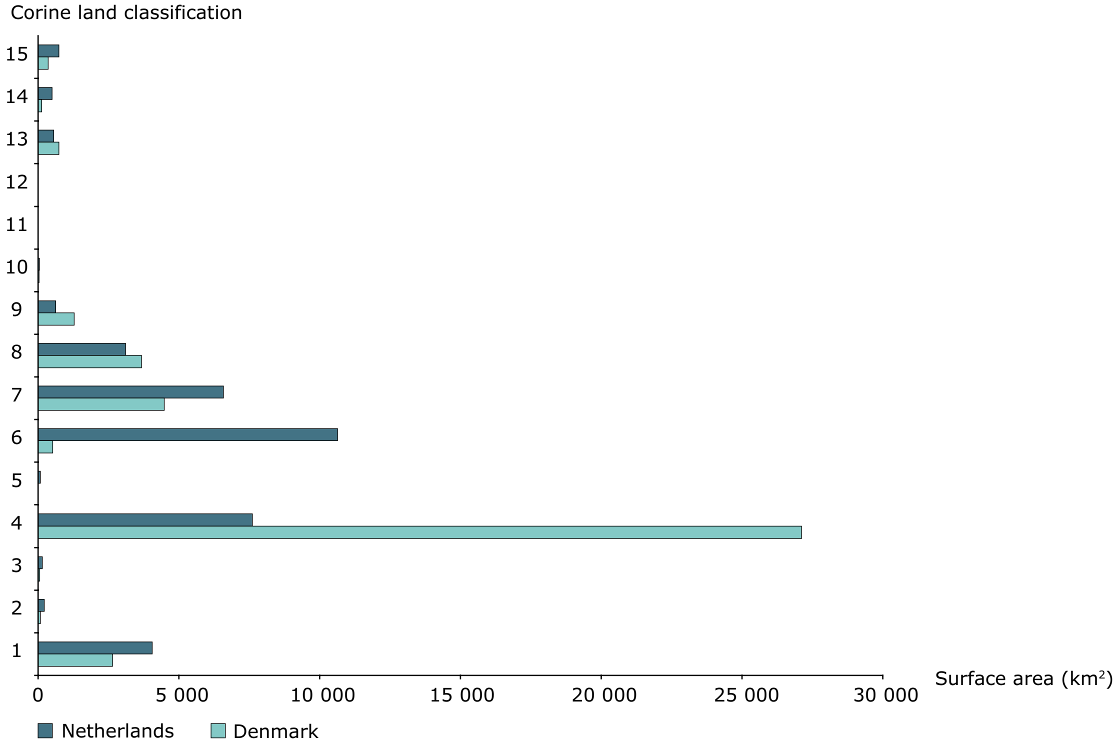
Limitations of wind energy potential are physical (including availability of wind resources, other land uses), economic and social. Some of the social barriers such as opposition from the local public, lack of awareness in edition to regulatory barriers are difficult to quantify in a pan-European scale. Therefore, we analysed some of the EU countries where wind energy deployment were significant to reach a penetration level that can be used as a proxy to represent the current feasible penetration level in Europe. By applying these proxies to other European areas with similar geographical locations the future expansion capacities are investigated.

Denmark had the third highest wind turbine installed capacity in Europe behind Germany and Spain with 3 122 MW onshore installed capacity at the end of 2005 (19) (EWEA, 2006). Being a small country, wind power density is highest in Denmark (EWEA, 2008b) The total surface area of Denmark is greater than that of the Netherlands but in terms of Corine land classification it is similar to the Netherlands, being extensively pasture or arable land with low surface roughness (Figure 7.1).

This chapter aims to analyse the penetration of wind turbines in Denmark, based on the land area of wind farms, and to investigate:

- 1 the effect on Danish national wind energy capacity of 'repowering' all the wind turbines in Denmark to a 2 MW capacity;
- 1 the potential impacts for installed capacity in the Netherlands if the penetration achieved in Denmark were applied there.

Figure 7.1 Land surface area within the 15 Corine land classifications for Denmark and the Netherlands



Source: EEA, 2008.

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(19) By 2008 Denmark has the sixth highest wind turbine capacity in Europe, behind Germany, and Spain, Italy, France and the United Kingdom, with 3 180 MW onshore installed capacity at the end of 2008 (EWEA, 2009). This assessment, however, is based on the 2005 data as the wind turbine locations were gathered for that year.

This analysis can give some idea of the 'feasible penetration' levels of wind energy in Europe. 'Feasible penetration' is placed in quotes because what is currently feasible is likely to change, for example through changes in societal perceptions and preferences and through government policies, as discussed elsewhere in this report.

In Denmark average wind power density is approximately 0.06 MW/km^2. However, in several municipalities power density is close to or greater than twice this national average. It is conceivable that the national average could be raised to the level in these municipalities. For this reason we do not assume here that Denmark has reached a 'saturation' limit with respect to wind power. Instead we are interested in investigating the impact of applying the relatively high levels of wind power penetration in Denmark, to other European areas with similar geographical characteristics.

Data on the location of all wind turbines existing in Denmark for the years 2000 to 2005 was gathered from the Danish Energy Agency (2007a). Equivalent data was gathered for wind turbines in the Netherlands. The penetration of wind turbines in Denmark was calculated by assuming a footprint of 0.2 km^2 for each turbine based on a power density of 10 MW/km^2 achieved with five 2 MW turbines. The total area covered by wind turbines was then calculated, discounting the area of overlap between turbines, in the 15 Corine land classifications and subdivided by the mean 2000–2005 wind speed over each area, grouped into 0.5 m/s intervals.

The total wind turbine coverage then defines the number of 2 MW turbines that could be supported if the current turbines were 'repowered'. For Denmark, the wind turbine coverage area calculated using the above methodology is 368 km^2. Since each 2 MW turbine has a footprint of 0.2 km^2, this leads to a total of 1 840 turbines and hence an installed capacity of 3 680 MW, around 500 MW more than the existing installed capacity. The same calculation was carried out for wind turbines in the Netherlands to arrive at the coverage of wind turbines by land type and wind speed. The penetration of wind turbines, expressed as a percentage of the total national land area within each land type and wind speed range, is shown in Table 7.1 for Denmark and Table 7.2 for the Netherlands.

It can be seen from Table 7.1 that the greatest penetrations of wind turbines in Denmark occur for:

- 1 CL-3, at a wind speed range of 7–7.5 m/s;
- 1 CL-4, at wind speed ranges of 5.5–6 and 7.5– 8 m/s;
- 1 CL-5 at a wind speed range of 4.5–5 m/s.

No wind turbine penetration is calculated for CL-2, CL-10, CL-11, CL-12, CL-14 or CL-15. However, wind turbine penetration is seen in the remaining Corine land classifications for most wind speeds between 4 m/s and 7.5 m/s, and in the range 7.5–8 for CL-4, CL-7 and CL-13.

In the Netherlands, wind speeds are typically lower than in Denmark, as illustrated by Figure 7.2, which shows the percentage of the total surface area of Denmark and the Netherlands that falls into 0.5 m/s wind speed intervals.

For the period 2000–2005, an average of 45 % of the Netherlands surface area shows wind speeds of less than 4 m/s, whereas none of Denmark falls below this threshold. Over the same period, predicted winds across 84 % of Denmark's surface area were greater than 4.5 m/s, compared with 23 % for the Netherlands.

Table 7.2 indicates that for wind speeds less than 6 m/s the penetration of wind turbines is typically higher in the Netherlands than in Denmark.

This difference in penetration levels at wind speeds below 6 m/s is more apparent in Figure 7.3, which provides a graphical presentation of the penetration of wind turbines as a percentage of the total national area within each wind speed interval. Penetration levels across all Corine land classes are higher in the Netherlands for wind speeds between 5 and 6 m/s. For wind speeds above 6 m/s, penetration is higher in Denmark despite its greater total land area with wind speeds of this magnitude. It might be concluded that suitable land for wind turbines in the Netherlands typically does not experience wind speeds greater than 6 m/s. As a result, penetration levels peak within the 'premium' wind speed interval of 5.5–6 m/s, reaching values up to 7.7 % for CL-2, 25 % for CL-3 and 6.3 % for CL-4.

If the 'penetration' levels achieved in Denmark were exactly replicated in the Netherlands, while preserving the turbines within land classes for which there is no penetration in Denmark, the result would be a decrease in the installed capacity from its current level of around 1 500 MW to nearly 1 200 MW. If Danish penetrations were applied only to those land class and wind speed categories where the penetration is greater than

Table 7.1 **Penetration of wind turbines in Denmark: area covered by wind turbines (assuming that all turbines have a capacity of 2 MW) expressed as a percentage of the total land area in Denmark in each Corine land classification and wind speed range**

Fraction of 2000–2005 mean land area

CLC class	Land type description	Wind speed (m/s)									% of total national surface area in each land class
		3.5–4	4–4.5	4.5–5	5–5.5	5.5–6	6–6.5	6.5–7	7–7.5	7.5–8	
1	Continuous/discontinuous urban fabric; industrial/commercial units; green urban areas; sport and leisure facilities	–	0.10 %	0.03 %	0.03 %	0.57 %	0.10 %	0.31 %	0.44 %	–	0.10 %
2	Road/rail networks and associated land; ports; airports	–	–	–	–	–	–	–	–	–	–
3	Mineral extraction/dump/construction sites	–	–	0.57 %	–	–	2.50 %	–	14.12 %	–	0.79 %
4	Non-irrigated arable land; permanently irrigated land; rice fields	–	0.52 %	1.27 %	1.05 %	2.99 %	1.60 %	2.16 %	0.18 %	5.17 %	1.26 %
5	Vineyards; fruit trees and berry plantations; olive groves	–	–	4.05 %	–	–	–	–	–	–	1.92 %
6	Pastures	–	0.05 %	0.43 %	0.64 %	0.35 %	2.59 %	–	0.33 %	–	0.42 %
7	Annual crops associated with permanent crops; complex cultivation patterns; principally agricultural land with significant areas of natural vegetation; agro-forestry areas	–	0.10 %	0.54 %	0.28 %	0.72 %	0.47 %	0.34 %	0.31 %	0.42 %	0.38 %
8	Broad-leaved/coniferous/mixed forest	–	0.06 %	0.07 %	0.04 %	–	–	0.03 %	0.03 %	–	0.05 %
9	Natural grasslands; moors and heathland; sclerophyllous vegetation; transitional woodland-shrub	–	–	0.06 %	0.03 %	–	0.26 %	–	0.05 %	–	0.04 %
10	Beaches, dunes, sands	–	–	–	–	–	–	–	–	–	–
13	Inland marshes; peat bogs; salt marshes; salines; intertidal flats	–	–	0.11 %	0.19 %	0.13 %	0.68 %	0.09 %	0.08 %	0.28 %	0.14 %
14	Water courses; coastal lagoons; estuaries; sea and ocean	–	–	–	–	–	–	–	–	–	–
15	Water bodies	–	–	–	–	–	–	–	–	–	–

Source: EEA, 2008.

in the Netherlands, a 100 MW increase in the Netherlands' installed capacity would result.

Reversing this analysis and applying penetrations achieved in the Netherlands to Denmark, where penetration is greater than those in Denmark, would cause the installed capacity in Denmark to increase to nearly 5 000 MW. Taking into account the similarity of society and landscape, these results suggest that in both countries there is still scope for further expansion: 'feasible penetration' levels can change.

From Table 7.3 it is clear that the 'feasible penetration' level, in terms of estimated area covered by wind turbines both in Denmark and the Netherlands, is low, coming to 0.9 % and 0.4 % of the national land area, respectively. No land area in Denmark experiences wind speeds less than 4 m/s, therefore the total 'feasible penetration' for land

Table 7.2 **Penetration of wind turbines in the Netherlands: area covered by wind turbines (assuming that all turbines have a capacity of 2 MW) expressed as a percentage of the total land area in the Netherlands in each Corine land classification and wind speed range**

Fraction of 2000–2005 mean land area

CLC class	Land type description	Wind speed (m/s)									% of total national surface area in each land class
		3.5–4	4–4.5	4.5–5	5–5.5	5.5–6	6–6.5	6.5–7	7–7.5	7.5–8	
1	Continuous/ discontinuous urban fabric; industrial/ commercial units; green urban areas; sports and leisure facilities	0.01 %	0.09 %	0.12 %	0.38 %	0.29 %	1.04 %	–	–	–	0.08 %
2	Road/rail networks and associated land; ports; airports	0.20 %	2.07 %	6.56 %	4.26 %	7.69 %	22.86 %	1.19 %	–	–	3.06 %
3	Mineral extraction/ dump/construction sites	–	–	8.49 %	–	25.07 %	–	–	–	–	2.94 %
4	Non-irrigated arable land; permanently irrigated land; rice fields	0.92 %	0.91 %	0.70 %	1.88 %	6.26 %	0.02 %	–	–	–	1.05 %
5	Vineyards; fruit trees and berry plantations; olive groves	4.30 %	0.92 %	–	–	–	–	–	–	–	2.20 %
6	Pastures	0.11 %	0.14 %	0.65 %	1.18 %	1.13 %	–	0.33 %	0.12 %	–	0.28 %
7	Annual crops associated with permanent crops; complex cultivation patterns; principally agricultural land with significant areas of natural vegetation; agro-forestry areas	0.01 %	0.02 %	0.03 %	–	1.44 %	–	–	–	–	0.02 %
8	Broad-leaved/ coniferous/mixed forest	–	0.06 %	–	0.18 %	–	–	–	–	–	0.02 %
9	Natural grasslands; moors and heath land; sclerophyllous vegetation; transitional woodland-shrub	–	–	–	–	–	–	–	–	–	–
10	Beaches, dunes, sands	–	–	1.01 %	–	–	2.76 %	–	–	–	0.26 %
13	Inland marshes; peat bogs; salt marshes; salines; intertidal flats	0.18 %	0.55 %	0.71 %	0.87 %	0.84 %	–	0.90 %	0.47 %	–	0.44 %
14	Water courses; coastal lagoons; estuaries; sea and ocean	–	0.51 %	0.60 %	0.56 %	2.86 %	–	–	–	–	0.44 %
15	Water bodies	0.32 %	1.52 %	0.23 %	1.17 %	11.20 %	–	–	–	–	0.87 %

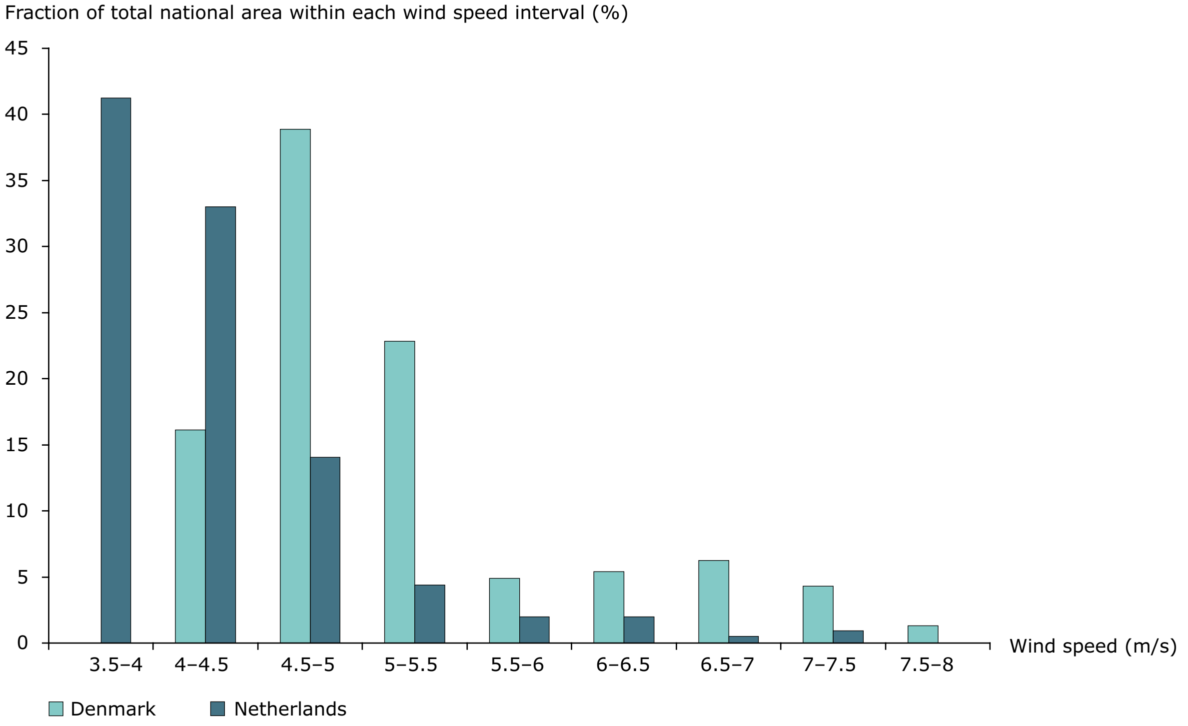
Source: EEA, 2008.

greater than 4 m/s is also 0.9 %. In the Netherlands, however, the 'feasible penetration' of viable wind speed land (i.e. the coverage of wind turbines within areas of wind speeds greater than 4 m/s divided by that area) is 0.6 %.

Map 7.1 depicts full load hours in agricultural areas. The 'penetration' levels of wind on agricultural land and for land types CL-4 (non-irrigated arable land, permanently irrigated land and rice fields), CL-6 (pastures) and CL-7 as a whole, and for CL-4 on its own, are given in Table 7.1.

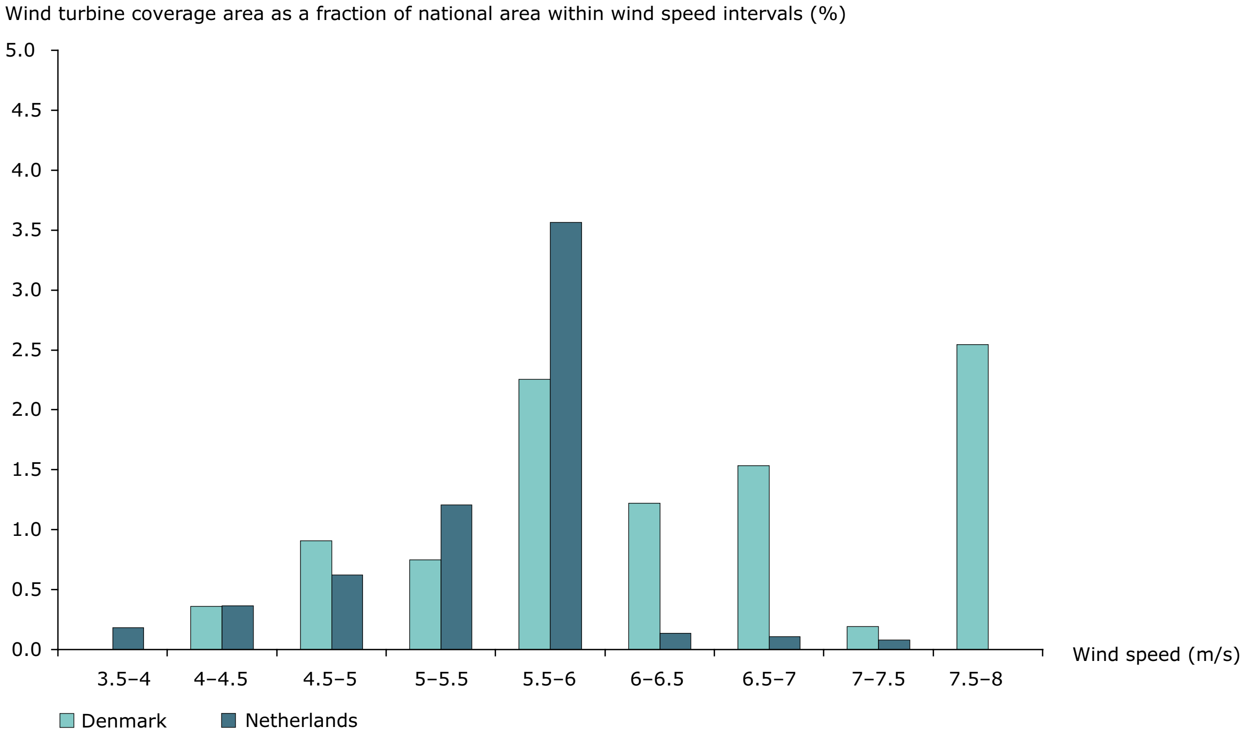
Land type CL-7 is associated with permanent crops, complex cultivation patterns and land principally used for agriculture, with significant areas of natural vegetation and agro-forestry. 'Penetration' levels are greater than for the total wind speed on viable land: i.e. 1.13 % for Denmark and 0.62 % for the Netherlands. For CL-4 on its own, 'penetration'

Figure 7.2 **Surface area of land in Denmark and the Netherlands for all Corine land types in each wind speed interval expressed as a percentage of the total national area**



Source: EEA, 2008.

Figure 7.3 **Penetration area of wind turbines in a range of wind speed intervals expressed as a percentage of the area within each wind speed interval across all Corine land classifications**



Source: EEA, 2008.

Table 7.3 A comparison of feasible penetration levels for Denmark, the Netherlands, considering total national land area as separate from agricultural land

Country	Variable	Total	Total	CLC-4, CLC-6, CLC-7	CLC 4
Denmark	Area of turbine (km²)	368	368	3 662	342
	Total land area (km²)	41 118	41 118	32 116	27 111
	Penetration	0.90 %	0.90 %	1.13 %	1.26 %
Netherlands	Area of turbine (km²)	138	112	87	61
	Total land area (km²)	34 880	18 973	13 978	5 420
	Penetration	0.40 %	0.59 %	0.62 %	1.13 %

Source: EEA, 2008.

levels are higher still: i.e. 1.26 % in Denmark and 1.13 % in the Netherlands.

7.1 Conclusions

Above section discussed the results of analysing the levels of penetration in Denmark and the Netherlands. It was found that 'repowering' the current turbines installed in Denmark to 2 MW would result in a 500 MW increase in the installed capacity, from approximately 3 200 MW to nearly 3 700 MW. Predicted wind speeds across the Netherlands were shown to be generally lower than across Denmark. Consequently, penetration levels attained a greater magnitude than in Denmark for the highest wind speed ranges in the Netherlands. As a result, applying Danish penetration levels to the Netherlands situation caused no significant increase in the installed capacity.

One conclusion for Denmark and the Netherlands is that greater penetration levels are generally achieved, and therefore socially accepted, where peak wind speeds are experienced within a particular country or region. This quick analysis of only two countries suggests that both have more or less achieved a penetration level that is consistent with the potential, notwithstanding a different history of wind power development, policies and social attitudes. This could be considered as providing support to the significance of our analysis. It would be worthwhile to do a more comprehensive comparative analysis using detailed data from other countries.

Feasible penetration levels were calculated for Denmark and the Netherlands. Relatively low penetration levels were found in Denmark and the Netherlands for viable wind speed land of 0.9 and 0.6 %. 'Feasible penetration' levels within CLC-4 (arable land) were found to be 1.26 % in Denmark and 1.13 % in the Netherlands, higher than the 'feasible penetration' across all land types.

7.2 Grid integration

Grid integration of wind energy has been a topic of discussion for many years. Variable energy sources such as wind energy affect the way an electricity system operates. There is, however, no accepted maximum penetration level for wind energy, as each electricity system's capacity to compensate for intermittency differs. Current penetration levels of wind energy are relatively high in Denmark. In 2007, wind share of electricity demand in Denmark was around 21 % (EWEA, 2008a). Andersen (2007) estimates that the penetration of wind energy on a large grid can be as much as 15 % to 20 % without additional precautions with respect to power quality and grid stability. On the other hand, a recent Danish study concludes that even the integration of 50 % wind power into the Danish electricity system is technically possible without threatening the security of supply (Ea Energy Analysis, 2007). TENNET (2005) finds that in the Netherlands the existing network (2012 configuration) could integrate wind energy to provide 15 % of total supplies without losses, while at a penetration of 30 % approximately 15 % of generated wind energy could not be absorbed.

As the literature on the issue suggests varying figures maximum penetration level of 25 % wind is assumed and the amount of suitable land required to achieve this is calculated. When land areas with more than 2 000 full load hours and offshore areas with more than 2 500 full load hours (between 10 and 50 kilometres from the coast) are applied as restrictions, on average 8 % of the suitable land and sea area is required to meet the 25 % of the electricity supply by wind power in 2030 according to the low-carbon energy pathway scenario (EEA, 2005). In

Map 7.1 Full load hours in agricultural areas only

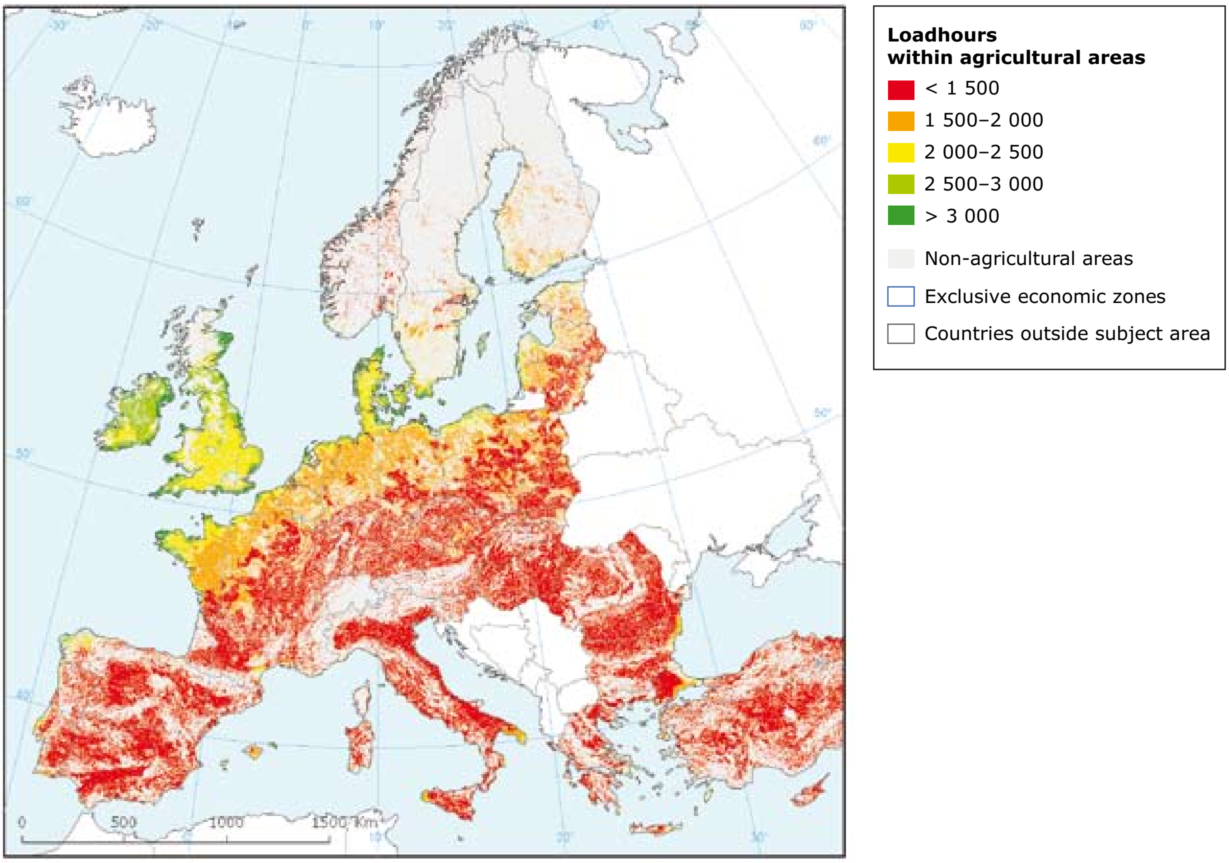
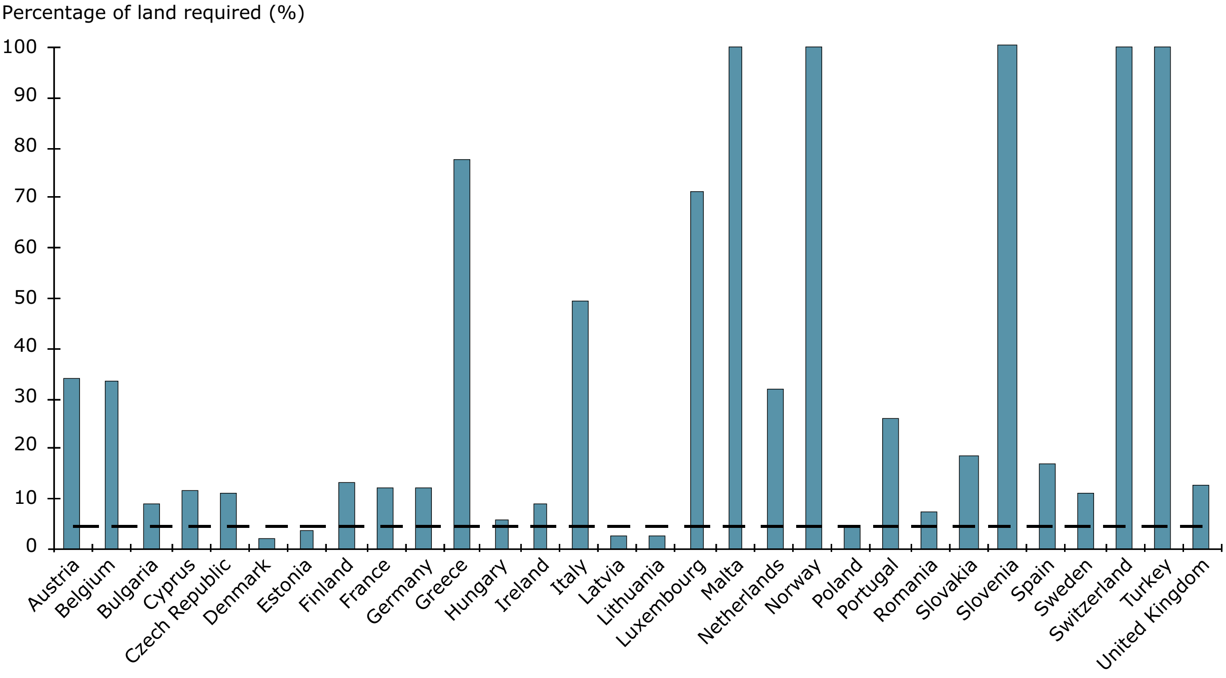


Figure 7.4 Percentage of agricultural land required to fulfil 25 % of the electricity demand in 2030



Source: EEA and EC, 2008a.

a number of countries the amount of land required is less than 4 %.

A further analysis has been done on the amount of agricultural land required to achieve the 25 % wind energy integration into the grid. Previous chapters have already indicated that agricultural land is more appropriate for sitting wind turbines.

The feasible penetration analysis for agricultural land in the previous chapter revealed feasible penetration of wind on agricultural land as 1.26 % in Denmark, 1.13 % in the Netherlands. Based on these countries and some facts from Germany the average feasible penetration of wind turbines is derived as 4.4 %.

This percentage is used as an approximation of the minimum share of land that could be used across Europe for wind turbines. Figure 7.4 shows the percentage of suitable locations needed to meet 25 % of electricity demand through wind energy by 2030. The horizontal dashed line is set at 4.4 %, countries below this line are considered to achieve a 25 % penetration under current social and environmental constraints.

8 Future considerations

This study confirms that, alongside other renewable sources such as biomass, wind energy can play a major role in achieving Europe's renewable energy targets.

Generally, the areas with the largest technical potential also have the largest economic potential. Technical potential is most significant in agricultural and industrial areas on land as well as in low-depth offshore areas. Deep offshore potential is even larger but is unlikely to contribute in any significant way to the energy mix within the time horizon of this study, primarily due to significantly higher costs.

Looking ahead, there are several clear avenues for more in-depth analysis. First, the proxies and assumptions used in this study to evaluate technical and constrained wind energy potential have facilitated quantitative analysis but clearly have limitations, which imply uncertainties in the resulting wind potential estimates. As outlined in the sections below, efforts should address the uncertainties with respect to the natural, technological and economic variables, as well as issues relating to the choice of model used.

Future research should also include cross-country trend analysis of social constraints in EEA member countries and an inventory and analysis of policy-driven wind energy success stories in Europe and elsewhere. Further examination is also needed to determine biodiversity vulnerability with respect to specific species and landscapes. In addition, this study's localised analysis can guide the selection of interesting areas for regional studies, such as the Baltic.

8.1 Uncertainties in physical variables

The physical variables needed to calculate technical wind energy potential include meteorological data (ECWMF wind fields) and information on land-use characteristics (CLC, CDDA, Natura 2000). Uncertainties arise from potential monitoring errors (both meteorological and land-cover data) and variability over time. The relatively short time frame (only 5 years) for the wind speed assessment might introduce an error, as might regional inaccuracies in the ECMWF data.

The assumption that future wind speed and land-cover characteristics are the same as today introduces another set of uncertainties, since climate change may affect wind conditions and land-use changes. This may lead to changes in land cover and associated roughness. Finally, the shortage of data to assess wind energy potential in complex terrain, in forests and at offshore sites across Europe creates large uncertainties with respect to the estimates.

8.2 Uncertainties in technological and economic variables

Assumptions for various technological and economic variables are required to estimate economic potential. These include assumptions on rated power, rotor diameter, hub height, theoretical and practical wind turbine output (full load hours), construction depth offshore and distance to the coast. Assumptions on economic characteristics include investment, operation and maintenance costs, costs for upgrading and extending the grid and system balancing, and competition issues with other energy sources.

Due to the large geographical scope and the relatively limited experience with large-scale wind farms, particularly offshore, the assumptions contain a certain level of uncertainty. For instance, the cost data are based on single-wind turbines but prices will be different when large orders are made. On one hand, prices are likely to decrease when larger quantities are ordered by 10–55 % (Junginger, 2005). On the other hand, at high penetration rates, increasing demand beyond the industry's normal expansion of capacity may lead to increased prices for turbines and therefore increased investment costs.

8.3 Uncertainties regarding social and environmental constraints, and policy choices

Future wind energy potential depends on human (political) choices. Environmental and social concerns and government policies place many constraints on wind farm development. Examples of key judgements include the minimum distance to the shore and density of windmills on land and offshore, including 'no-go' areas designated for the protection of wildlife.

Such constraints may change over time, in part due to evolving priorities and government policies. For example, people tend to view wind turbines more positively after they have been constructed than beforehand, especially if they have a financial stake in profits. To address this type of uncertainty in determining wind energy potential, particular scenario assumptions are made. These will clearly need to be reviewed in future research in the light of both greater understanding of the issues and evolving social preferences.

The effects of wind energy on biodiversity are still relatively new and unknown. National or regional strategic impact assessments of policy plans, environmental impact assessments of wind turbine projects and monitoring programs of existing wind farms remain essential tools for minimizing and learning about environmental impacts. The lack of data for offshore Natura 2000 areas did not allow this study to assess the biodiversity concerns for offshore areas. Thus, further studies need to include this very important aspects.

More over, the proxies applied to assess the constrained potential incurs large uncertainties. They require further sensitivity analysis.

8.4 Uncertainties related to model choices

Modelling wind speeds across Europe requires assumptions and simplifications which create uncertainties. Such steps include translating landscape characteristics and associated roughness factors into effects on wind speeds, determining the relationship between wind speed and power density for different hub heights, and converting construction, operation and maintenance costs into electricity costs.

In this study, the first type of uncertainty is specifically analysed by comparing the modelled wind velocities in the grids with actual wind speeds from the NOOA database. This analysis suggests a reasonable fit, with some overestimation of wind speeds in low-lying and flat areas, and underestimation in mountainous areas. Another area of uncertainty is the assessment of the sub-grid variation from the wind data, considering that there is a wide variation of wind speeds contained in a single ECMWF grid point (20 x 15 km^2).

This study did not estimate all uncertainties quantitatively. As a rough approximation, the order of magnitude of the uncertainties in the physical, technological and economic variables are smaller than the uncertainties related to human choices, notably the social and political constraints. While this may be seen as a weakness of the analysis, it should be noted that this category of uncertainties can be most influenced by policy decisions that address the various constraints.

8.5 Steps to address uncertainties

This overview of uncertainties suggests some improvements for further research to fill gaps in knowledge. They include:

- 1 sensitivity analysis for key economic and technological assumptions;
- 1 more detailed analysis of areas where model prediction and observed wind velocities differed most, notably mountainous and forested areas;
- 1 cross-country trend analysis of social constraints in EEA member countries, with emphasis on the countries with high economic wind energy potential;
- 1 inventory and analysis of policy-driven wind energy success stories in Europe and beyond;
- 1 further analysis of specific vulnerabilities for biodiversity related to specific bird and other species and landscapes, and application of such vulnerabilities in mapping wind energy potential in Europe.

8.6 Future challenges

Policy targets at EU level, in particular the renewable energy directive's binding targets for each Member State, will drive wind energy development. Nevertheless, a number of challenges lie ahead. Apart from technical issues that need to be resolved (especially those related to offshore wind energy) there are a number of issues related to legislation, planning and support instruments that could well benefit from a coordinated European approach.

8.6.1 Wind farms and the Birds and Habitat Directives

The lack of clarity on the conditions under which wind farms can be build in or close to areas designated for protection under the Birds and Habitat Directives or other protected nature conservation areas is considered an important barrier. Failure to identify such areas increases uncertainty of the potential suitability of any given site for wind farms. In contrast to spatial planning on land, Member States generally lack relevant experience and suitable governance structures and rules for integrated planning in the marine environment. Only limited progress has been made so far in developing an integrated planning approach that looks simultaneously at the spatial distribution of wind resources, constraints imposed by other marine activities or interests and electricity grid aspects. This increases uncertainty and the risk of delays or failure of wind energy projects at sea (EC, 2008d).

A more strategic and coordinated approach will be important in order to exploit Europe's potential wind resources. Planning instruments at EU or regional level can play a role. For both onshore and offshore wind energy the European Commission has proposed that the new Directive on energy from renewable energy sources should contain an obligation to prepare national action plans. Implementing the EU's Integrated Maritime Policy and the recent 'Roadmap for Maritime Spatial Planning: Achieving common principles in the EU' (EC, 2008e) provides Member States an opportunity to consider offshore wind farms in their overall assessment of the pressure and impacts on the marine environment.

Strategic Environmental Assessments (SEAs) (20) that include sensitivity mapping at regional or national level could identify areas where conflicts may occur or where wind development is unlikely to conflict with biodiversity conservation. Maps showing Natura 2000 and other protected areas provide a starting point but not all designated areas are equally sensitive and some unprotected areas, such as bottleneck sites for bird migration and some marine areas, are more vulnerable than many designated sites.

In most cases proper siting can ensure that the biodiversity impacts of wind farm development are minimised to levels of no significant concern. Strategic planning on a national or regional level is a prerequisite for developing a coherent plan for wind energy deployment. If there are potential trans-boundary effects, international cooperation could be sought (and is required within the EU). The impact of the plan or programme must be assessed in combination with other plans and programmes, both for wind farms and other developments, in order to take account of combined and cumulative effects. For instance, one issue to be addressed relates to the fact that shallow water areas are highly attractive for the wind industry but are also moulting and wintering grounds for the vast majority of European seaducks, which feed in areas with depths between 5 and 20 metres. Map 8.1 presents an example of mapping of marine protected areas and wind farm development in Danish waters.

8.6.2 Location of European offshore wind capacity

Offshore wind energy planning mostly relates to grid infrastructure development and system integration. Offshore wind resources are not equally distributed across the continent and are primarily in northern Europe. Large-scale development of offshore wind power would imply that production would need to feed in to the grid via entry points on the coast in northern Europe. The capacity of the existing grid to transmit the power from the new wind farms to the consumers may be insufficient. In some Member States, especially in Germany, a bottleneck exists already or is expected in case of significant wind capacity expansion in the North Sea.

A coordinated European approach is needed to ensure interconnection and enable integration of offshore wind into the European grid. Regional cooperation within the new European Network of Transmission System Operators (ENTSO) proposed under the 'internal market package' will be an important tool for optimizing the electricity grid for implementing large scale wind energy. Such interregional cooperation can benefit offshore wind energy initiatives at sites such as the North Sea (Denmark, German, the Netherlands, Norway and the United Kingdom), the Baltic Sea (Estonia, Finland, Latvia, Lithuania, Poland, Sweden, etc.) and sites in the Mediterranean Sea (Greece, Italy, Turkey, etc) and the Irish Sea (Ireland and the United Kingdom).

8.6.3 Other barriers

While land-based wind energy will remain dominant in the immediate future, installations at sea will become increasingly important. This study shows the high potential for offshore wind energy but it is important to note that existing legislative frameworks and established procedures are sometimes designed for land rather than offshore applications. As a result, laws and regulations on the process and/or criteria for obtaining development consents, permits and concessions are not clear or do not exist.

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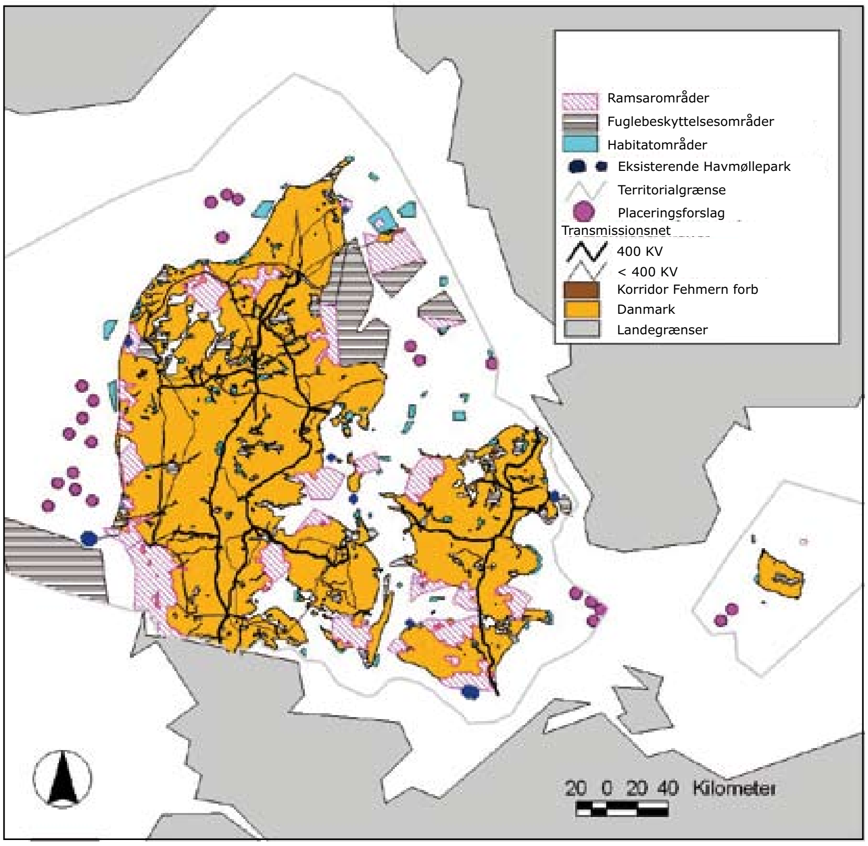
(20) Strategic Environmental Assessments (SEAs) are strategic appraisals of major programmes or plans, assessing the impact that various options for achieving a pre-defined goal might have on the environment.

Map 8.1 **Marine protected areas and wind farm development in Danish waters**



Note:
- Pink hatched areas: Ramsar areas, black hatched areas: bird protection areas.
- Blue coloured areas: habitat areas, dark blue dots: existing offshore wind farms.
- Pink circles indicate proposed areas for future wind development.

Source: Danish Energy Agency, 2007.

Another issue is lack of clarity on Environmental Impact Assessments (EIA) and the need for guidelines and information exchange at the international level to prevent regional and national obstacles. The variety of authorities involved in consent procedures is considered an inefficient, unnecessary bottleneck (EC, 2008d).

At the national level, among the most important factors to encourage people to support wind energy is public participation. Soerensen *et al.* (2002) identified three means of boosting public involvement in projects: information about the development; involvement in the decision-making process; and financial involvement. Public confidence can be increased when these means are utilised.

Public engagement has been promoted successfully using the concept of 'community wind' in Denmark and Germany. In Germany, the most common form is a limited partnership with a limited liability company as general partner. Danish community wind projects have the form of general partnerships (Bolinger, 2001). The structure of these general partnerships is quite simple: individuals pool their savings to invest in a wind turbine and sell the power to the local utility at an attractive rate. The role of community wind has evidently been critical to the global development of wind power (Kildegaard and Meyers, 2006). General partnerships (cooperatives) have played an important role in Denmark, especially by increasing local acceptance, where resistance can otherwise be high due to visual or noise impacts (Soerensen *et al.*, 2002). Other countries using 'community wind' are Sweden and the United Kingdom.

In conclusion, a consistent policy process that ensures long-term effective support instruments and removes legislative hurdles, together with a high social involvement at both the national and international levels will succeed in larger uses of wind potential where the environment is safeguarded

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Annex 1 List of abbreviations

AEWA	African Eurasian Waterbird Agreement
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas
ACCOBAMS	Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area
BWEA	British Wind Energy Association
CDDA	Common Database on Designated Areas
CLC	Corine Land Cover
Corine	Name of programme that developed the Corine Land Cover map
DOWEC	Dutch Offshore Wind Energy Converter
EEA	European Environmental Agency
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
ECN	Energy research Centre of the Netherlands
EEZs	Exclusive Economic Zones
EIA	Environmental impact assessment
ENTSO	European network of transmission system operators
ERA-40	ECMWF Reanalysis-40
EREC	European Renewable Energy council
ESRI	Software development and services company providing GIS
EU	European Union
EWEA	European Wind Energy Association
GIS	Geographical Information System
GLC	Global land cover
GWEC	Global wind Energy Council
HELCOM	Helsinki Commission — Baltic Marine Environment Protection Commission
IBAs	Important Bird Areas
IPCC	Intergovernmental Panel on climate Change
MARS	Meteorological Archival and Retrieval System Natura 2000
MSFD	Marine Strategy Framework Directive
NCEP	National Centre for Environmental Prediction, USA
NCAR	National Centre for Atmospheric Research, USA
NOAA	National Oceanic & Atmospheric Administration, USA
NGDC	National Geophysical Data Centre
O&M	Operation and Maintenance
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PRIMES	A modelling system that simulates a market equilibrium solution for energy supply and demand in the European Union (EU) Member States
RICS	Royal Institute of Chartered Surveyors
SACs	Special Areas of Conservation
SEA	Strategic Environmental Assessment
SPAs	Special Protection Areas
VLIZ	Vlaams Instituut voor de Zee (The Flanders Marine Institute)
WBGU	German Advisory Council on Global Change
WFD	Water Framework Directive

Annex 2 Corine Land Cover classes and hub height conversion ratio

Table A1.1 Average hub height conversion ratio used in 15 Corine Land Cover classes

CLC class number	Av ratio	CLC code and label Level 3	
CL-1	1.91	111	Continuous urban fabric
		112	Discontinuous urban fabric
		121	Industrial or commercial units
		141	Green urban areas
		142	Sport and leisure facilities
CL-2	1.64	122	Road and rail networks and associated land
		123	Port areas
		124	Airports
CL-3	1.32	131	Mineral extraction sites
		132	Dump sites
		133	Construction sites
CL-4	1.43	211	Non-irrigated arable land
		212	Permanently irrigated land
		213	Rice fields
CL-5	1.52	221	Vineyards
		222	Fruit trees and berry plantations
		223	Olive groves
CL-6	1.47	231	Pastures
CL-7	1.51	241	Annual crops associated with permanent crops
		242	Complex cultivation patterns
		243	Land principally occupied by agriculture with significant areas of natural vegetation
		244	Agro-forestry areas
CL-8	1.85	311	Broad-leaved forest
		312	Coniferous forest
		313	Mixed forest
CL-9	1.33	321	Natural grasslands
		322	Moors and heath land
		323	Sclerophyllous vegetation
		324	Transitional woodland-shrub
CL-10	1.30	331	Beaches, dunes, sands
CL-11	1.30	332	Bare rocks
		333	Sparsely vegetated areas
		334	Burnt areas
CL-12	1.24	335	Glaciers and perpetual snow
CL-13	1.34	411	Inland marshes
		412	Peat bogs
		421	Salt marshes
		422	Salines
		423	Intertidal flats
CL-14	1.21	511	Water courses
		521	Coastal lagoons
		522	Estuaries
		523	Sea and ocean
CL-15	1.21	512	Water bodies
No CLC data used see Table A1.2			Norway/Switzerland/Turkey
	1.23		Offshore

Source: EEA, 2008.

Table A1.2 Global Land Cover (GLC) classes reclassified to wind roughness classes on basis of the CLC2 000 wind classification table

No.	GLC Global class (according to Land Cover Classification System terminology)	Wind roughness class
1	Tree cover, broadleaved, evergreen, with >15 % tree cover, tree height >3m	CL-8
2	Tree cover, broadleaved, deciduous, closed	CL-8
3	Tree cover, broadleaved, deciduous, open, with 15–40 % tree cover	CL-8
4	Tree cover, needle-leaved, evergreen	CL-8
5	Tree cover, needle-leaved, deciduous	CL-8
6	Tree cover, mixed leaf type	CL-8
7	Tree cover, regularly flooded, fresh water (& brackish)	CL-8
8	Tree cover, regularly flooded, saline water, with daily variation of water level	CL-8
9	Mosaic: tree cover/other natural vegetation	CL-9
10	Tree cover, burnt	CL-1
11	Shrub cover, closed-open, evergreen	CL-9
12	Shrub cover, closed-open, deciduous	CL-9
13	Herbaceous cover, closed-open	CL-9
14	Sparse herbaceous or sparse shrub cover	CL-11
15	Regularly flooded and/or herbaceous cover	CL-13
16	Cultivated and managed areas	CL-7
17	Mosaic: cropland/tree cover/other natural vegetation	CL-7
18	Mosaic: cropland/shrub or grass cover	CL-7
19	Bare areas	CL-11
20	Water bodies (natural and artificial)	CL-15
21	Snow and ice (natural and artificial)	CL-12
22	Artificial surfaces and associated areas	CL-1

Source: EEA, 2008.

Annex 3 Introduction to environmental and social constraints

Biodiversity aspects

Introduction

The replacement of fossil fuels by wind energy offers clear environmental benefits. Wind energy is essentially pollution free and reducing emissions of carbon dioxide and other greenhouse gases helps limit climate change and associated hazards to biodiversity. Recent development of wind energy has created concerns, however, about the adverse effects on birds and other wildlife due to factors such as collision with rotors and exclusion from optimal feeding sites. The challenge is thus to meet the wind energy targets in a way that minimises the negative impact on biodiversity.

There is a strong environmental legislative framework at the EU level to help reconcile wind energy development with nature conservation. The Birds and Habitats Directives (EC, 1992; EC, 1979) provide a framework for conserving species and habitats of interest, including the designation of Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) under the Natura 2000 network. Any development likely to have a significant adverse effect on these areas must be subject to an appropriate impact assessment. If an assessment concludes that there will be damage or significant disturbance to the nature values then the development can only proceed if there are no alternative solutions, it is of overriding public interest and compensatory measures are provided.

Other international conventions on wildlife protection confer responsibilities on signatories. Such instruments include the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention) and the other agreements concluded under its auspices: the African-Eurasian Waterbird Agreement (AEWA), the Agreement on the Conservation of Populations of European Bats (Eurobats), the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS) and the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS). They also include the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention), EU Directive (EC, 2000) (the Water Framework Directive — WFD), the Ramsar Convention on Wetlands, the OSPAR Convention, and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention).

The Marine Strategy Framework Directive (MSFD) (EC, 2008e) which entered into force in 2008, requires that EU Member States ensure that their marine waters achieve 'good environmental status' by 2020. Together with the WFD, the MSFD provides an overall legal framework for developing and implementing marine management strategies. In this context Members States can consider offshore wind farms in their overall assessment of the pressures and impacts on the marine environment.

Impact of wind farms on biodiversity

Overview of potential impacts

A review of the literature suggests a number of potential issues, which may be grouped as follows:

Collision risk. Birds and bats may collide with rotors, towers and nacelles or with associated structures such as cables and meteorological masts. There is also evidence of birds being hit by the wake behind the sweeping rotor blades (Winkelman, 1992). With some notable exceptions the majority of studies have recorded relatively low levels of collision mortality but most were based only on finding corpses — a method that may underestimate mortality.

Barrier effect. Wind farms are thought to force birds to change their flight direction, both during migrations and regular flights. Whether this is a problem will depend on the size of the wind farm, the spacing of turbines, the extent of displacement of flying birds and their ability to compensate for increased energy expenditure, and the degree of disruption of linkage between, e.g., feeding and roosting sites.

Displacement. Birds and marine mammals may be displaced from areas within and surrounding wind farms due to visual, noise and vibration impacts. Disturbance may also arise from increased human activity during construction work and maintenance visits, especially for offshore wind farms, and infrastructure improvements to facilitate access.

The scale and degree of disturbance determines the significance of the impact, together with the availability and quality of other suitable habitats that can accommodate the displaced animals. Habituation may occur, especially for resident birds and mammals, but in several cases impacts have been shown to persist or worsen with time (Stewart *et al.*, 2004).

Habitat loss or degradation. The scale of direct habitat loss resulting from constructing a wind farm and associated infrastructure depends on the size of the project. It is generally small, although effects may be more widespread where developments interfere with hydrological patterns or geomorphological processes. Losses are likely to be significant only if the habitat is rare, or if the site is within an area of national or international importance for biodiversity. However, direct habitat loss compounds effective habitat loss due to displacement. Additionally, it is unclear to what extent improved infrastructure facilitates other economic activities, leading to further habitat loss.

Positive effects. The most important benefits of substituting wind energy for fossil fuels obviously stem from the reduced emission of greenhouse gases. A discussion of the effects of climate change on biodiversity and the extent to which a development of wind energy can help counteracting these effects is beyond the scope of this review. There are, however, also more direct benefits:

- 1 wind farms may act as refuges if no fisheries or hunting are allowed within the wind farm area;
- 1 development of wind farms may relieve other pressures such as military activities, recreation activities or urbanisation;
- 1 offshore wind turbine structures may act as artificial reefs, increasing structural diversity and thus allow an increase of species diversity; this may further provide new feeding opportunities to marine mammals and seabirds;
- 1 changes in land management next to wind turbines, including the interruption of monotonous agriculture, may benefit a number of species, such as birds.

Significance of impacts and cumulative effects

It is essential to assess the significance, in population terms, of possible impacts. Proximate, local effects, such as the death of an individual bat due to collision or the exclusion of 2 000 sea ducks from their preferred feeding ground, must be viewed in a population perspective. For sub-lethal effects an attempt should be made to quantify the impact in terms of reduced fitness or, ultimately, changes in population level, the common currency by which all effects can be compared. This is a highly complex and largely theoretical task that ideally involves quantification of each of the different elements in models such as the one shown in Figure A3.1.

The loss of one or more individuals has very differing consequences for the population depending on its size and species fecundity. Population simulations have shown that significant decreases in the size of bird and bat populations may be caused by relatively small (0.1 %) increases in annual mortality rates, provided they are additive (i.e. are not compensated by reduced mortality from other factors) and are not counteracted by density-dependent increases in reproduction rates (Hötker *et al.*, 2004). In most species, however, a certain level of mortality compensation and density dependence applies. Desholm (2006) suggests the use of an Environmental Vulnerability Index, composed of abundance and a demographic vulnerability indicator, in order to identify the most sensitive bird species.

Cumulative effects may arise when several wind farms are present within an area or along a flyway corridor, or as the result of the combined impacts of wind farms and other types of development. The key question is: At what point do accumulated habitat loss (including effective habitat loss due to exclusion), barrier-effect induced increases in energy costs and collision mortality, acting in concert, impact significantly on population size? Converting the different measurements of potential impact to a common currency, such as changes in birth and mortality rates or population density, becomes even more important when impacts from different anthropogenic or natural factors are to be compared or combined. Addressing the key question remains far from straightforward and it may be most effectively considered at a strategic level, hence the need for Strategic Environmental Assessment (SEA).

Impact of wind farms on selected species groups

Impact on birds

Birds are the biodiversity element most obviously at risk of wind farm mortality and the vast majority of studies dealing with impacts on wildlife have focused on birds. Major reviews have been compiled by Langston and Pullan (2003) and Drewitt and Langston (2006). Although the basic issues are the same, onshore and offshore wind farms are most conveniently dealt with separately.

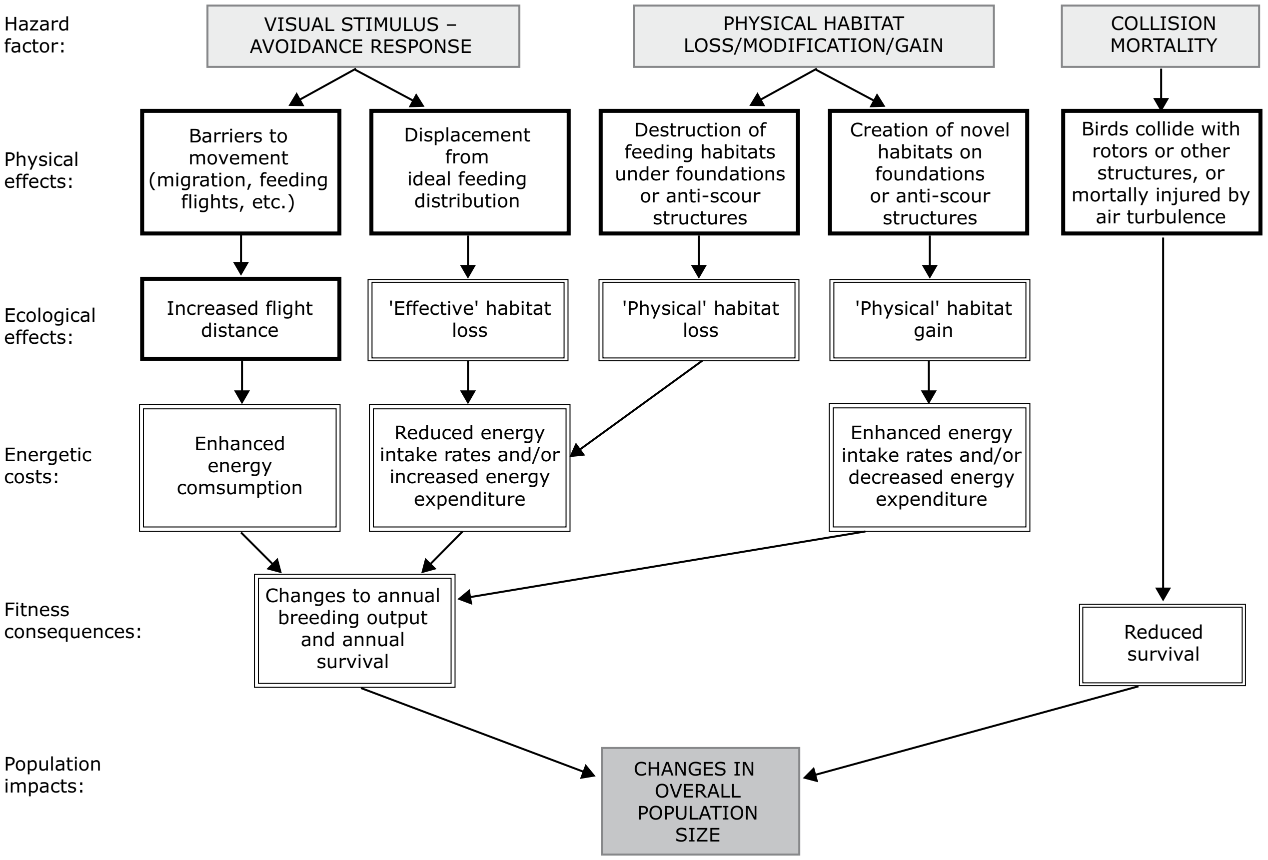
Onshore

From a biological perspective, the history of modern wind turbines is short and only a single study has been sufficiently comprehensive and long-lasting to produce a thorough analysis of population impacts. This is the study of the golden eagle in the Altamont Pass Wind Resource Area in the Coast Range Mountains of California. Here, wind energy development began in the 1970s and when the number of wind turbines peaked in 1993, 7 300 turbines were operational within an area of about 150 km^2. An estimated 35 000–100 000 birds, 1 500–2 300 of them golden eagles, have been killed by collision here during the past two decades (Thelander and Smallwood, 2007). Population modelling has shown that the golden eagle population in the Altamont region is declining and that at least part of this decline is due to wind farm mortality (Hunt, 2002).

Other studies in mountain areas have also revealed high numbers of collision victims, mainly where extensive wind farms have been built in topographical bottlenecks and large numbers of migrating or local birds fly through a relatively confined area, such as a mountain pass, or use rising winds to gain lift over ridges. In Navarra, Spain, a total of 227 dead griffon vultures were found in 13 wind farms in 2000–2002 (Lekuona and Ursúa 2007). At one particularly poorly sited wind farm with 33 turbines, an estimated 8 vultures were killed per turbine per year. Population modelling was not attempted, but the number of fatalities should be compared with a total breeding population of approximately 2 000 pairs in Navarra and 20 000 pairs in Europe as a whole.

The majority of studies of collisions caused by wind turbines have recorded relatively low levels of mortality, perhaps reflecting the fact

Figure A3.1 Major hazard factors for birds that arise from offshore wind farm construction



Note: The flow chart describes the three major hazard factors presented to birds by the construction of offshore wind farms, showing their physical and ecological effects on birds, the energetic costs and fitness consequences of these effects, and their ultimate impacts on the population level. The boxes with a heavy solid frame indicate potentially measurable effects and the double framed boxes indicate processes that need to be modelled.

Source: Desholm, 2006.

that many of the studied wind farms are located away from large concentrations of birds. Carcass searches usually underestimate collision mortality, however, especially for small birds, because corpses are quickly removed by scavengers or may be overlooked. Correction factors should therefore be applied.

A compilation of existing evidence for the German Federal Ministry of Environment (Hötker *et al.*, 2004) showed that at almost half of the wind farms studied, the number of fatalities was less than one bird per turbine per year. At a few wind farms fatality rates of more than 50 birds per turbine were recorded annually. High-risk farms were either placed on mountain ridges, where chiefly raptors were killed, or near wetlands, where gulls were the main victims. The birds killed by turbines (such as eagle and vultures) were mainly those that in disturbance studies seem unaffected by wind turbines whereas birds that are easily disturbed, such as geese and waders, are only rarely killed.

Disturbance effects are variable and are specific to individual species, seasons and sites. Generally speaking, breeding birds seem less affected than feeding or roosting birds, although few studies are conclusive in their findings. Some studies show a tendency for open-nesting waders to be displaced by wind farms while others do not. Waders are often long-lived and site-faithful, implying that their attachment to a location may outweigh any potential response to change. Therefore, the true impact may not be evident until new recruits replace the old birds. For non-breeders, significant negative effects on local populations have been demonstrated in a number of species of, e.g. geese and waders. Several reliable studies indicate negative effects up to 600 m from wind turbines but displacement distances vary between studies and may be much smaller, e.g. 100–200 m in a Danish study of pink-footed geese (Larsen and Madsen, 2000). In a large wind farm, however, even relatively small exclusion areas around individual turbines may amount to a cumulatively significant exclusion area or area of reduced use. Birds may habituate to the presence of a wind farm over time but there is no general evidence of this. Also, crucial information about the consequences of displacement for survival and breeding productivity is lacking.

Migrating, raptors and other diurnal migrants often concentrate along linear features such as coastlines or valleys and at peninsulas and narrow sea passages. Wind farms placed in these migration corridors may present a particular problem because of collision risk and possible barrier effects, and also because birds may lower their flight height at these locations. By contrast, nocturnal migrants, such as most passerines, migrate over a broad front, making them less vulnerable.

Migration flight altitude differs widely between species and further depends on factors such as weather, wind speed and direction, air temperature and humidity, time of day and topography. Most nocturnal migration by passerines takes place well above turbine height but under adverse weather conditions, such as rain, fog or strong winds, when visibility or the birds' ability to control flight manoeuvres is reduced, migration altitudes tend to be much lower, increasing the risk of collision.

Daily movements of waders and ducks between feeding and roosting areas occur in coastal areas, often at night, and flight altitudes on these movements frequently coincide with rotor heights (Dirksen *et al.*, 2007). Wind farms in such areas, e.g. a row of turbines placed along a dike, may intersect these flight corridors, leading to a relatively high risk of collision or disrupting the linkage between areas otherwise unaffected by the wind farm. At Zeebrugge, Belgium, high mortality was recorded among terns that had to cross a line of wind turbines on their foraging trips between nesting and feeding grounds. Depending on the species, collision probability was 0.046–0.118 % for flights at rotor height and 0.005–0.030 % for all flights (Everaert and Stienen, 2006).

Offshore

Information on collision mortality at offshore wind farms is very limited, largely as a consequence of the obvious difficulties of detecting collisions at sea. Improved methods to monitor bird movements and measure collisions and avoidance behaviour are urgently needed. One major technique currently used is radar and thermal imagery, which allows the number of casualties to be modelled from:

- 1 the number of birds passing the area of interest;
- 1 the proportion of birds entering the wind farm area;
- 1 the proportion of birds flying at rotor height;
- 1 the proportion of birds flying within the horizontal reach of rotor-blades;
- 1 avoidance behaviour (at each of the preceding levels);
- 1 the probability of passing through the area swept by the rotor without being hit.

(Desholm, 2006; Desholm *et al.*, 2006).

Such a modelling approach has been applied to the offshore wind farm at Nysted, Denmark, where 72 turbines have been erected in an area that is passed by approximately 240 000 common eiders on their autumn migration. The estimated collision rate for eiders is as low as 0.7 per turbine per autumn because of avoidance movements at all spatial scales. Most eider flocks start to divert their flight paths up to 3 km away in daytime and within 1 km at night, completely avoiding the turbine cluster. Those that enter the wind farm lower their flight height to pass below the rotor blades, fly down the corridors between turbines and tend to minimise the number of rows crossed by taking the shortest route out of the farm. Possible fitness consequences of the extra energy expenditure involved remain unstudied. Collision risks are certainly species-specific and vary between wind farms.

Offshore wind farms are passed by species other than seabirds. Each year, several hundred million birds of roughly 250 species cross the North and Baltic Seas on their journey between the breeding grounds and their winter quarters. Using the above-mentioned techniques, combined with visual and acoustic observations, Hüppop *et al.* (2006) estimated that almost half of the birds crossing the German Bight fly at altitudes that risk collision with wind turbines. Migrating birds are normally able to avoid obstacles even at night but under poor visibility passerine birds in particular are attracted by illuminated offshore obstacles and may collide in large numbers. A wide range of lit structures including lighthouses can bring about this phenomenon on land (California Energy Commission, 1995; Erickson *et al.*, 2001) although sizable mortality will probably be limited to a few nights per year. Modification of the illumination to intermittent rather than continuous light may reduce the risk of collision.

The avoidance behaviour described for sea ducks reduces collision mortality but may also cause a loss of usable habitat if wind farms are placed at important seabird feeding sites in shallow (< 20 m) sea areas. Studies at the Danish wind farms at Tunø Knob and Horns Rev have shown a decrease in the number of eiders and common scoters in the years following construction (Guillemette *et al.*, 1998; Guillemette *et al.*, 1999; Petersen *et al.*, 2006; Petersen and Fox, 2007). Within a few years the number of eiders at Tunø Knob increased again but in 2006, four years after the completion of the wind farm at Horns Rev, common scoters still did not use the wind farm area. In early 2007, wintering scoters began to feed inside the area, indicating that habituation may occur as the birds gain experience. One group of birds, the divers (loons), still avoided the wind farm area. In both studies, changes in the distribution of food resources act as a confounding variable, perhaps at least partly due to the wind turbines affecting hydrology and sediment transport and introducing new, hard substrate on otherwise soft seabed.

Impact on other species groups

Bats

Bat fatalities at wind farms have been known since the early 1960s. Their extent is not well documented, however, despite the fact that bat collisions in some areas may be more frequent than bird collisions. Disturbance and other non-lethal effects are supposed to be of minor importance compared with direct mortality (Brinkmann and Schauer-Weisshahn, 2006). Hötker *et al.* (2004) compiled data from 12 quantitative studies, showing collision rates between 0 and 50 bats per turbine per year (median 1.6). The number of fatalities is probably underestimated as dead bats are even harder to find than birds. Using correction factors for search efficiency and scavenger removal, Brinkmann & Schauer-Weisshahn (2006) estimated a mean of 16.4 bat fatalities per turbine per year at 16 study sites in south-west Germany.

Many different bat species are involved but solitary, tree-roosting species and species travelling over long distances seem to be most at risk. In some of these species a significant impact on populations cannot be excluded (Sterner *et al.*, 2007). Most fatalities occur in late summer and autumn during the period of dispersal and migration. A common assumption has been that bats use echolocation to avoid wind turbines but for energy-saving reasons bats may not use echolocation when travelling over long distances in open areas (Keeley *et al.*, 2001). The highest collision rates were found in wind farms near forest but bat collisions have also been reported from turbines in open areas and even at offshore wind farms. Crevice-dwelling species seem to be less common victims but wind farms should probably not be placed near important hibernacula where large numbers of bats forage before and after hibernation.

Marine animals

Marine mammals (seals and cetaceans) may be affected by offshore wind farms in several ways. During the construction phase, noise and vibration from pile driving and other works may exclude the animals from a large area. The emitted energy from pile driving is most certainly high enough to impair the hearing of porpoises and seals in the surrounding area (OSPAR, 2004). During operation, sound and vibration are still emitted into the water body, potentially disturbing the communication and foraging behaviour of the animals. Harbour porpoises and other cetaceans rely heavily on echolocation for navigation and foraging but the frequencies used are far above those emitted by wind turbines, so disturbance of sonar systems is unlikely. Transmission of electricity through cables within the wind farm and to shore creates artificial electromagnetic fields that may interfere with short- and long-range orientation systems. Such systems may be used by cetaceans and by some fish but disturbance effects could be particularly pronounced in elasmobranchs (sharks and rays) that are highly sensitive to magnetic fields. However, except for a few metres around cables and other devices, field strength is well below that of the earth's geomagnetic field. Studies at the offshore wind farm at Nysted did not reveal any effect of a 132 kV alternating cable on the overall distribution or migration patterns of fish around the cable (EnergiE2, 2004).

Monitoring of seals at the Nysted and Horns Rev wind farms showed that pile driving temporarily expelled animals from the wind farm area (Teilmann *et al.*, 2006b). Later in the construction phase and during operation the abundance of seals in the area was unaffected. Both wind farms are part of much larger areas used by seals and all haul-out sites are at least 4–5 km from the wind farm. Harbour porpoises were monitored in the same areas, mainly by automatic sound detectors. At both wind farms, a substantial but short-lived effect of pile driving was observed. At Horns Rev, a slight decrease in porpoise abundance was found during construction and no effect during operation. At Nysted, a clear decrease was found during construction and operation, and this effect still persisted after two years of operation, albeit with indications of a slow, gradual recovery (Teilmann *et al.*, 2006a).

Other marine species and habitats

The abundance and distribution of seals and porpoises may also be affected by changes in the distribution of their food resource. Evidently, restrictions on fisheries in the wind farm area have a positive effect on populations of fish and several species of benthic animals but fish may also be impacted by the same factors that potentially affect marine mammals. In addition, some fish species are known to be sensitive to low frequency sound (Popper and Carlson, 1998). The major impact of wind turbines on marine biodiversity, however, is probably the reef effect, where the introduction of hard substrate enables new species to settle within the area. This may completely alter the characteristics of local species compositions and as filter-feeders dominate the faunal part of fouling assemblages they can with their high biomass alter the biological structure at a local level and introduce a large secondary production (Petersen and Malm, 2006). Evaluation of this should therefore be an integral part of offshore wind farm environmental impact assessment.

Identification and mapping of sensitive areas

Current evidence suggests that locations with high bird use, especially by species of conservation concern, should generally not be used for wind farm development. Habitats with a high risk of conflicts are wetlands, woodlands, mountain ridges and other areas heavily used by raptors and other large soaring species, zones with dense migration and important sites for sensitive non-breeding birds (the last two categories both onshore and offshore). Conflicts with bats are most likely to arise near woodlands and close to large hibernacula.

In the EU hibernacula for bats shall be designated as SACs if they are of importance for species listed under Annex II of the Habitats Directive (EC, 1992). Offshore, important spawning and breeding grounds and areas near known haul-out sites for seals may also be sensitive, together with areas with uncommon marine communities and habitat types. Many of these sites of potential conflict are protected, e.g. through the Natura 2000 network or as national parks, nature reserves, or core zones of biosphere reserves, while others do not have any strict protection.

Maps showing SPAs, SACs and other protected areas are usually available from authorities at the national and regional scale, and at EU level a geographical information system has been developed for Natura 2000 sites. However, although the implementation of the Habitats and Birds Directives requires designation of marine sites as part of the Natura 2000 network, progress in fulfilling this has been slow and very few offshore marine sites have so far been designated (European Environment Agency, 2007). The marine component of Natura 2000 is due to be completed by Member States in 2010 and, for areas beyond territorial waters where Member States have jurisdiction, a network of marine protected areas has also to be established according to commitments under the Convention on Biological Diversity by 2012. The adoption of the Integrated Maritime Policy (EC, 2007) has given a new impetus to several sea mapping initiatives both regional (e.g. BALANCE for the Baltic Sea) and European, which may eventually support this purpose (i.e. sensitivity mapping). Furthermore, several sites outside this network of protected areas may be equally vulnerable, especially along major bird migration routes and in the marine environment. Some wind development in SACs may on the other hand take place without undermining the conservation objectives at the site (but may still be unacceptable for other reasons, such as landscape or social constraints).

Flyways are not easily defined as they are dynamic and subject to some variation but major bottleneck sites where large numbers of migrant birds concentrate, such as mountain passes or narrow sea-crossings, are usually well known. These areas are often not designated as SPAs but most are included in the network of Important Bird Areas (IBAs) in Europe, i.e. sites of international importance for bird conservation identified on the basis of standard, internationally recognized criteria (Heath and Evans, 2000). Thus, for birds, identification of potential sites of conflict should start from the list of IBAs and Ramsar sites, rather than from the list of SPAs. Maps of IBAs are available through the BirdLife International network.

In most European countries a major gap relates to the marine environment beyond the coastal zone, especially the offshore marine environment where the establishment of a network of Natura 2000 sites is still not advanced. In particular, the designation of areas for small cetaceans and other marine mammals may still be insufficient as most marine SACs have been designated for the presence of reefs and other habitat types rather than for occurrence of particular animal species. For birds, marine IBAs were initially identified and maps produced for the Baltic Sea, the North Sea and the Channel (Durinck *et al.,* 1994; Skov *et al.,* 1995; Skov *et al.,* 2000). A Wind Farm Sensitivity Index quantifying the vulnerability of different areas in relation to seabirds and offshore wind farms has been developed by Garthe and Hüppop (2004), who applied their index to the German sector of the North Sea.

Such maps of protected areas and other vulnerable sites may be combined with maps of wind energy potential to allow a first identification of suitable sites for wind development and areas where conflicts are likely to arise. It should be emphasized that development of wind farms in Natura 2000 areas is not prohibited by the Birds or Habitats Directives, provided that the development takes conservation values into consideration. Member States may, however, introduce stricter measures under these Directives, and in several countries wind farms are in practice excluded from Natura 2000 and other designated areas.

As part of the implementation of the Birds Directive, Denmark originally designated 111 SPAs in 1983. Most of the SPAs are situated on land but the designation also included several coastal areas. No marine areas were included primarily because no knowledge existed of important bird areas offshore. In connection with plans to develop offshore wind farms in Danish waters in the 1990s, several surveys were carried out with the purpose of identifying whether offshore areas sensitive to biodiversity (with focus on seabirds) had been overlooked in Danish waters. These studies, which used airplanes to survey the areas, led to the discovery of several very important offshore wintering areas for sea ducks. Several marine SPAs and SACs were subsequently designated. In practical terms, Denmark's SPAs and SACs correspond to 'zones where wind farm development is incompatible with biodiversity priorities'.

Mitigation and compensation measures

Proper siting of wind farms, as described in the previous sections, will always be the most efficient way of avoiding adverse impacts on biodiversity. If negative effects cannot be avoided, suitable mitigation measures should be employed to reduce or remedy them. Adverse impacts that cannot be mitigated require compensation if the project proceeds.

Mitigation measures

Mitigation measures may be separated into general (best practice) measures and more site-specific measures. However, the two categories overlap and implementation of mitigation measures should always be based on a site-specific environmental impact assessment (EIA). The following overview of possible measures is not exhaustive.

Wind farm configuration. The most suitable configuration will depend on the specific problems identified at each site and will always be a compromise between technical and environmental considerations. Generally, aligning turbines perpendicular to the main flight direction of birds should be avoided. Depending on the location, turbines should be placed as close together as technically feasible to minimise the overall footprint.

Alternatively, flight corridors of sufficient width (aligned with main flight trajectories) between turbines or clusters of turbines may be provided.

Design of turbines and associated structures. Towers and nacelles should be designed to avoid providing resting places for birds and bats. Transmission cables should be installed underground wherever possible. At sites where the collision risk is high, visibility of rotor blades may be increased by the use of, e.g., high contrast patterns, although this may sometimes be unacceptable on landscape grounds. Illumination should be reduced to a minimum, using intermittent rather than continuous lighting but future research may bring to light more precise recommendations with respect to colour and frequency. For offshore wind farms, underwater surfaces and scour protection material that minimise settlement of organisms should be used at sites where reef effects are unwanted.

Minimising disturbance. Construction works should be carefully timed to avoid sensitive periods such as reproduction or moulting periods. The exact time periods depend on the species potentially affected. Appropriate working practices should be implemented to protect sensitive habitats and species. For example, pile driving should start gently to allow porpoises to move away from the source of noise. During operation, disturbance may be minimised by careful timing and routing of maintenance trips.

Temporary shutdown. It has been suggested that turbines should be turned off at critical times of year, such as during nights with high migration activity (Hüppop *et al.*, 2006). The benefits for birds may be questionable, however, because birds also collide with stationary structures and the removal of auditory cues may increase the risk of collision (Langston and Pullan, 2003). Benefits for bats are more certain because bats apparently do not collide with stationary rotors (Kerns *et al.*, 2005).

Habitat management plans may reduce or prevent deleterious habitat changes and provide habitat enhancements if appropriate. However, enhancement of habitat within the wind farm may require further associated measures to avoid increasing the risk of collision if, for instance, densities of suitable prey organisms are increased. Mitigation measures aiming at deterring birds from utilising a wind farm area should only be used if the need for preventing collisions outdoes any displacement or barrier effects.

Whichever mitigation measures are used, a post-development monitoring programme should be implemented to determine their effectiveness.

Compensation

Compensation should be a last resort and should only be considered if mitigation measures will not reduce adverse impacts to an acceptable level. Compensation shall offset any significant loss or damage to habitats or species. It may, however, be difficult to achieve, e.g. compensation for loss of marine habitats. Compensation for habitat loss shall offer comparable habitat in the vicinity of the development, taking into account that collision risk shall not be increased. Everaert and Stienen (2006) describe an example of a misplaced compensation habitat. Compensation for collision mortality may involve the development of species management plans to increase the populations elsewhere with the aim of (more than) offsetting increased mortality due to collisions. If Natura 2000 areas are affected, compensation measures must ensure that the overall coherence of the Natura 2000 network is protected. As for mitigation, the effectiveness of compensation measures should be checked by a monitoring programme.

Conclusions

As a climate change mitigation measure wind energy in general represents a positive global and long-term contribution to preserve biodiversity, also in a more local, short-term context wind development may benefit biodiversity if no hunting or fisheries are allowed within a wind farm and may relieve pressures on the flora and fauna from recreation activities and urbanisation. There are, however, concerns about possible negative impacts on wildlife, in particular regarding birds, bats and marine mammals because of collision mortality, loss of habitat and disturbance. Further wind development is likely to increase the number of conflicts, unless due attention is paid to possible biodiversity constraints throughout the planning process.

Birds are the biodiversity element most obviously at risk due to wind farm development and correspondingly most studies have focused on them. However, as the history of modern wind turbines is short only a few long-lasting studies have been carried out. Most studies indicate low frequency of bird strikes at onshore and offshore wind farms but there are notable exceptions. Wind farms on mountain ridges and other area frequented by large birds of prey (in particular eagles and vultures) may lead to unsustainable levels of collision mortality. Wetlands, coastal areas and migration hot-spots are other areas where high collision mortality has been recorded. The significance of disturbance and loss of habitat is an open question, as is the extent to which birds habituate to the presence of wind turbines.

Bat fatalities are less well documented but collision mortality rates may be sizable near forests and in areas with large hibernacula and a significant impact on bat populations cannot be excluded.

Marine mammals are displaced during construction works but according to existing evidence gradually reoccupy the wind farm area afterwards. The major impact on marine biodiversity probably stems from the introduction of hard substrate on otherwise soft seabed (reef effect) which enables new species to settle within the area.

Strategic Environmental Assessments (SEAs) that include sensitivity mapping at regional or national level can identify no-go areas, areas where conflicts may occur and areas where wind development is unlikely to conflict with biodiversity conservation.

Social aspects

Social acceptability is a key aspect to be considered in addressing the potential for deployment of wind energy.

This considers the visual, noise and other impacts on public acceptance of wind power.

Visual impact

The visual impact of wind turbines on the landscape is one of the most important elements that incites opposition to wind power. The visual impact refers to the effect of siting wind turbines on the visual or aesthetic properties of the surroundings (EWEA, 2004). As dominant structures in the landscape, wind turbines often create negative attitudes towards land-based wind power. Some landscapes, especially industrialised areas, may be better able to accommodate such visual impacts, because wind turbines are less prominent when placed among other large structures.

For offshore wind parks, visual aspects could also play an important role, since wind turbines appear in an otherwise structureless landscape (Henderson *et al.*, 2001). However, the visual impact of offshore wind farms can generally be mitigated more easily than onshore by siting the wind farms further away from the shore or coastal area. The visual impact to viewers at sea level is assumed to be negligible for farms at a distance of about 8 km from the coast (University of Newcastle, 2002). The curvature of the earth means that wind farms at a distance of more than 45 km are not visible at all.

The market trend of wind power emphasises bigger turbines and larger projects, with increasing dominance in the landscape (EWEA, 2004). Opinions about these large modern wind turbines is not per definition negative since more spacing between the individual turbines and lower rotational speeds of the blades are perceived by viewers to be calmer than more numerous smaller turbines.

In general, public acceptance increases when turbines of all sizes are sited with due consideration of the landscape. In general, the siting of wind turbines on land can be harmonised with the surroundings by connecting the siting of the turbines to existing elements in the landscape. Simple geometrical patterns often work well in flat areas, because these are easily perceived by the viewer. In mountainous areas, however, it is more feasible to site wind turbines in such way that the contours of the landscape are followed (DWIA, 2009).

There is no one optimal solution in terms of formation, number and size for the siting of wind turbines. In fact, the siting of wind turbines must be done in a very careful way for each individual project. Wind-power siting studies, which are done for all new wind power projects, address the issue of the siting of wind turbines and can offer advice on preferred locations. National and local governments have an important role here in developing a vision on how new wind turbines can best be fitted into the landscape. Some countries, like Ireland, have developed planning guidelines that provide support to the different parties involved in wind power development.

Noise

There are generally two sources of noise during the operation of a wind turbine: mechanical sounds from the interaction of turbine components; and aerodynamic sounds, produced by the flow of air over the blades (BWEA, 2000). The mechanical noise of wind turbines can be described as a 'hum' or 'whine' at a steady pitch. Depending on the wind turbine model and wind speed, the aerodynamic noise can be described as a buzzing, whooshing, pulsing and even sizzling (Alberts, 2006). Turbines that are placed downwind are known to cause a thumping sound when blades pass the tower. For modern large wind turbines, the blade passes the tower at a frequency of once every second.

Table A3.1 Comparative noise levels from different sources

Source/activity	Indicative noise level (dBA)
Threshold of pain	140
Jet aircraft at 250 m	105
Pneumatic drill at 7 m	95
Truck at 48 kph at 100 m	65
Busy general office	60
Car at 64 kph at 100 m	55
Wind farm at 350 m	35–45
Quiet bedroom	35
Rural night-time background	30–40

Source: Sustainable Development Commission, 2005.

It is a difficult task to define how noisy wind turbines are. Background noise levels are an important factor in defining whether the sound power level from wind turbines is perceived as 'noise'. In rural or low-density areas sounds from wind turbines become annoying at lower sound power levels because of lower background noise than in urban areas. Since wind turbines are located at sites where wind speeds are high, the background noise levels produced by the wind sometimes mask the sound produced by the wind turbine (AWEA, 2007). When the wind falls, often during the night, noise from wind turbines can become more prominent. In some circumstances, for example when people are sheltered from the wind, wind turbine sounds can be heard.

The reported sound power level from a single wind turbine is usually between 90 and 100 dB(A). At a distance of 40 m from the turbine this is 50–60 dB(A), which is the same noise level as having a conversation. At a distance of 500 m downwind the equivalent sound pressure level would be 25–35 dB(A). In general, at a distance of 300 to 400 metres from a wind turbine in a normal landscape, no sound (produced by the turbine) can be heard. Table A3.1 lists comparative noise levels from different sources.

Although noise problems from wind turbines can be solved by ensuring a large enough distance between the wind turbine and residents, there have been reported complaints over the years. It appears that the worst noise problems occur at night when there is a combination of little wind at ground level and low background noise levels but enough wind at hub height for the turbines to operate. Under these specific circumstances wind turbine noise can be distinctively heard. A well-documented Dutch case shows that a distance of 300–400 metres from wind turbines will not be enough to ensure sound levels below the threshold of what is being perceived as 'noise'. The combination of low background noise and high wind speeds at hub height made the wind park audible at distances of 500–1 000 m (van den Berg, 2003). Past experience indicates that noise problems depend on a number of local factors that can change over time.

The most common method for dealing with potential noise is to require a minimum distance between wind turbines and the nearest residence; this distance should be sufficient to reduce the sound level to a regulatory threshold. In Denmark, the maximum sound level at residences (outside) is set at 42–44 dB (DWIA, 2007). In the Netherlands, wind farms up to 15 MW have to comply with environmental regulations that give threshold values for sound levels. The threshold values range from 40 dB(A) for rural areas to 50 dB(A) for urban areas. At night the established threshold values are lower and range from 30 to 45 dB(A).

After extensive measurements, however, van den Berg (2003) discovered that the methods used by wind turbine developers at that time could underestimate wind speeds at hub height. As a direct consequence noise levels might also be underestimated. Especially for low wind speeds up to 4 m/s the wind speed at hub height can be 2.6 times higher than expected on the basis of logarithmic wind profiles. Accordingly, residents had been experiencing sound levels that were 15 dB higher than expected.

In conclusion, noise can be a source of decreased amenities in an area and a potentially significant source of negative public reactions to wind farm development. Ways to reduce the likelihood of noise problems from wind projects include noise analyses.

These types of studies are carried out taking into account the characteristics of the wind turbines and the site where the project is planned. On the basis of such studies the distance required to other objects can be defined.

Other concerns

Besides the noise and visual impacts of wind turbines, there may be other concerns that influence public opinion on wind farm development:

- 1 Wind turbines can cast shadows on the ground or reflect sunlight from the turbine blades. Residents living nearby may perceive the resulting shadows and flickering to be annoying. Careful planning of the wind turbine site can avoid these problems effectively. Currently, however, planning authorities have not set explicit rules for avoiding these impacts.
- 1 Concerns regarding the amount of land needed for wind farms may be overstated. An entire wind farm including towers, substation and access roads occupies only about 5 % of the allotted land (CWEA, 2007). Wind turbines themselves occupy only 1 % of the land area. EWEA estimates that only a few hundred square kilometres are needed to build 150 GW of wind power on the European mainland by 2030. In most cases the original activities (e.g. agricultural) on the land where a wind farm is built can continue.
- 1 The negative impact of wind turbines on residential property values is often put forward. Very recent research includes an investigation done by the Royal Institute of Chartered Surveyors (RICS) and Oxford Brooks University into the relationship between the proximity to wind farms and transaction prices. They found no change in property prices more than one mile (1.6 km) from the wind farms. Within a distance of one mile the negative impact on prices seems to be most noticeable for terraced and semi-detached houses (RICS, 2007). In a previous RICS study, carried out in 2004, 60 % of the respondents with experience in house transactions suggested that proximate wind farms would decrease the property values if the turbines were in view (RICS, 2007).

Conclusions

Social acceptance of wind projects often relates to the visual impact of wind turbines on the landscape, both for wind turbines on land and offshore. Landscape architecture can overcome many of the visual impacts. Furthermore, local resistance can be lowered by local ownership structures, which give residents direct benefits from wind power.

Besides the visual impact of wind turbines, noise might also be a reason for low social acceptance of wind energy projects. This barrier can be overcome effectively by careful siting of wind turbines and considering minimum distances to nearby residents. Noise analysis allows wind turbines' effect on the sound level to be determined.

Annex 4 An algorithm for estimating sub-scale effects in ECMWF reanalysis

Introduction

In this report large-scale datasets for elevation, land use (from which the aerodynamic roughness is derived) and wind speed are used to quantify the possibilities for wind energy. The wind speed dataset used has a resolution of 0.25 degrees x 0.25 degrees.

Preliminary result showed that, when the value derived from the full wind power analysis (ECMWF wind speed plus roughness upscaling to hub height plus power curve = number of full load hours) falls below the economic minimum necessary for turbine erection, the whole grid cell is discarded. This led to a situation where for example Spain had lower potential than the already installed capacity.

Thus, excluding grid cells based on just one value is not realistic. There will always be some areas where local effects increase the wind resource sufficiently to sustain a wind farm economically. Those effects are predominantly orographic, i.e. speed-up on hilltops. A simple tool to calculate those speed-up effects is the WAsP (21) programme by Risø DTU, essentially operationalising a linear flow model to account for speed-up effects and other atmospheric effects. However, to calculate the whole grid in 50 m resolution with a full blown wind resource model is not realistic. Even at 250 m resolution on a modern personal computer, WAsP requires about 20 minutes to calculate a grid cell. With over 38 000 grid cells in the area in question, this was not possible in the time available.

Methodology

The variation in wind power within a grid cell due to varied elevation is parameterised. Using an Excel spreadsheet with all grid point IDs and some sub-scale orography measures like minimum, maximum, range, mean, median and standard deviation of elevation, 8 sites with reasonably different characteristics to tune the algorithm given below are chosen. The WAsP orographic flow model is used to calculate a few selected grid cells. The elevation came from the United States Geological Survey Shuttle Radar Topography Mission version 2 dataset, with 90 m resolution in the horizontal. The roughness needed for WAsP to calculate is set to a uniform 3 cm roughness, typical for 'wind power country', i.e. areas where wind turbines would usually be erected — wide open spaces with little to disturb the flow, often farmland. Eight different standard deviation and range values were chosen for the analysis. Areas predominantly in Western Europe were considered as this enabled comparison with the results contained in the European Wind Atlas, which was done for EU-15 Member States in the 1980s. However, the analysis is later done with the standard wind climate of WAsP to make the results fully comparable.

The eight sites are:

- 1 very flat terrain in the Saone Valley, France;
- 1 a site in central Portugal with a higher range than the Saone Valley but a similar mean;

Table A4.1 Locations of reference points

PointID	Long.	Lat.	ISO	Label	Min.	Max.	Range	Mean	STD	Median	FWHM (a)
26360	5.00	46.75	FR	Saone	171	215	44	191.9	11.8	190	40
23242	5.50	49.75	BE	BE	260	503	243	391.8	51.2	393	166
33874	– 1.50	39.50	ES	ES	421	999	578	7 16.0	120.3	712	205
33585	– 8.75	39.75	PT	PT	3	458	455	178.4	93.9	167	225
35334	38.50	38.25	TR	Eden	775	2 419	1 644	1 511.6	374.4	1 581	448
25623	15.75	47.50	AT	AT	575	1 775	1 200	1 003.7	217.2	970	730
32117	14.25	41.25	IT	Molise	13	869	856	196.0	162.4	132	910
26646	11.50	46.50	IT	Dolomites	306	2 635	2329	1 327.2	458.4	1 303	1 065

Note: (a) 'FWHM' is the Full Width Half Maximum of the visually estimated Gaussian distributions.

Source: Risø, 2008.

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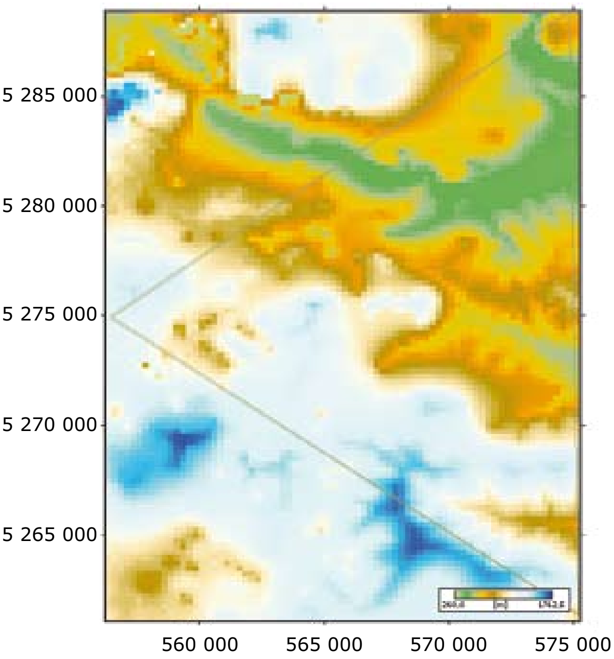
(21) Details about the WAsP programme can be found at the website: www.wasp.dk

- 1 some medium-complexity terrain sites at different altitudes in Belgium, near the border to Luxembourg;
- 1 south-eastern Turkey;
- 1 Molise, Italy;
- 1 near Valencia, Spain;
- 1 a pre-alpine site near Wiener Neustadt, Austria;
- 1 a very complex site in the Dolomites, Italy.

The first step in the process was to construct a map of each location. The images below are from the medium-complexity site in Austria. The Shuttle Radar Topography Mission (SRTM) data are downloaded from NASA, cut to size, converted to a WAsP map and a single roughness line with 3 cm roughness on both sides is added.

Figure A4.1 **Height distribution of Austria cell**



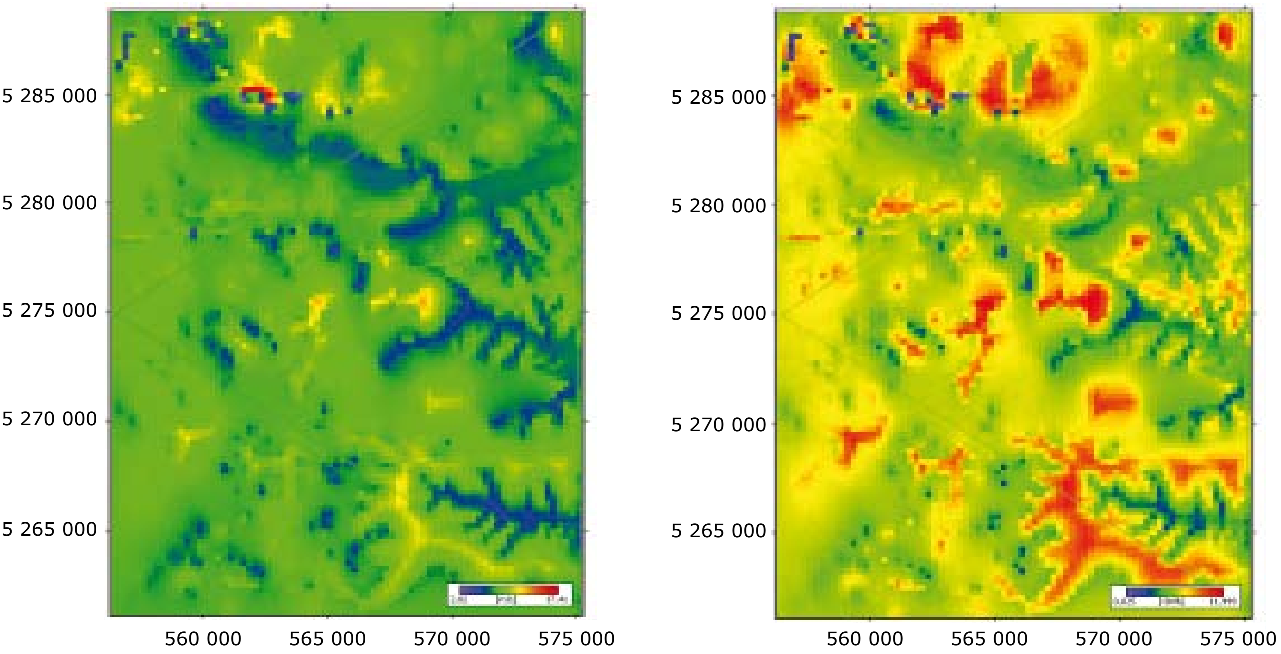
Source: Risø, 2008.

One can see that the range of annual energy production (AEPs) (divide by two to get full load hours, as the turbine used was a Vestas 2 MW with 80 m hub height) is quite large within the grid cell. This means that there would be many potential sites to choose for a wind power developer, even if the ECMWF wind speed was not very favourable.

In the next step, the data is imported again in SAGA GIS (System for Automated Geoscientific Analyses), and histograms are plotted. Finally, the Full Width Half Maximum is estimated from the plots, and converted into a FWHM of full load hours. The result is presented as a function of the standard deviation of variation in height in Figure A4.3.

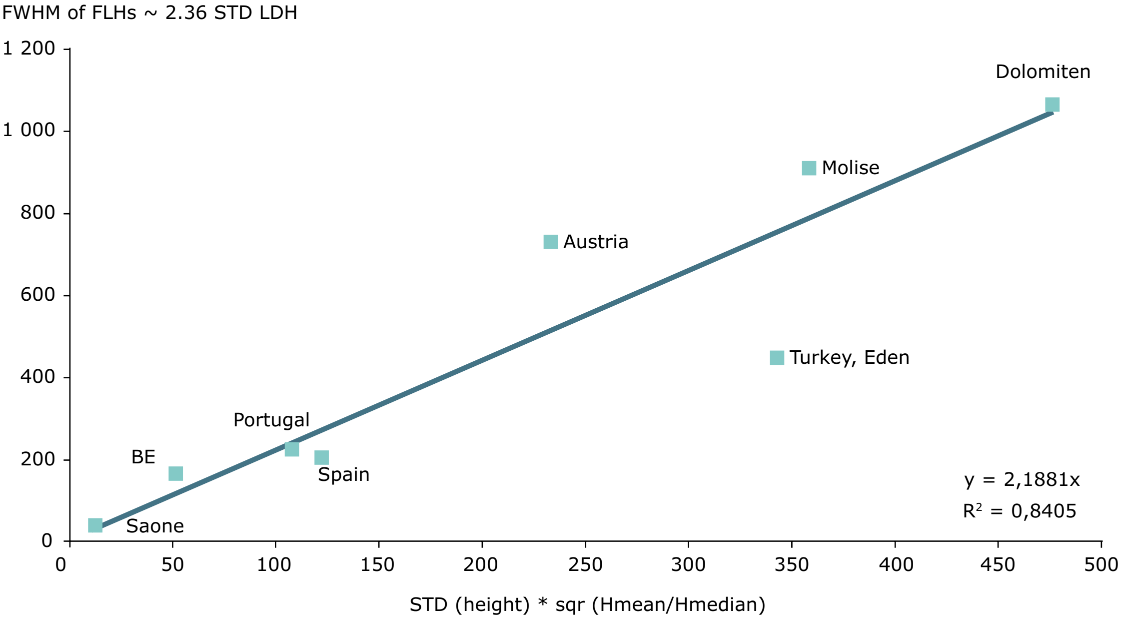
There is a reasonable trend line in the plot. However, some points are clearly far off,

Figure A4.2 **Distribution of wind velocity (left) and annual energy distribution (right)**



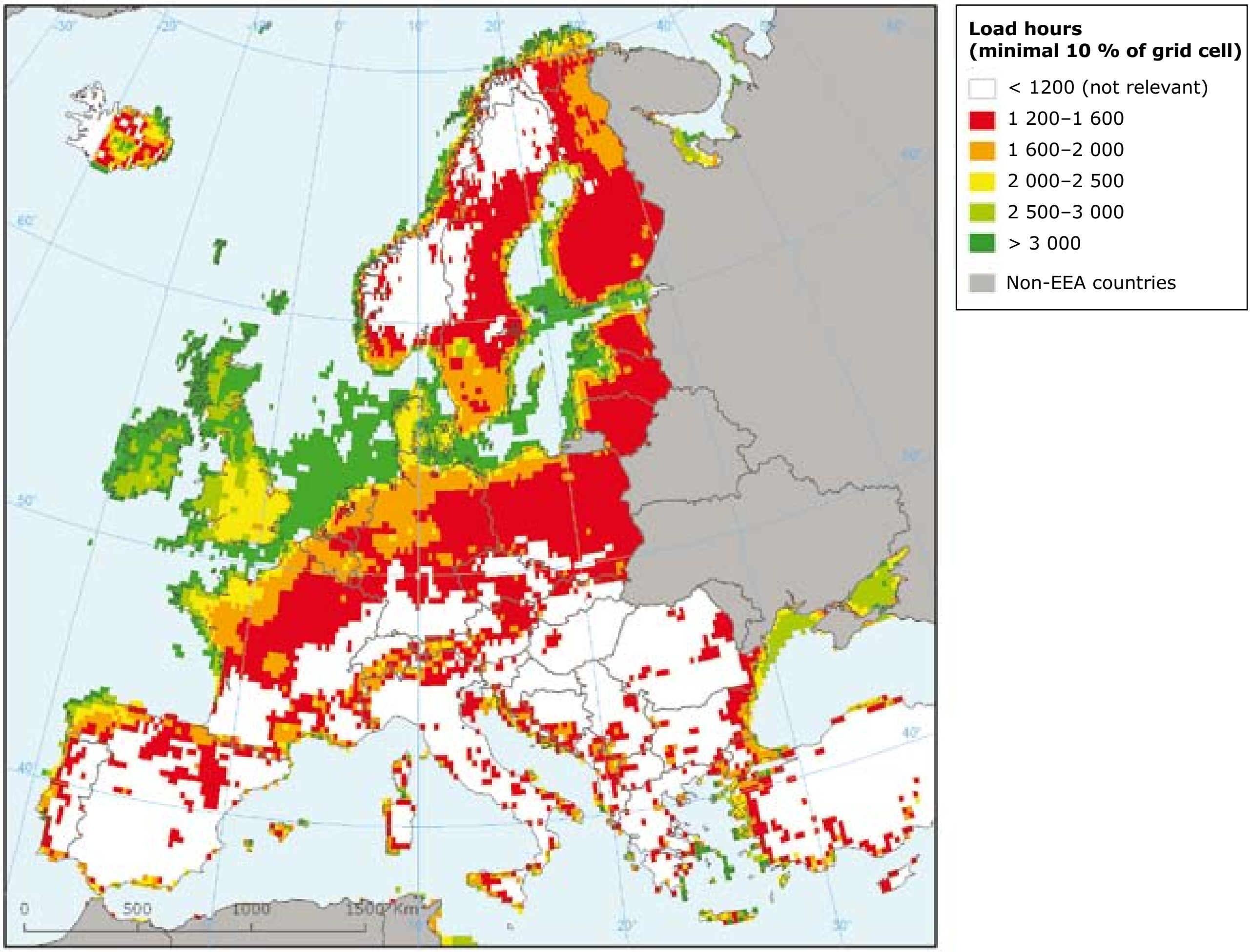
Source: Risø, 2008.

Figure A4.3 **Variation in FWHM of full load hours as function of standard deviation of variation in height**



Source: Risø, 2008.

Map A4.1 **Distribution of full load hours in Europe for the ninetieth percentile (at least 10 % of the sub grids has the minimal indicated load hour)**



especially Austria (at FWHM 730) and Turkey (at FWHM 420). Looking through the histograms of elevations, one can see that those are grid cells with quite non-Gaussian/non-lognormal distributions of elevations. Standard deviations are therefore less applicable, which leads to inconclusive results.

To account somewhat for non-Gaussian distributions, the term containing the ratio between the mean elevation and the median elevation is introduced into the formula below. The idea behind this is that a large deviation between mean and median value indicates a non-Gaussian distribution of elevations within the grid cell. As most grid cells are at the low end of standard deviations, more emphasis is given to those. The trend line captures the variation reasonably well. Nevertheless, the analysis should be done with more points in order to reach more reliable results.

The algorithm proposed is as follows:

- 1 calculate the number of full load hours in the usual fashion all over the map of Europe (i.e. use the result already available);
- 1 to account for sub-scale variation, use the full load hours results as the centre for a Gaussian distribution of full load hours;
- 1 parameterise the width of the distribution from the elevation standard deviation as:
  $$\sigma_{FLH} = {}^{2,19}\!/_{2,36} * STD * \left({}^{Hmean}\!/_{Hmedian} \right)^2$$
- 1 to get to the full amount of installable wind power, calculate the distribution of full load hours based on the above formula; the cumulative sum of all classes over all grid cells for a certain country delivers the full load hour distribution for that country;

Map A4.1 depicts areas in which at least 10 % of sub grids have the minimal indicated load hours.

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