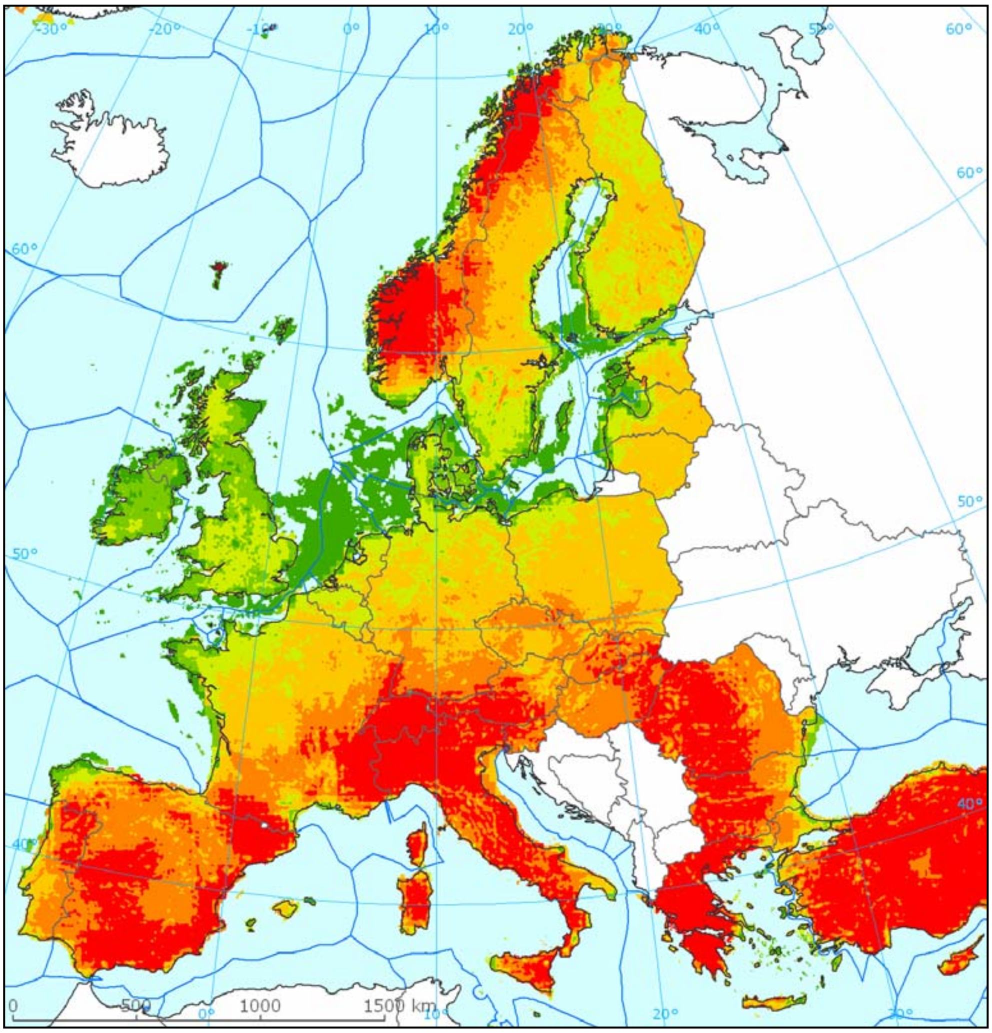
Wind-energy potential in Europe 2020-2030



ETC/ACC Technical Paper 2008/6
December 2008

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European Topic Centre
on Air and Climate Change

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Front page picture:
The combined annual average (2000-2005) wind speed at 80m (onshore) and 120 m (offshore). (Figure 2.5 of this paper.)

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Executive Summary

The exploitation of renewable energy sources can help the European Union achieve many of its environmental and energy policy targets, including its obligation to reduce greenhouse gases, with the aim of increasing the use of renewable energy and reducing energy import dependency. The share of renewables in the total European energy consumption would have to grow from 6 % in 2003 to 12 % by 2010 and 20 % by 2020.

This paper addresses the potential for wind energy in Europe in the future, with a time horizon up to 2030. Indicative quantitative estimates of the technical and economic potential, both on shore and offshore, are presented geographically, taking into account climatologic, technical, and economic criteria. How environmental and social factors further impose constraints on the actual potential is discussed in a qualitative way and estimates of their constraining effect are presented based on the current practice of forerunner member states.

This study forms part of the EEA's renewable energy programme, which aims to evaluate how much renewable energy can technically be made available for energy production in Europe in an environmentally sound manner. It represents a follow-up to the 2006 report 'How much bio-energy can Europe produce without harming the environment?'. The results of this study can be used as benchmark for the evaluation of the potential role of wind energy at European scale. They can also be used in further modelling studies and indicate areas where more detailed analysis would be useful. This study is not meant to replace in any way assessments made at regional, national or local scale, which usually determine wind energy potential as a function of market growth and technological development. The method used can be regarded as a 'top-down' approach, using Europe-wide data on meteorology, land cover, sea depth, and wind turbine technology and their costs. To put the top-down approach into perspective, the method was calibrated against real-world data for countries for which they are available, and the potentials are compared with the actual wind power installed in frontrunner countries (evaluation of feasible penetration levels).

As is well-known from various national studies, the technical potential of wind energy is very high, especially if the current trends in learning and cost reductions with every doubling of wind energy capacity continue. This study is the first to explore this potential at the European scale in a geographically explicit manner, using one consistent methodology. If building of wind turbines would be allowed at high power density wherever the wind speed is adequate, the technical potential by 2020 could be as much as 50,000 TWh onshore and 25,000 TWh offshore - enough to cover the anticipated electricity demand in Europe 15 times by that time. But also taking into account economic feasibility, the economic potential could deliver more than 8 times Europe's anticipated electricity by 2030, at a cost below 6.7 eurocent per kWh, The market potential, however is significant lower due to social, institutional or environmental constraints, not taken into account in the estimate for the economic potential. Such constraints further decrease the actual market potential significantly from the technical and economic potential, in a way that is regionally different across Europe. While it is very difficult to quantify these important constraints, it is also important to note that these constraints can be influenced by policy action.

Particularly on land in countries in which the share of wind power is high, environmental and social constraints limit the acceptable wind power density. The average fraction of land endowed with average wind speeds above 4m/s that is currently used in Denmark (0.9 %), the Netherlands (0.6 %) and Germany (4.7 %) is 2.1%, which could be considered as the current feasible penetration level given existing policy frameworks. If this power density could be realised Europe-wide, it would translate into 1200 TWh, enough to cover a very significant 27% of Europe's electricity consumption by 2020 and 25% by 2030 by onshore wind energy alone. However, even within those three countries there are communities or regions with much higher wind power densities, which could revise the result significantly upwards.

Because of high wind velocities and higher acceptable power densities, offshore wind presents the greatest opportunity. Taking into account the actual situation in Denmark, the Netherlands and Germany as influenced by social, environmental and technical constraints, this study suggest that the exploitable fraction of the suitable area less than 10 km and more than 50 km from the shore is limited to 4 %. Between 10 and 50 km, this number could be about 10 % of the total suitable offshore area.

Even if only these restricted offshore areas could be exploited at the technical power density of 10-15 MW turbine per km^2, offshore wind could generate 3000 TWh, enough to cover 60 % of Europe's electricity consumption by 2030.

The figures presented above indicate that wind energy technology has a large practical and economic potential to reduce Europe's greenhouse gas and air pollution emissions, and improve the security of energy supply. The potential is highest in the countries around the Atlantic, North and Baltic Seas. The high numbers also indicate that particularly in those areas there is a significant level of choice for siting wind farms in those areas where they would have the least, if not positive, environmental and social impacts. The introduction of a North Sea electricity grid is also investigated. Above an accumulated installed capacity of 15 GW the benefits of an electricity grid start to emerge. At an accumulated capacity of 40GW an electricity grid could reach a share of 5% which would increase to 20% at 65 GW installed capacity. At 65 GW and above an electricity grid financed by governments (assuming a 4% social discount rate) would be beneficial compared to direct connection to the coast.

Overall, wind energy development is beneficial to the environment because of its low emissions and natural resource requirements. It could also be beneficial to biodiversity at the local level when such areas are closed for alternative activities. However, poorly sited wind farms can also have a significant negative impact on certain species, in particular, birds and bats. Proper siting of wind farms is the key to avoiding or minimizing adverse biodiversity effects. Strategic Environmental Assessments (SEAs), which include sensitivity mapping at regional or national level, can be used to identify no-go areas, areas where conflicts may occur and areas where wind development is unlikely to conflict with biodiversity protection. Maps showing Natura 2000 and other protected areas provide a starting point, but not all designated areas are equally sensitive. Besides, some unprotected areas, such as bottleneck sites for bird migration and marine areas, are more vulnerable than many designated sites. The Environmental Impact Assessment (EIA) of projects is a very useful tool to minimise the negative impacts of wind farms on wildlife and biodiversity at the project level. Whenever adverse effects of a proposal for wind development cannot be ruled out, an EIA has to be used to evaluate the significance of the impact, and consider different project options to minimise negative impacts. Our analysis suggests that biodiversity constraints on the development of wind energy are not dominant. Even if all Natura2000 or Designated Natural Areas were to be excluded from wind development, the pan-European wind-energy potential would only be reduced by approximately 14%.

Social constraints dominate the actual development of wind energy; if included only 2-4 % of the available technical potential on land can probably be used under the current attitudes and policies. The willingness of the citizens of a number of European countries to pay a higher price for electricity from offshore wind farms that are remote and out of sight, indicates that the potential for further onshore expansion is approaching feasible penetration in these countries. The lessons learned from advanced wind-energy countries such as Denmark, Germany and the Netherlands can be very useful: notwithstanding the general positive attitude of the public towards wind energy, people do react to excessive visual intrusion of wind turbines in the landscape and can react strongly to noise (or shadow/ reflection flickering) caused by wind turbines. Landscape architecture and the involvement of nearby communities at all stages of planning, construction and operation of wind farms, including the financial participation of local citizens and co-operative financing, can avoid a lot of problems.

Many factors affect the wind energy potential, leading to considerable uncertainties in our estimates. These factors include natural factors, technological and economic factors, and factors dependent on human choices. The variation (hourly, daily, monthly and yearly) of wind energy potential is significant - with important implications for wind energy integration into the electricity system. Current understanding could be further improved on the short term by extended evaluation of current penetration levels in frontrunner countries, additional model analysis to determine the potential for different policy scenarios, sensitivity analysis for key economic and technological assumptions, more detailed analysis for areas for which model and observed wind velocities agree the least, and exploration of a zoning approach to account for biodiversity constraints. Research questions that require greater efforts include cross-country trend analysis of social constraints in EEA member states, inventory and analysis of policy-driven wind energy success stories in Europe and beyond, and further analysis of specific vulnerabilities for biodiversity with regard to specific species and landscapes. The spatially explicit analysis of this report can guide the selection of interesting areas for additional regional studies, such as the Baltic.

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Acknowledgements

Eva Royo Gelabert, Rania Spyropoulou, Pavel Stastny, Ayla Usly and Ioannis Economides Project Managers at the EEA for their extensive comments and suggestions during the drafting of this technical report. Andre Jol, Head of the Climate Change and Energy group at the EEA and other colleagues at the EEA and the ETC ACC for their contribution of useful ideas and support during this project. During the project a great number of people has contributed to this report, without being complete we want to thank Hans Eerens (overall co-ordination), Chris Coppens (chapter 2, annex 2), Rob Swart (chapter 1), Peter de Smet (chapter 2) , Joost-jan Schrander (chapter 7), Paul Ruyssenaars (chapter 7), Hugo Gordijn (annex IV) and Maarten Piek (annex IV, all PBL); Erika de Visser (chapter 2-6), Monique Hoogwijk (chapter 2 and 5) and Marios Papalexandrou (chapter 5, all Ecofys); Pavel Kurfürst and Jan Horalek (all CHMI), Bo Svenning Petersen, Flemming Pagh Jensen (chapter 8, all Orbicon), Michael Harfoot (chapter 4, AEA-T), Roger Milego (chapter 2, UAB), Gregor Giebel and Niels-erik.Clausen (annex 3 and for their useful comments, all Risoe). Maps in this report have been produced by Pavel Kurfust of the Czech Hydrometeorological Institute (Český hydrometeorologický ústav).

Hans Eerens Task Manager Renewable energy

Abbreviations

ACCOBAMS	Agreement on the Conservation of Cetaceans in the Black Sea,
AEWA	African Eurasian Waterbird Agreement
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas
AWEA	American Wind Energy Association
CDDA	Common Database on Designated Areas
CLC	Corine Land Cover
Corine	Coordination of Information on the Environment
CWEA	Canadian Wind Energy Association
dB	Decibel
DOALOS	Division for Ocean Affairs and the Law of the Sea
ECMWF	European Centre for Medium-range Weather Forecasts
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EWEA	European Wind Energy Association
GIS	Geographic Information System
GWEC	Global Wind Energy Council
HELCOM	The Helsinki Commission
IBA	Important Bird Area
IPCC	Intergovernmental Panel on Climate Change
MARS	Meteorological Archival and Retrieval System
	Mediterranean Sea and contiguous Atlantic area
MSD	Marine Strategy Directive
NCDC	National Climatic Data Centre
NOOA	Oceanic and Atmospheric Administration (USA)
O&M	Operation & Maintenance
OPTRES	European project entitled 'Assessment and optimisation of renewable support schemes in the European electricity market'
OSPAR	Oslo and Paris Convention
PR	Progress ratio
RICS	Royal Institute of Chartered Surveyors
SAC	Special Areas of Conservation
SEA	Strategic Environmental Assessment
SPA	Special Protected Areas
TGC	Tradable Green Certificates
UCTE	Union for the Co-ordination of Transmission of Electricity
WFD	Water Framework Directive

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1 Discussion and conclusions

1.1 Context

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 (Council Decision 2002/358/EC) and the aim of securing energy supply (COM(2002) 321 final and European Commission, 2005[1]). As early as 1997, the European Union set an ambitious 2010 indicative objective of 12% for the contribution of renewable sources of energy to the European Union's gross inland energy consumption by 2010 for its then 15 member states (EC, 1997). In 2001, the EU adopted a directive on the promotion of electricity produced from renewable energy sources in the internal electricity market, which included a 22.1 % indicative share of electricity produced from renewable energy sources in total Community electricity consumption by 2010 (EC, 2001).

Discussions for targets beyond 2010 have now commenced. For example, the European Parliament has by an overwhelming majority called for a 25% target for inclusion of renewable energies in the EU's overall energy consumption by 2020 (European Parliament resolution of 14 December 2006). The Commission has published a Road Map that sets out a long-term vision for renewable energy sources in the EU as an integral part of the Strategic European Energy Review. Here it proposes that the EU establish a mandatory (legally binding) target of 20% for the share of renewable energy in energy consumption in the EU by 2020 and a binding minimum target of 10% for transport bio fuels for the EU by 2020. It also proposes a pathway [?? Of: timetable] for bringing renewable energies in electricity, heating and cooling, and transport into the economic and political mainstream (EC, 2007).

According to EEA (2006a), the production of energy and electricity from renewable energy sources grew steadily between 1990 and 2003, with particularly large increases in wind and solar electricity. In 2003, the share of renewables in total energy consumption and gross electricity consumption was 6 % and 12.8 %, respectively. Comparing this with the targets leads to the conclusion that a significant further expansion will be needed to meet the EU-25 indicative targets of a 12 % share in total energy consumption and 21 % share in gross electricity consumption by 2010. Hence, a substantial rise in the use of renewable energy sources is required to meet the targets. The purpose of the EEA project on renewable energy is to assess how much renewable energy could technically be available for energy production in Europe without increasing pressures on the environment.

In 2005, the EEA started with a study to assess the effect of increased production of biomass on agricultural and forestry biodiversity and on soil and water resources. This resulted in a report that outlined a set of environmental criteria that will help to safeguard biodiversity and reduce pressure on soil and water resources. The technical potential for exploiting biomass in an environmentally-compatible way was calculated using these criteria (EEA, 2006b).

In 2006, the EEA started with a similar project on wind energy as a follow-up. This project aims at deriving a number of environmental criteria for wind energy production, which are then used as assumptions for modelling the Europe-wide 'primary' potential. This potential is still a high estimate, since local spatial, institutional, legislative and social constraints can further reduce the actual potential. The criteria are general and the resulting potential may be used as benchmarks for the European scale; they are not meant to replace in any way assessments made on regional, national and local scales. At the moment very few other assessments have been carried out in a consistent manner beyond local and national scales. Some of these included Europe as one region in a global assessment. Most of these studies estimate the total wind energy potential as a function of market growth and technological (capacity and efficiency) development. Our study is the first Europe-wide study that looks at

[1] European Commission (2005) Report On The Green Paper On Energy - Four years of European initiatives.

the actual potential that can be derived from actual wind velocities in Europe using one consistent methodology, both onshore and offshore, in a geographically explicit manner.

An expert meeting has been held to discuss the approaches for the project and subsequently the EEA sent out a questionnaire to the EEA National Focal Points, the European Commission and other organisations (ACC, 2006). Based on the responses to the questionnaire, the EEA decided to organise a one-day expert meeting on 9 November 2006 to discuss follow-up activities that the EEA could undertake. The next phase of this project is described in this technical paper, i.e. the environmentally compatible potential of wind energy in Europe in different land-use and marine categories, taking into account the recommendations from the expert meeting. The proposed approach can be regarded as a 'top-down', where Europe-wide data on meteorology land cover, sea depth and windmill technology are used.

1.2 General conclusions

This study confirms that – in addition to other renewable sources such as biomass – wind energy can play major role in achieving the European renewable energy targets. The largest offshore potential can be found in the North and Baltic seas and the Atlantic Ocean, with some local opportunities in areas of the Mediterranean and Black Seas. Generally, the areas with the largest technical potential also have the largest economic potential. The technical potential in agricultural and industrial areas as well as low-depth offshore areas is the most significant. The deep offshore potential is even larger, but is not likely to contribute in any significant way to the energy mix within the time horizon of this study, primarily due to its significantly higher cost. In practice, actual environmentally sound and socially acceptable potentials are considerably lower than the technical potential. To get closer to the technical and economic potential, social concerns can be mitigated by appropriate ownership arrangements, stakeholder involvement, siting, wind turbine design and landscaping.

The results can be used as benchmark for the evaluation of the potential role of wind energy on the European scale. They can also be used in further modelling studies and indicate areas where more detailed analysis would be useful. This study is not meant to replace in any way assessments made at regional and local scale, which usually determine wind energy potential as a function of market growth and technological development in relation to a certain target. The method used can be regarded as a 'top-down' approach, using Europe-wide data on meteorology, land cover, sea depth, and wind turbine technology and their costs. To put the top-down approach into perspective, the method is calibrated against real-world data for countries for which they are available, and the potentials are compared with the actual wind power installed in frontrunner countries (evaluation of feasible penetration levels).

The theoretical potential of wind energy can be very high, the unrestricted economic potential could deliver more than 35 times Europe's anticipated electricity demand by 2030, at a cost below 6.9 Eurocent per kWh. However, this is an unrestricted technical/economic potential.

On land, environmental and social constraints limit the overall acceptable installation density in countries with a high share of wind power. The average acceptable feasible penetration level for wind on land in Denmark, the Netherlands and Germany is currently 2.1%, %, though much higher levels exist on a regional or local basis. This translate into 1200 TWh, the environmentally compatible technical potential, still enough to cover a very significant 27 % of Europe's electricity consumption by 2020 and 25 % by 2030. Offshore wind presents the greatest opportunity. Social and technical constraints limit the exploitable area to 4 % of the distance classes 0 – 10 km and > 50 km and to 10% of the total offshore area in distance classes 10 – 30 km and 30 – 50 km. Even if only these restricted offshore areas could be exploited at their technical power density of one 8 MW turbine per 0.8 km^2, offshore wind could generate 7 000 TWh, enough to cover more than 100% of Europe's electricity consumption by 2030. The above numbers indicate the potential of wind energy as a practical and economic technology to reduce Europe's greenhouse gas and air pollution emissions and improve the security of energy supply. These numbers also indicate that there are many opportunities to develop wind farms in places, where they would have the least, if not positive, environmental and social impact.

Many factors affect the wind energy potential, leading to considerable uncertainties in our estimates. These factors include natural factors, technological and economic factors, and factors dependent on human choices. The variation (hourly, daily, monthly and yearly) of wind energy potential is significant - with important implications for wind energy integration in the electricity system. Current understanding could be further improved on short term by:

- extended evaluation of feasible penetration levels in frontrunner countries;
- additional model analysis to determine the potential for different policy scenarios;
- sensitivity analysis for key economic and technological assumptions;
- more detailed analysis for areas in which model and observed wind velocities agree the least;
- exploration of a zoning approach to account for biodiversity constraints.

Research issues that will require greater efforts, include cross-country trend analysis of social constraints in EEA member states, and an inventory and analysis of policy-driven wind energy success stories in Europe and elsewhere and further analysis of specific vulnerabilities for biodiversity with regard to specific species and landscapes. The spatially explicit analysis of this report can guide the selection of interesting areas for additional regional studies, such as the Baltic.

Our methodology involved many subjective assumptions and uncertainties, but we believe that the general conclusions are robust: there is a very large wind energy potential in Europe, and tapping only part of it on a relatively small land and sea area can make a major renewable contribution to the European electricity supply. The potential is however very different between countries: for some northern countries it is very large and wind energy can theoretically cover the total electricity demand many times over, while in other countries it can only play a marginal role. It depends on economic, political and practical constraints which share of the potential will eventually be captured.

1.3 Comparison with other studies and objectives

The European Wind Energy Association (EWEA, 2003c) has set targets for the EU-15 to have 75 GW installed by 2010 and 180 GW by 2020, which is about 5.5 and 12,1 % of the total power supply, respectively. EWEA considers these targets to be conservative, and achievable, taking into account a background of robust market growth and technological progress to date.

In the Greenpeace and the Global Wind Energy Council (Greenpeace & GWEC, 2006) project, wind power in Europe grows in a reference scenario from about 41 GW in 1990 to 77 GW by 2010, 142 GW by 2020, and 186 GW by 2030. In their ‘‘Moderate-Market Growth’ scenario these numbers for 2010, 2020 and 2030 are 77 GW, 175 GW and 294 GW respectively. In their most optimistic ‘‘Advance market growth‘‘, the numbers further increase to 77 GW, 241 GW and 385 GW. These studies are based on market extrapolations and technological development expectations rather than wind availability

One of the few studies that actually used meteorological data at a grid level (0.5*0.5°) to estimate wind energy potential is a study by the German Advisory Council on Global Change, ‘World in Transition – Towards Sustainable Energy Systems’ (WBGU, 2003) that arrived at a global technical potential for energy production from both onshore and offshore wind installations of 278 000 TWh (approximately 140 000 GW. The report then assumed that only 10–15% of this potential could be produced in a sustainable fashion, taking into account that urban areas and natural areas would not be used; the figure resulting was approximately 39 000 TWh (20 000 GW) per year as the contribution from wind energy in the long term. However, the global nature of the report does not allow us to derive a number for Europe.

1.4 Summary of detailed conclusions

1.4.1 Methodology and data

Chapter 4 establishes that wind speeds predicted using the model methodology employed for this study, generally show agreement with observations of surface wind speed at European meteorological stations. Good agreement is found for geographical regions where low surface roughness land types are extensive, for example, throughout Denmark, the Netherlands and Germany. The uncertainty associated with agricultural land is evaluated at 95%, with confidence intervals of ± 1.88 m/s. The model predicting wind speeds shows poor agreement in forested area and in mountainous regions. On balance, the uncertainties are found to be smallest for relatively flat low-lying areas that generally are most suitable for the establishment of wind energy turbines.

The costs data are based on single wind turbine costs. The prices of wind turbines in the context of orders for larger wind farms are variable. On the one hand, they decrease because of larger numbers which may reduce the price between 10 – 55% (Junginger, 2005). On the other hand, at high penetration rates increasing demand beyond the industries normal expansion capacity may lead to increased prices for turbines and therefore the investment costs.

This study focuses on wind energy investment, operation and maintenance costs. The costs of wind energy when penetrating the electricity system (e.g. transmission, back up, spinning reserve, storage and imbalance) have only been considered at a flat rate. A more preferred approach would consider these costs in the context of an electricity model and a penetration scenario. Studies have shown that at high penetration levels, indicatively above 20-40 %, the cost reductions due to technological learning might be offset by the additional costs of system integration (e.g. Hoogwijk et al., 2006).The main cost assumptions of the parameters are summarised in Table 1.1.

Table 1.1: Main conclusions on the assumptions of the future technological and cost development of wind energy

	Unit	**Onshore**		**Offshore**	
		2020	2030	2020	2030
Rated power	MW	2	2	8	10
Hub height	m	80	80	120	120
Turbine costs	€/kW	600	480		
Total turnkey costs	€/kW	720	576	1080	975
O&M costs	%	4	4	4	4
System integration cost	€ct/kW	2	2	2	2

1.4.2 Biodiversity and social constraints

Biodiversity can be negatively affected, for example birds and bats. In particular, raptors (which exhibit little displacement because of wind farms) and other non-hunted species with similar behavior, are the most affected if present in an area. Wind farms in open hunting areas will generally benefit the hunted bird population under the practice of closing such areas for hunting.

Biodiversity constraints are less important in marine areas. The usual practice of closing wind farm areas for fishing, in combination with the artificial reef effect of turbine foundations, would normally have a positive effect on local marine biodiversity.

Designating closed areas for wind development could aid the planning process and the reduction of conflict between the stakeholders concerned. Requiring local governments to designate areas for wind development appears to have been a success factor in Germany.

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 programmes of existing wind farms remain essential tools for minimizing and learning about environmental impacts.

Social acceptability of wind turbines often has to do with the visual impact of wind turbines on the landscape, both for wind turbines onshore and offshore. Offshore potential away from the coastline (10–50km) is presented with few social barriers, although costs can be significantly higher. In the end, visual impact is a matter of taste and therefore wind projects probably will continue to meet resistance; however, there are a number of ways to reduce the public resistance related to visual aspects. For wind turbines on land, landscape architecture has the ability to overcome many of the barriers of visual impact. Single line wind-turbine configurations appear often more elegant. Furthermore, local resistance can be lowered by local ownership structures, where residents experience direct benefits from wind power. Agricultural and industrial areas generally face the least social (and environmental) reaction to onshore wind development without exceeding this power density

Different wind energy support policies have been put forward by the Member States of the European Union, with feed-in tariffs having the best results so far. With regard to planning frameworks, prior planning procedures have been a success factor in Germany (Federal Building Code). France (wind power development zones) and Denmark also know local planning procedures where areas for wind power development are to be selected. It is too early to state whether these procedures will be as successful as in Germany.

With the number of wind farms increasing and visual and noise impacts being major concerns of people, there will be an important task for national governments to develop a vision on the future implementation of wind farms in existing landscapes. It becomes important then to study the suitability of different type of landscapes for the implementation of wind turbines.

1.4.3 Results

The technical wind energy potential in the EU-27 (and the EU-15) would be more than 15 times the total electricity demand by 2020 in a low-greenhouse gas emissions scenario that is consistent with the EU's long-term climate change objective. Whereas the electricity demand is projected at about 5 000 TWh, the technical wind potential is estimated at 75 000 TWh, including both offshore and onshore resources, with the only restriction being the availability of wind. If we increase the load hour threshold for onshore areas to 2 000 full load hours[2] and only include the parts of the economic zones within 10–50 kilometres from the coast for offshore areas, the available potential drops to 19 000 TWh for 2020 and 21.000 TWh in 2030.

The results show significant differences in wind energy potential between countries. . There are however significant differences among the individual countries. For some inland central European countries (such as Austria, Czech Republic,and Slovenia wind energy is not a very significant option to satisfy the national domestic electricity demand. The wind potential in these countries is not able to supply more than 5% of the electricity demand in 2030 in these countries. Other countries that have more suitable locations to develop wind energy, but whose wind energy potential is still less than the national electricity demand in 2030 are Romania, Slovakia and Spain. About 75% of the land wind resources in Spain are below 1600 full load hours and not included in this example.

In a number of countries the offshore technical potential exceeds the domestic electricity demand in 2030 by more than 10 times: Denmark, Estonia, Ireland and Latvia. When restricting offshore wind developments to areas with a minimum of 2500 full load hours and to areas within a distance of 10 to 50 kilometers from the coast, the offshore potential still exceeds the electricity demand by a factor of almost 10 in these countries. But even using

[2] Added to this potential should be some expectations about the increase in load hours as function of wind speed, recently (December 2008, RenewableEnergyWorld) it was reported that a wind farm in Denmark (eastern Jutland) was repowered (from existing 2MW wind turbines) with new 2.3 MW machines with longer blades (more capture area), which are expected to yield double as much energy per year as the previous one.

their onshore wind energy potential only, these four countries can theoretically produce more than 10 times their electricity demand in this scenario.

Another group of countries in Northern and Western Europe, including Finland, Sweden, United Kingdom, the Netherlands, Lithuania and Norway can also easily meet their domestic electricity demand in 2030 assuming a minimum of 2 000 full load hours for onshore wind resources and including the offshore potential at 10 – kilometres from the coast. The combined onshore and offshore wind energy potential exceeds the electricity demand in 2030 by 2 to 7 times.

While these potentials are interesting, they may paint a misleading rosy picture, even if economic factors are taken into account through the load hour threshold. Various constraints have been introduced to arrive at a more realistic potential for wind, the so-called ‘social and environmental compatible’ potential.

Noticing that the progress of further development of wind energy in new locations onshore is slowing down in Denmark, Netherlands and Germany, possible, 'feasible penetration' levels for onshore wind turbines are calculated for Denmark, the Netherlands and Germany. Compared to Germany (penetration level of 3.8 – 4.7%), relatively low overall penetration levels are found in Denmark and the Netherlands for a viable wind speed of 0.9% and 0.6% respectively. Feasible penetration levels for arable land were found to be 1.3 % in Denmark and 1.1 % in the Netherlands. However, the definition of 'feasible penetration' is flexible and can be changed by policy and societal changes over time.

‘Repowering’ the current turbines installed in Denmark to 2 MW is found to 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 reached a higher magnitude than in Denmark for the highest Netherlands’ wind speed ranges

Following the recommendations from chapter 4 on ‘Biodiversity constraints’, siting of wind turbines is restricted to area outside Natura 2000 and other designated area. This assumption is applied as a first attempt to include biodiversity constraints in the potential estimation for wind on land, resulting in a drop of 18% in the onshore technical. Areas with wind speeds below 4 m/s were hereby not taken into account.

The offshore technical potential is restricted by both economic and social constraints. The visual aspect of offshore wind farms close to the shore limits the potential of wind that can be exploited in these areas. Other uses of the sea area might also limit the practical implementation of wind. Offshore areas with low wind speeds and with a distance to the coast of more than 50 kilometres are excluded due to economic reasons. Considering these limitations, the offshore potential for wind drops from 25 000 TWh to 3 000 TWh.

The market potential, based on private costs and private discount rates, is estimated at 14 000 TWh for 2020 and 41.000 TWh for 2030. In most countries the wind energy potential is much larger than the national electricity demand in 2030. When limiting the penetration of wind energy in the electricity system to 25%, in the low-greenhouse gas emissions scenario an average of 8% of the suitable national land and sea area will be needed to fulfil the electricity demand.

Further analysis included the fact that not all types of land are equally suitable to site wind turbines on. Inland countries have to rely on land based wind energy resources, with agricultural land being the most appropriate to place wind power on. With the restriction that only 4.4% of the available agricultural land can be used for siting of turbines only Denmark, Estonia, Latvia and Lithuania still have sufficient land available to cover 25% of their domestic national electricity demand in 2030..

1.4.4 Uncertainties and gaps in knowledge

The results of the analysis in this report are subject to a large number of uncertainties of different kinds. Various methodologies and associated assumptions and the uncertainties involved are discussed in detail in this report. This paragraph summarises the various sources of uncertainty, the assumptions made for the analysis in this report and the implications for the results. The sources of uncertainties can be grouped into four categories.

1.4.4.1 Uncertainties in physical variables.

Physical variables necessary for the calculation of the technical wind energy potential include the meteorological data (ECWMF wind fields) and the information on land-use characteristics (CLC, CDDA, Natura2000). As to observations, the uncertainties are caused by potential monitoring errors (both meteorological and land-cover data) as well as variability over time. The relatively short time of 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. And this may lead to changes in land cover and associated roughness.

1.4.4.2 Uncertainties in technological and economic variables.

Assumptions for various technological and economic variables are required to determine the economic potential. They include assumptions on technology characteristics such as 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. What is different for the technological and economic variables from the physical variables above, is that it has to be determined how they may develop over time, while introducing an additional set of uncertainties that are partly related to the human choices below.

1.4.4.3 Human choices.

The results for future wind energy potential are dependent on human (political) choices. For example, the report discusses many constraints imposed on the construction of onshore as well as offshore wind turbines related to the protection of nature and biodiversity and also to social and cultural concerns (such as visual aesthetics and noise) and government policies. Examples include the minimum distance to the shore, and the limits of different types on (the number of) windmills per unit area of land use and offshore areas, including 'no-go' areas related to nature protection objectives. Such constraints may change over time, inter alia as a result of evolving priorities and government policies. For example, people appear to value wind turbines more positively after they have been established, not before, or if they have a financial stake in them. To address this type of uncertainties in determining the wind energy potential, particular scenario assumptions are made. To explore the importance of such factors, in the analysis available detailed data about the actual situation in Denmark (the one country for which detailed information was readily available) were used to calibrate the model and to evaluate the feasible penetration level of primarily offshore wind farms.

1.4.4.4 Uncertainties related to model choices.

In addition to uncertainties related to the value of various variables used in the methodology, uncertainties are also generated by process assumptions in the model structure. Examples are the translation of landscape characteristics and associated roughness factor into an effect on wind speed, the relationship between wind speed and power density for different hub heights, the conversion of construction, operation and maintenance costs into electricity costs. For this paper, 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, 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 (20x15 km^2).

In this report, we present and assess different types of wind energy potential: the theoretical potential, the technical, the economic and the market potential; on to the realistic socio-economic potential. The economic potential is smaller than the technical potential, which again is smaller than the theoretical potential. The market potential is smaller than the economic potential because of higher discount rates used in the real market. However, the socio-economic potential can be smaller or larger than the market potential, the latter in case people may prefer wind energy over other sources of energy, even if it would be more expensive. The above four categories are related to this sequence: the uncertainties in physical variables affect the theoretical potential, the technological uncertainties affect the technical potential, the economic uncertainties affect the economic potential, and uncertain human choices affect the market and socio-economic potential. The methodological assumptions in this report can introduce uncertainties in all the potential categories.

We did not estimate all uncertainties quantitatively. However, as a rough approximation we assess the order of magnitude of the uncertainties in the physical, technological and economic variables to be smaller than that of 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.

This overview of uncertainties suggests some improvements for further research to fill gaps in knowledge. Some of these may require major research efforts, other could be addressed at shorter notice, for example in the context of the ETC/ACC work plan.
The latter include:

- Improved evaluation of feasible penetration levels in frontrunner countries, dependent on the availability of detailed wind energy data;
- Additional model analysis (e.g. with Green-X) to determine the potential for different scenarios for government energy policies;
- Sensitivity analysis for key economic and technological assumptions;
- More detailed analysis for areas for which model and observed wind velocities agreed the least, notably mountainous and forested areas;
- Attempts to apply a three zone-category to Europe to account for biodiversity constraints (no-go areas, areas where more research is needed, and suitable areas), for instance,in collaboration with or by using information from Birdlife International.

Research issues that require greater efforts include:

- Cross-country trend analysis of social constraints in EEA member states, with emphasis on the countries with high economic wind energy potential;
- Inventory and analysis of policy-driven wind energy success stories in Europe and beyond;
- 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;

1.5 Outline of the report

This paper has two main objectives:

(1) Develop and apply a methodology to assess the onshore and offshore wind energy potential and its costs at a European level in a consistent and geographically explicit manner. Much attention has been given to constructing an updated inventory of input data;

(2) The potential and cost estimations for wind energy in Europe by 2020 and 2030 can serve as new input for comparison with other studies at different levels and with the European renewable energy targets. Furthermore, the potential and costs estimations can be used in further modelling studies of the European renewable energy potential, such as with the Green-X model.

Chapter 2 deals with the first main objective of this paper, describing the methodology and data processing (ECMWF wind fields, Corine land cover, data on existing wind turbines). This chapter also presents the results of the ‘top-down’ analysis performed. An overview of the wind energy potential is provided, expressed in technical, economic and 'social, environmental feasible penetration' potential for the 2020-2030 period.

Chapter 3 describes the results of the study. The methodology as developed and described in chapter 2 is applied for calculating the wind energy potential in 2020 – 2030, based on an assessment of available information on the technical potential for wind energy and the physical and other constraints.

Chapter 4 – 8 present detailed information on the constraints. The results in Chapter 3 are calculated and assessed on the basis of the detailed information provided in these chapters.

Chapter 9 presents a special case, the effect of a North Sea Grid on the costs.

2 Methodology

2.1. Introduction

What is the European wind energy potential? First, we have to define what we mean by ''potential''. In the context of greenhouse gas emissions, IPCC (2007) distinguishes among technical, economic and market potential. The technical potential is the amount by which it is possible to reduce greenhouse gas emissions or improve energy efficiency by implementing a technology or practice that has already been demonstrated. The economic potential is the mitigation potential that takes into account social costs and benefits; this assumes that market efficiency is improved by policies, and measures and barriers are removed (see Figure 2-1). The market potential is the mitigation potential based on private costs and private discount rates, which might be expected to occur under forecast market conditions, including policies (i.e. subsidies) and measures currently in place, noting that barriers limit actual uptake.

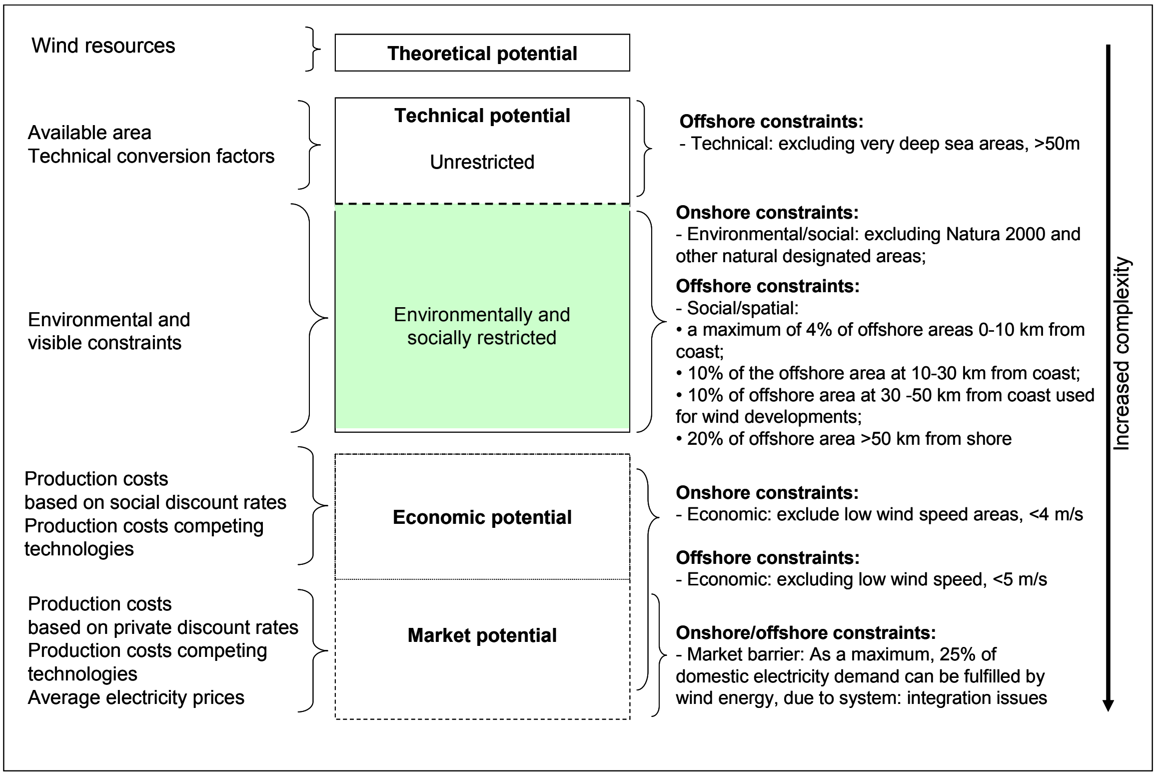

Figure 2-1: Definition of wind energy potential

Studies of market potential can be used to inform policy makers about mitigation potential with existing policies and barriers, while studies of economic potential show what might be achieved if appropriate new and additional policies were put into place to remove barriers and include social costs and benefits. The technical potential is greater than the economic potential, which again is generally (i.e. subsidies) greater than the market potential. In Figure 2-1, we also use the 'theoretical potential' to indicate the potential in case all technological, sea depth or landscape constraints would be removed. We also introduce the term 'socially and environmentally acceptable potential'. This is the share of the technical potential that is socially and environmentally acceptable, regardless of economic factors. Thus, our definition of economic and market potential only takes into account the economically feasible shares of the environmentally and socially acceptable potential.

It is generally accepted that wind energy potential in suitable areas, as well as the capacity of the grid to absorb this power, is determined primarily by economic, social and environmental constraints. Nevertheless, it is useful first to survey suitable wind energy areas to have a rough idea of the maximum technical potential before looking at these constraints. Just a few studies have done this on a European scale until now. Moreover, wind energy potential and economic and practical constraints are very different across Europe. Maps generated from a geographically explicit analysis allow for quick identification of areas in Europe where technical wind energy potential is large; further studies can focus on such areas.

Therefore, in this report, we focus primarily on the technical potential. The results can be used for further analysis by taking into account economic, social and institutional factors that would lead to estimates of (lower) market and economic potentials. Rather than determine a theoretical potential without any constraints (i.e. wind turbines can be built anywhere), we consider a number of constraints that are discussed in more detail later in this chapter. For example, it generally does not make sense to determine wind energy potential in very deep seas, in areas where there is hardly any wind, or where other land uses (like urban or nature protection areas) prevent wind turbines from being built. These restrictions to the theoretical potential lead to the definition of a more realistic technical potential for wind energy – the ''environmentally compatible'' technical potential for wind energy. We analyse the potential of a number of cost categories to compare the resulting electricity prices with current prices to get some idea about the economic potential. We discuss social, institutional and biodiversity constraints in a more qualitative fashion to put the technical potential into context.

One of the major concerns during the member states consultation and the expert meeting, which were held in November, 2006, was the issue of a realistic 'top-down' analysis. To address this concern, we (a) ''calibrate'' our ''top-down'' results by comparing them with real-world data, and (b) apply a case study for Denmark and the Netherlands as a complementary ''bottom-up'' analysis. The overall scheme is depicted in *Figure 2-2*. The elements are described below. In this way, we attempt to translate the abovementioned qualitative discussion on social and environmental constraints into a preliminary quantitative estimate to address the question: which percentage of the technical potential can be exploited in practice.

2.2. Top-down methodology

Top-down methodology calculates wind energy potential by starting from the calculation of the theoretical potential (top) and arriving to some realistic potential (bottom) as depicted in Figures 2–1 and 2–2.

The potential for wind energy is determined by the number and type of wind turbines that can be (profitably) realised. The decision to install a wind turbine depends on the expected return on invested capital. This requires information on the amount of electricity that can be generated at a certain location (full load hours, depending on wind speed and turbine characteristics), local and national regulations, costs (investments and operation and maintenance costs) and the (expected) price and/or subsidy for the generated electricity. In the top-down methodology, analysis is focused on the best suitable locations to generate wind energy at particular costs. This results in various maps and tables showing (spatially specific) locations in Europe where wind energy can be generated below a certain cost per kWh (e.g. maps for EUR cents 4–10/kWh for 2020 and 2030) differentiated over various land covers (e.g. agricultural land, protected areas, water).

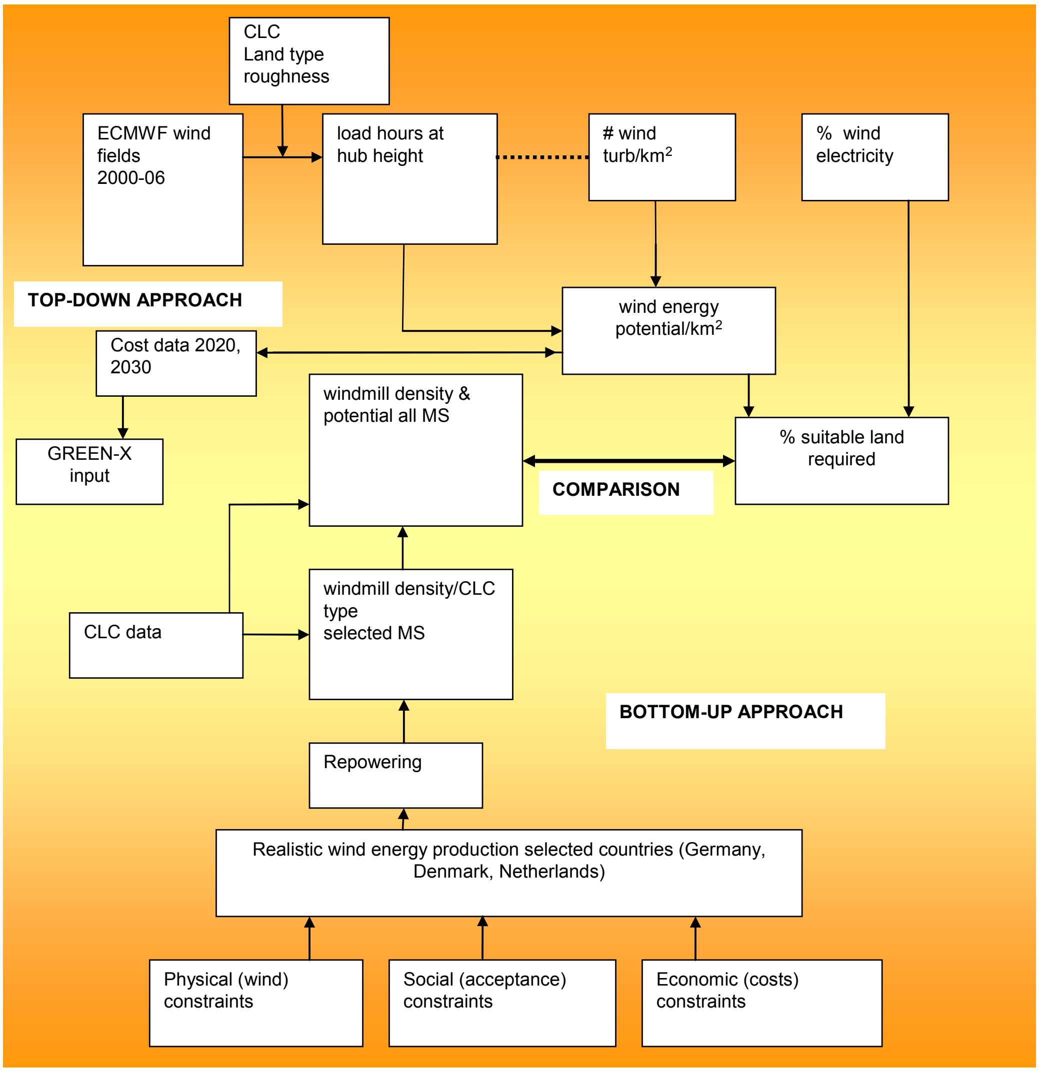

Figure 2-2: Analysing the European technical wind energy potential

The starting point of top-down analysis is the 40-year re-analysed ECMWF wind fields for Europe (see Chapter 3 for a detailed discussion). An average wind speed of 10 m is recalculated to generate the expected wind speed at hub height. This is done by taking into account the surface roughness for different land cover types, as specified by the Corine Land Cover database (CLC) (see next section for details). Since meteorological circumstances vary from year to year, we used average wind speeds for the period 2000–2005 for wind on land.

Assuming a potential of 5 2 MW wind turbines per square kilometre onshore and a 1.25 8 MW wind turbine per square kilometre offshore, an average wind energy production potential per square kilometre is calculated. We calibrated the results by comparing the full load hours generated by existing wind turbines at a certain location with the calculated full load hours. The necessity of calibration will be discussed in Chapter 4. The results of this top-down approach can be expressed as the percentage of suitable land that is required to generate a certain percentage of electricity supply in a country, or, conversely, what percentage of the electricity supply in a country can be provided by wind energy for a certain price.

2.3. Bottom-up methodology

Bottom-up methodology starts from the existing power generation in some wind-energy advanced countries (bottom) and calculates a higher future realistic potential (up) by assuming the adoption of anticipated state of the art practices — basically re-powering existing onshore sites with fewer, bigger and more efficient turbines plus developing some of the offshore potential.

Limitations of wind energy potential are physical (availability of wind, other land uses), economic (costs) and social (regulation, acceptance, risks of wind turbines at a certain location). This last aspect is the most difficult to quantify in a pan-European study. One way of dealing with this is to consider those countries in which wind energy has penetrated most, and assume that this level of penetration is representative of the maximum feasible penetration of windmills in terms of numbers per unit of area in Europe, as a rough estimate. For our ‘‘bottom-up’’ analysis, we assume that the high penetration of wind-turbines in countries like Denmark, Germany and the Netherlands is representative of limitations due to regulations and non-technical factors (e.g. not allowing wind turbines in bird collision sensitive areas).

As a first step, we acquired data on the existing wind turbine locations for several European countries. As a second step, we assumed these locations to be ‘‘re-powered’’ with the selected wind turbine of the top-down approach (with the additional constraint of four to five–wind turbines per square kilometre). In the topdown approach we selected wind turbines with the latest technology, which are generally more powerful than existing wind turbines. This allowed for a comparison between our top-down and bottom-up calculations. As a third step, we calculated the percentage of wind power coverage of a particular CORINE land cover type (see Chapter 3) for various load hour classes (e.g. >2500, 2300–2500, 2100-2300, 1900–2100, 1700–1900, 1500–1700, <1500). In step four, we use these percentages for similar CORINE land cover types in other European countries that have a relatively low penetration grade. In step five, we calculate the wind potential for various costs categories and compare it with the top-down approach.

2.4. Calibration

Based on a comparison of the full load hours generated by existing wind turbines and the calculated full load hours, an uncertainty range will be calculated and the necessity and/or potential for a calibration will be discussed.

2.5. Data handling

2.5.1. ECMWF wind fields

High-quality wind fields are an essential prerequisite for selecting suitable locations for wind turbines. The data used in wind power meteorology stem mainly from three sources: onsite wind measurements, the synoptic networks, and the re-analysis projects (Monahan, 2006, Petersen, 1997). Wind climate analysis, wind resource estimation and siting further require a detailed description of the topography of the terrain {with respect to the roughness of the surface, near-by obstacles, and orographical features). The wind close to the earth's surface is strongly influenced by the nature of the terrain surface, the detailed description of which is called topography. The interaction between the wind and the surface takes places on a broad range of length scales, and much effort in boundary-layer meteorology has been devoted to the separation of this range of scales into a number of characteristic domains which 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 meters above the ground, the effects of the topography can be divided into two typical categories:

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 the height usually much larger than the height of these. Obstacles close to an obstacle, such as a building or shelter belt, the wind is strongly influenced by the presence of the obstacle which may reduce the wind speed considerably.
2. Orography When the typical scale of the terrain features becomes much larger than the height of the point of interest, they act as orographic elements to the wind. 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.

Recently wind data from the global reanalyses projects (Kalnay et al. 1996, Gibson et al. 1996) have become available. Over the last decade, unprecedentedly long time series of sea surface wind speeds with global coverage have become available from two primary sources: reanalysis products and satellite-derived remotely sensed observations. Reanalyses combines meteorological observations with full atmospheric general circulation models (GCMs) to find model states that are optimally compatible with the observations; the resulting datasets are of long duration, with high resolution in both space and time (e.g., Kalnay et al. 1996; Simmons and Gibson 2000). The reanalysis GCM, however, is only an approximate representation of the real atmosphere. Consequently, reanalysis products have the drawback that they will be corrupted by model biases, especially in poorly sampled regions where the reanalysis data reflect the model more than the observations. On the other hand, remotely sensed sea surface wind speeds have the benefit of being more direct measurements of sea surface winds and are generally found to agree reasonably well with in situ buoy and ship-based observations (e.g., Meissner et al. 2001; Ebuchi et al. 2002; Bourassa et al. 2003), but they are generally of limited duration (e.g., Kelly 2004). Buoy data represent real, in situ observations, but their spatial coverage is limited, particularly in the open ocean. These wind fields are generally believed to be much more homogeneous than previous products, as they have been produced by global atmospheric circulation models that were used for reanalyzing existing observational data back in time for some decades using a frozen state-of-the-art data assimilation system together with an enhanced observational data base that additionally comprises observations that were not available in real time.

There are two large sets of reanalysis data. One produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) called ERA-40, (http://www.ecmwf.int/research/era/) and one produced by National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR), (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html).
The ERA-40 data set covers the period 1958 – 2006 (original 2001) and NCEP-NCAR reanalysis data is available from 1948 and forward (Larsson, 2006). Various studies on wind resource assessment using SAR data where carried out in various project funded by National or international Agencies i.e. the European Commission or European Space Agency (Sempreviva, 2007). The purpose of the EU FP5 'WEMSAR' Project was to provide a tool for offshore wind resource assessment (Hasager, et al., 2005). Wind speed maps for various atmospheric situations were retrieved at several European test sites, i.e. the west coast of Norway, the Horns Rev offshore site in Denmark, and the Maddalena Island in the northern part of the Sardinia Island in Italy and compared to offshore wind resources from a local scale (WAsP) model and a regional model. In North European Seas, a comparison of QuikSCAT derived winds with observations at Horns Rev indicated a relatively high correlation coefficient of 0.91 between the two datasets (Hasager, et al., 2006). In the Mediterranean area, wind climatology using the six years of wind data by QuikSCAT, in terms of spatial variation of wind roses, mean wind speed, seasonal and monthly variation is presented in Sempreviva, et al., (2006). Generally fair agreement on the monthly and seasonal variation at all sites was found and as expected all models agree best far from the coast.

In our analysis we decided to use the wind data at 10m height (2000-2005) from the reanalysis data set from the ECMWF as our primary data input to calculate the wind energy potential over Europe. This allows us to combine high resolution spatial wind data with high resolution land cover data and scale-up the wind field, using specific roughness correction, to 80m height. Actual meteorological surface layer parameter data for the years 2000-2005 were extracted from the Meteorological Archival and Retrieval System (MARS) of the ECMWF (European Centre for Medium-range Weather Forecasts; www.ecmwf.int). 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. The datasets from which we extracted parameter data needed to provide complete data coverage for the continuous period of at least 2000–2005 but preferably from 1990 to date and for the complete area of study. Specifications of the data, including its exact MARS parameter code references, which were ultimately extracted, are:

Spatial grid resolution:	0.25 x 0.25 degrees latitude/longitude, i.e. 15 x 15 minutes or ~ 20x20 km				
Geographic window:	Lower left corner 34 x –42 degrees lat./long; upper right corner 72 x 59.5 degrees lat./long. (i.e. covering the European-wide study area).				
Years:	2000–06				
From dataset:	Operational Surface Analysis Data Sets ('oper')				
Time resolution:	Daily 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

Wind speed as used in the calculations, is derived from the 10 metre height wind speed in U (10U) and V (10V) direction with magnitude $\sqrt{(10U)^2 + (10V)^2}$ 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. The reason we used a lower than maximum resolution lies in 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 time- and resource-consuming. The meteorological gridded data for the years 2000 to 2005 were transformed into ESRI GRID format. The averaging of both the original six-hour and the daily meteorological parameter values into annual averages on the given grid resolution needed to be executed in two steps as a way to cope with the limited calculation capacity of the relevant ArcGIS procedure. As a first step we averaged the six-hour values into half-month values and the daily values into two-month averages. As a second step, we derived the annual averages from these intermediate average values.

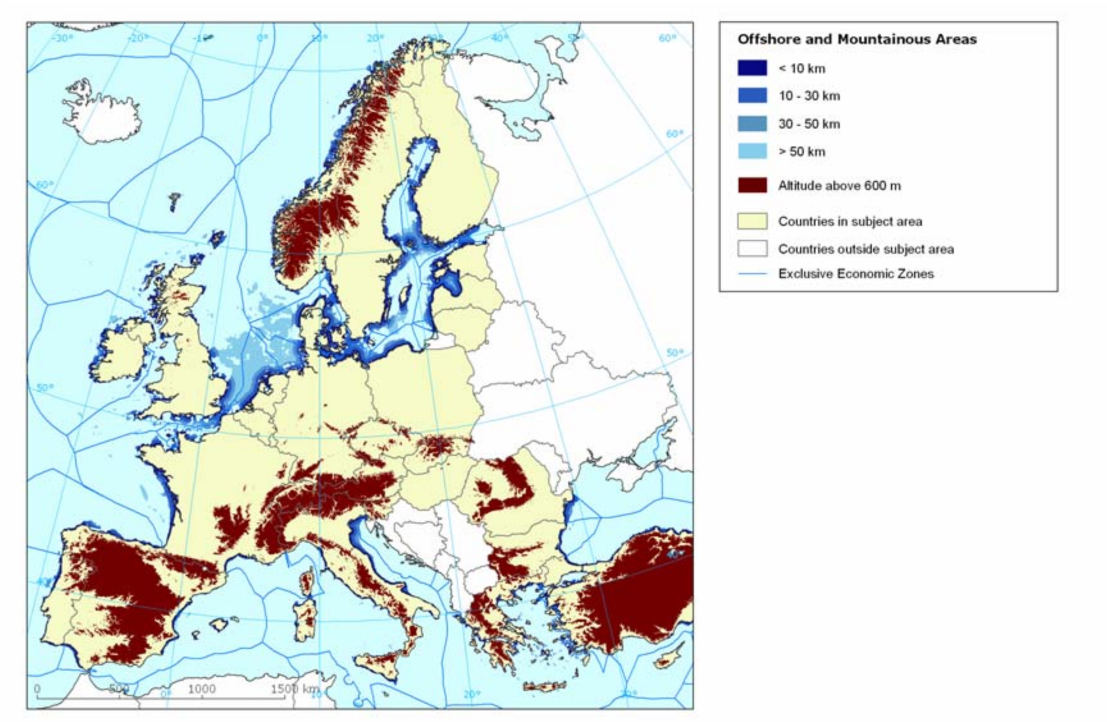

Figure 2-3:Mountaineous areas (above 600m) and offshore locations with a water depth of less then 50m in Europe.

An uncertainty introduced by the low resolution of the ECMWF data is the possibility of local speed-up effects caused by sub-grid scale orographic features. Even though there might be a low wind speed given by the ECMWF data generally for a particular grid cell, local effects might enhance the resource such that wind power is possible. One example of such a not modelled effect exists in one of Spains first areas for large scale wind power installations, around La Muela, on the edge of the Ebro river valley. The maps produced by our methodology show the area as not worthy of development, even though in the last years, many hundred MW have been installed.

An increase in wind speeds due to terrain speed-up effects (orography)
Highly elevated area is usually complex terrain. There are only few high plains in Europe, so most of the area above 600 m is divided between mountain ranges and valleys. In the valleys, the wind speeds are low, while on top of mountains wind speeds can be enhanced by more than 70 %. This speed-up effect depends on the local slopes. The grid cell size of the wind data grid is 22 km, therefore there is quite a distribution of high and low terrain within those grid cells (see *Figure 2-3* for lmountaineous loacatons inEurope). Wind power would realistically only be built on top of the mountains, where the wind speeds are best (see also annex 3). The results of annex 3 can be calibrated against the variation in wind speed around the grid average that would result in the same distribution of full load hours, The derived correction factor for wind speed can then be used to calculate the full load hours in a straightforward manner whereby the differentiation in Corine land Cover data can be preserved. The following correction factor has been applied for heights above 50m:

Vi = Vmean + 0,001508 * (Hi-Hmean)

I indicates the various height of the subcells within a certain ECMWF wind field cell.
See Figure 2-4 for the results after roughness correction based on CLV data.

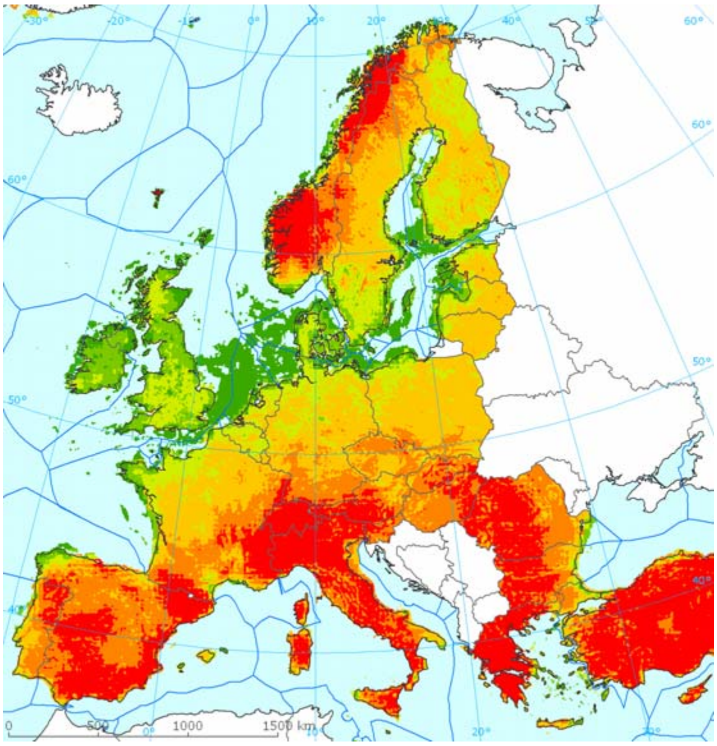

Figure 2-4: ECMFW wind field data after correction for Orography and local roughness (80m onshore, 120m offshore).

2.5.2. Corine land cover database and hub height conversion ratio

For a realistic assessment of windturbine capacity, the wind speed at the hub height (assumed to be 80 m onshore and 100-120 m offshore) is required rather than the 10 m ECMWF data. To derive this wind velocity at hub height, we used:

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

H stands for te hub height (m), V_H is the wind speed at hub height, V_{10} (m/s) is the wind speed at 10 m height (m/s) and z_0 is the roughness length (m).
This is the logarithmic wind profile for neutral conditions, in which thermal effects have been discarded (Ecofys, 2002).

Table 2-2-1: Average hub height conversion ration used in 15 Corine land cover classes (CLC)

CLC class number	**Av ratio**	**CLC code and label Level 3**	
		111	Continuous urban fabric
		112	Discontinuous urban fabric
CL 1	1,91	121	Industrial or commercial units
		141	Green urban areas
		142	Sport and leisure facilities
		122	Road and rail networks and associated land
CL 2	1,64	123	Port areas
		124	Airports
		131	Mineral extraction sites
CL 3	1,32	132	Dump sites
		133	Construction sites
		211	Non-irrigated arable land
CL 4	1,43	212	Permanently irrigated land
		213	Rice fields
		221	Vineyards
CL 5	1,52	222	Fruit trees and berry plantations
		223	Olive groves
CL 6	1,47	231	Pastures
		241	Annual crops associated with permanent crops
		242	Complex cultivation patterns
CL 7	1,51	243	Land principally occupied by agriculture, with significant areas of natural vegetation
		244	Agro-forestry areas
		311	Broad-leaved forest
CL 8	1,85	312	Coniferous forest
		313	Mixed forest
		321	Natural grasslands
CL 9	1,33	322	Moors and heath land
		323	Sclerophyllous vegetation
		324	Transitional woodland-shrub
CL 10	1,30	331	Beaches, dunes, sands
		332	Bare rocks
CL 11	1,30	333	Sparsely vegetated areas
		334	Burnt areas
CL 12	1,24	335	Glaciers and perpetual snow
		411	Inland marshes
		412	Peat bogs
CL 13	1,34	421	Salt marshes
		422	Salines
		423	Intertidal flats
		511	Water courses
CL 14	1,21	521	Coastal lagoons
		522	Estuaries
		523	Sea and ocean
CL 15	1,21	512	Water bodies
no CLC data used see table 2-2			Norway/ Switzerland/ Turkey
	1,23		Offshore

The Corine Land Cover database 2000 (CLC) is used as a starting point to take into account the difference in surface roughness (with a 250x250m resolution) of the various land cover types. Data in the CLC is aggregated into 15 CLC classes (see Table 2-2-1), which reflect similar land cover types with comparable roughness. See Annex 2 for details.

Data from ECMWF (ECMWF, 2007) for wind speed and Ecofys (Windsnelheden en ruwheden, Ecofys, 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 shown in the table below (Table 2-2-1). A similar approach is used to determine the conversion ratio for offshore areas.

Because CLC data was not available for Norway, Switzerland and Turkey, we used the Global Land Cover 2000 database of JRC (GLC2000, www-gvm.jrc.it/glc2000) released in 2001 with a 0.6 km resolution grid. A conversion table (see Table 2-2-2) between the Corine Land Cover classes and the Global Land Cover 2000 database was developed.

Table 2-2-2: Legend GLV land cover classes (Global Land Cover) reclassified to wind roughness classes on basis of the CLC2000 wind classification table.

nr	GLC Global class (according to LCCS terminology)	Wind roughness class
1	Tree cover, broadleaved, evergreen LCCS >15% tree cover, tree height >3m	CL8
2	Tree cover, broadleaved, deciduous, closed	CL8
3	Tree cover, broadleaved, deciduous, open LCCS: open 15-40% tree cover	CL8
4	Tree cover, needle-leaved, evergreen	CL8
5	Tree cover, needle-leaved, deciduous	CL8
6	Tree cover, mixed leaf type	CL8
7	Tree cover, regularly flooded, fresh water (& brackish)	CL8
8	Tree cover, regularly flooded, saline water LCCS: daily variation of water level	CL8
9	Mosaic: tree cover/other natural vegetation	CL9
10	Tree cover, burnt	CL1
11	Shrub cover, closed-open, evergreen	CL9
12	Shrub cover, closed-open, deciduous	CL9
13	Herbaceous cover, closed-open	CL9
14	Sparse herbaceous or sparse shrub cover	Cl11
15	Regularly flooded and/or herbaceous cover	Cl13
16	Cultivated and managed areas	Cl7
17	Mosaic: Cropland/tree cover/other natural vegetation	Cl7
18	Mosaic; cropland/Shrub or grass cover	Cl7
19	Bare areas	Cl11
20	Water bodies (natural & artificial)	Cl15
21	Snow and Ice (natural & artificial)	Cl12
22	Artificial surfaces and associated areas	Cl1

For display purposes the 15 CLC classes have been aggregated to 7 land cover classes (see Figure 2-5 and Table 2-2-3: Aggregated LC classes for LC map).

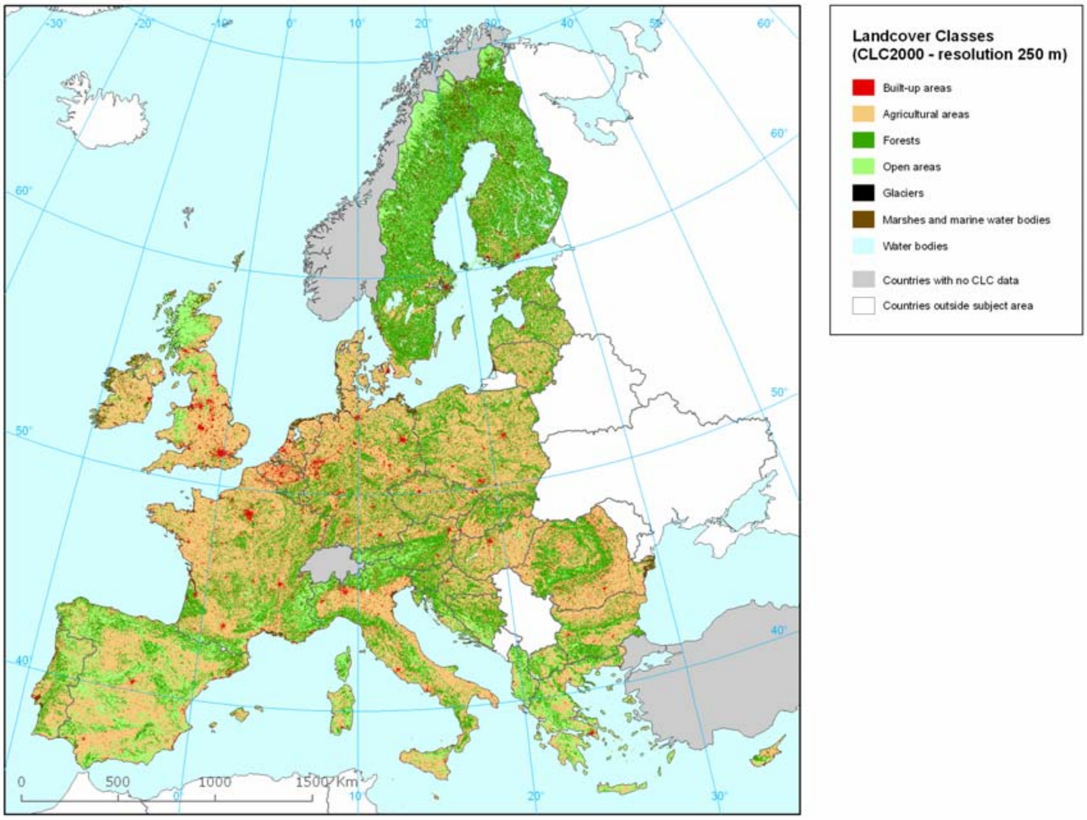

Figure 2-5: Spatial distribution after aggregation of Corine land cover into seven classes.

Table 2-4: Aggregated Land Cover classes for Land Cover map

Aggregated LC classes for LC map		Landcover class Onshore	Corine Code level 3	Corine Label Level 3
1	Built-up areas	CL 1	111	Continuous urban fabric
			112	Discontinuous urban fabric
			121	Industrial or commercial units
			141	Green urban areas
			142	Sport and leisure facilities
		CL 2	122	Road and rail networks and associated land
			123	Port areas
			124	Airports
		CL 3	131	Mineral extraction sites
			132	Dump sites
			133	Construction sites
2	Agriculture	CL 4	211	Non-irrigated arable land
			212	Permanently irrigated land
			213	Rice fields
		CL 5	221	Vineyards
			222	Fruit trees and berry plantations
			223	Olive groves
		CL 6	231	Pastures
		CL 7	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
3	Forests	CL 8	311	Broad-leaved forest
			312	Coniferous forest
			313	Mixed forest
4	Open areas	CL 9	321	Natural grasslands
			322	Moors and heathland
			323	Sclerophyllous vegetation
			324	Transitional woodland-shrub
		CL 10	331	Beaches, dunes, sands
		CL 11	332	Bare rocks
			333	Sparsely vegetated areas
			334	Burnt areas
5	Glaciers	CL 12	335	Glaciers and perpetual snow
6	Marshes and marine water bodies	CL 13	411	Inland marshes
			412	Peat bogs
			421	Salt marshes
			422	Salines
			423	Intertidal flats
		CL 14	511	Water courses
			521	Coastal lagoons
			522	Estuaries
			523	Sea and ocean
7	Inland water bodies	CL 15	512	Water bodies

2.5.3. Wind farms in mountainous areas

Only limited wind farms are installed in mountainous areas. In mid 2004 only 1.5% of the turbine capacity is installed in mountainous countries as Austria, Italy, France, Slovenia and Switzerland (Winkelmeier and Geistlinger, 2004). Lower accessibility of mountainous areas and the limited roads and grid connection result in less favourable conditions for wind farms. However, there are wind turbines at high altitudes. At levels above 2000 m most of the turbines installed are small turbines. In 2004, the highest large-scale wind park was situated at 2330 m in Switzerland . Because of the limited wind farms at high altitudes no extended research is done on the impact of the lower accessibility. Only one EU research project is found that considered the impact of wind farms in alpine area, Alpine Windharvest (2004).

Reduction of output

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

2.5.4. Offshore: Sea depth and selection of economic zones

For the offshore analysis we limited the potential area for wind energy generation in terms of sea depth and distance from coastline. For sea depth we analysed the offshore area with a depth less than 50 m using a global digital elevation model from NOAA's National Geophysical Data Center (NGDC) including bathometric data. Specific details: 30x30 seconds (1 km), including Sandwell & Smith bathymetry and ETOPO5 in polar areas. (Spatial reference system: Decimal degrees, GCS_Clarke_1866.) In order to attribute offshore area to specific countries we used the VLIZ Maritime Boundaries Geo database defining the Exclusive Economic Zones (EEZs) for every country (see *Figure 2-3*). The offshore area has been divided into different classes (<10 km, 10–30 km, 30–50 km and >50 km), which reflect distance from the coastline.

The legal Exclusive Economic Zone is the zone extending 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 should be described in a multilateral treaty. 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). Not all boundaries have been settled in treaties. In these cases, the median line has been used to establish the border of the EEZ. Since these undefined borders are not located in areas of wind energy potential, these uncertainties do not affect the outcome of our analysis.

2.5.5. Load hours

The average wind speed at hub height needs to be converted to full load hours of the turbine[3]. Depending on actual wind speed, a wind turbine will generate between 0–100% of its nominal power. The amount of full load hours as a function of the average annual wind speed can be calculated using a so-called Weibull distribution and the power curve from existing turbines.

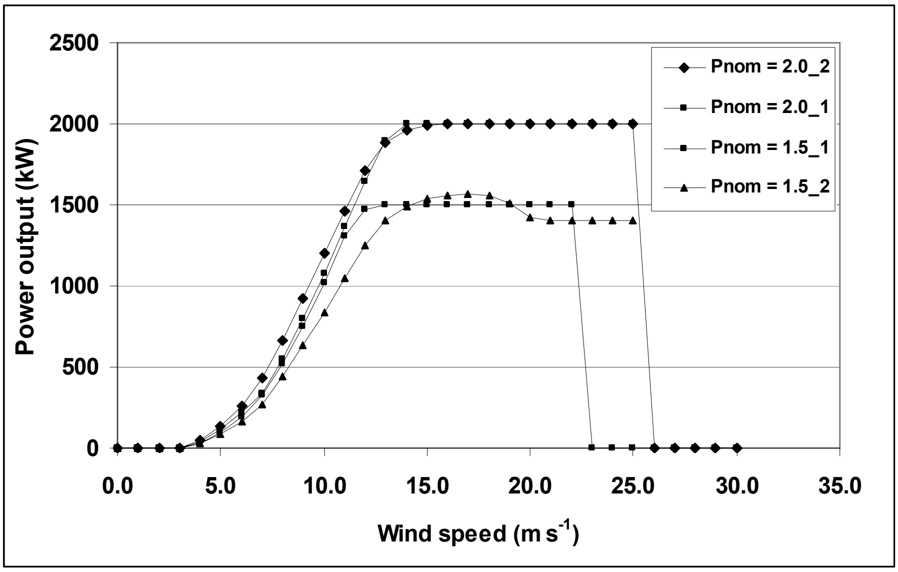

Figure 2-6: Power-velocity curves of four existing wind turbines

In Figure 2-6, the power output of various existing wind turbine types is given for different average wind speeds. Based on these output figures (kW) a Weibull distribution is calculated (with K=2[4]), which describes the variation in wind speeds over the year. The amount of full

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[3] The number of load hours is a standardized number giving the equivalent hours that a wind turbine should operate at full capacity to generate the electricity that a wind turbine generates in a full year. Full load hours thus corresponds to production (MWh/y) per installed power capacity (MW).

[4] Sensitivity analyse showed that in the range K=1.75 to 2.4 the results for annual wind speeds between 5 m/s and 11 m/s varies not more 10% in full load hour results

load hours as a function of the wind speeds is calculated from the outcomes and general trend lines are plotted. From these trend lines we derived linear regression functions in this study to calculate full load hours from known wind speed at hub height.

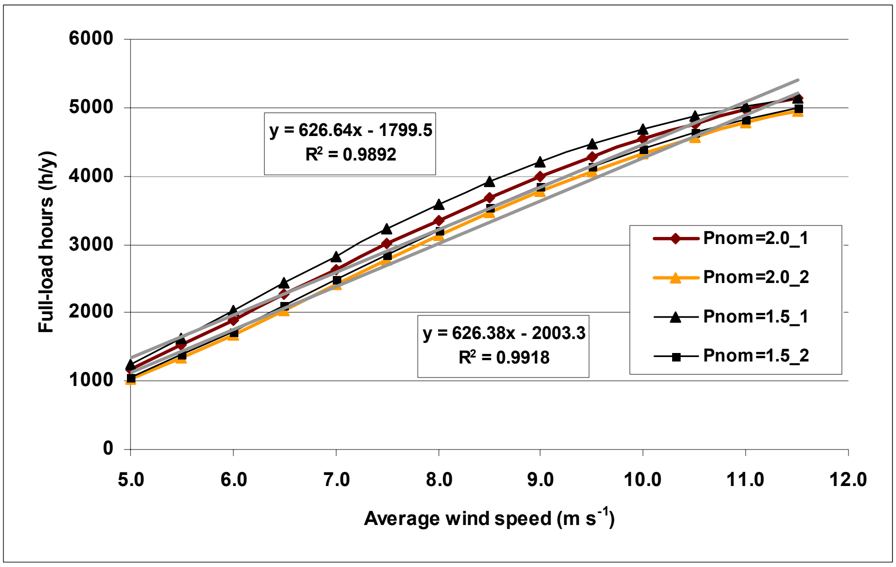

Figure 2-7 Estimated full load hours based on power-velocity curves and Weibull distribution

The calculated full-load hours of individual wind turbines are theoretical maximum values. The practical load hours are lower because of array efficiency and availability of the wind farm. 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 0.92,5 for onshore wind farms and 0.90 for offshore wind farms is assumed. The second efficiency factor, availability, refers to the fraction of the full-load hours in a year that the turbine is available. There are several reasons that a wind turbine may not be available such as maintenance and repair activities. The availability factor is set to 10 % for offshore and 3 % for onshore wind farms (Hoogwijk, 2004) below 600m height and 10% for turbines above 600m height.. In summary, the estimated 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 arrive at practical full-load hours.

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

(1) Average wind speed at hub height is calculated as:

- *average wind speed at hub height = (average 00–05 wind speed data) * (scaling factor dependent on CLC type)*

(2) Practical full load hours are calculated from the linear relation between the average wind speed and full load hours (see Figure 2-7):

- *practical full load hours grid onshore H< 600m = ((average wind speed at hub height)*626,51 – 1901)*0.90*
- *practical full load hours grid onshore H>600m = ((average wind speed at hub height)*626,51 – 1901)*0.83*
- *practical full load hours grid offshore = ((average wind speed at hub height)*626,51 – 1901)*0.81*

3. Results

3.1. Introduction

Chapter 2 ('Methodology') discusses how this study defines theoretical, technical, economic, market and socially and environmentally compatible potential. The focus of this study is on the socially and environmentally compatible potential of wind energy. Various restrictions to the unrestricted technical potential have been taken into account to arrive at the socially and environmentally compatible potential. In fact, the most optimal way of wind turbine siting is not a pure technical matter, but needs consideration of various other aspects such as aesthetics and environmental aspects. Figure-3-1 shows the type of restrictions (left side) that have been applied to define the different potential of wind energy (right side).

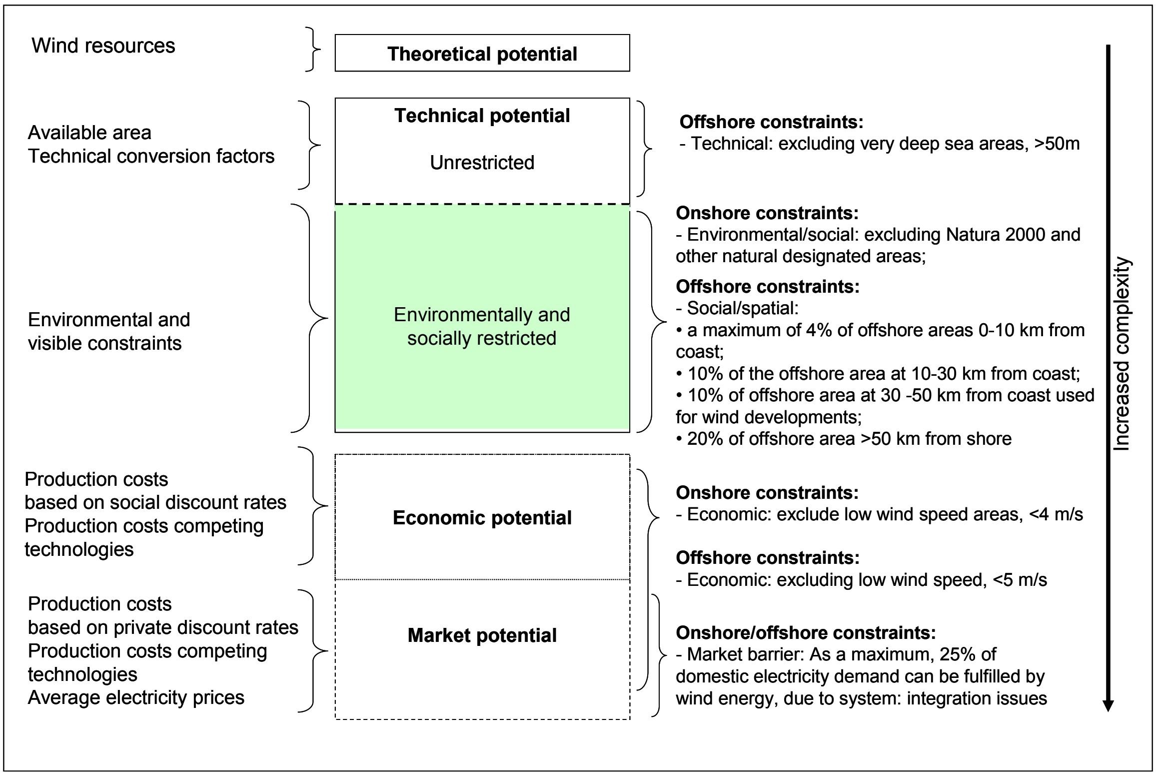

Figure-3-1 Environmental, social, economic and technical restrictions to the wind energy potential

3.2. Unrestricted technical potential

3.2.1 Onshore

The unrestricted technical potential estimation for wind on land is based on wind speeds per type of land cover. The 15 CORINE land cover classes are aggregated to 7 classes according to the method displayed in table Table 2-2-2. The unrestricted technical wind energy potential for 2020 and 2030 is based on wind power density and technological development of wind turbine technology. All types of land are included, independent of their suitability for wind turbine developments. Figure 3-2 gives the available area in seven aggregated land cover classes. The total land area sums up to 5.4 million km^2 in all EEA countries together. According to Figure 3-2, agricultural land and forests are represented best in the EEA countries. The aggregated class 'forests', made up of original CLC classes 8 to 11, and the aggregated class 'agricultural land', made up of original CLC classes 4 to 7 cover about 90% of total land available. France and Turkey have the largest areas of agricultural land and, Sweden, Finland and Turkey have by far the largest area of forests. The amount of agricultural land is of interest, because section 4 showed that the feasible penetration of wind turbines is on agricultural land (CLC 4, 6 and 7) is higher compared to the average feasible penetration on all land cover types together in the Netherlands, Germany and Denmark. There are several reasons to expect agricultural land to be attractive for wind developments. First, the installation of wind turbines 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 lay-out or spacing than is optimal.

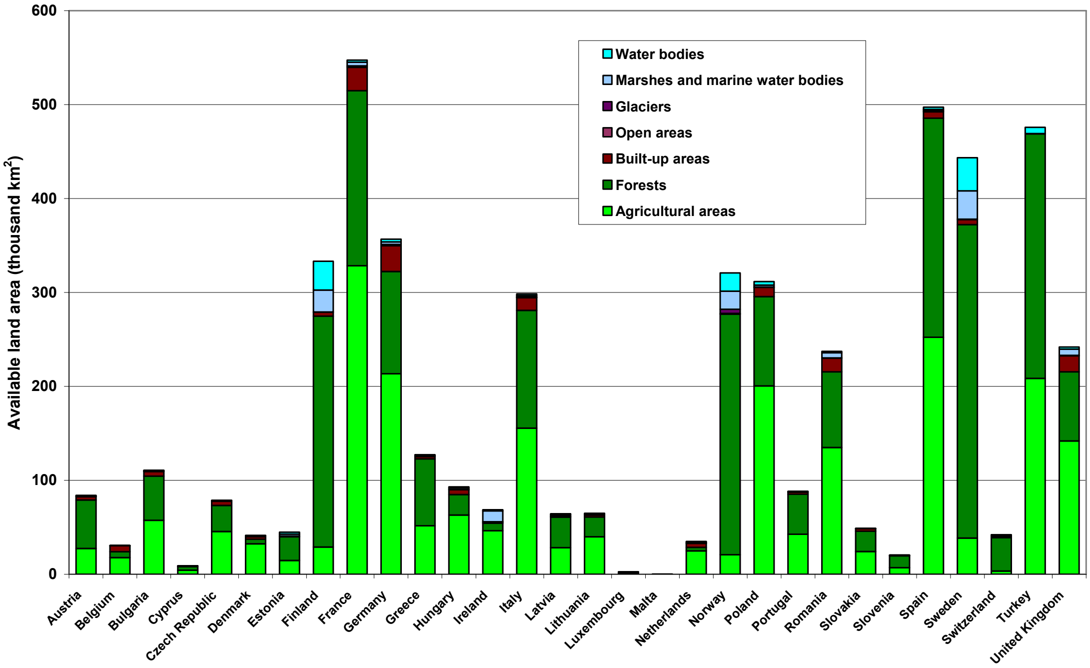

Figure 3-2: Area available per type of aggregated land cover class (km^2)

For each aggregated CLC class (1 to 7) the technical potential for onshore wind has been calculated on a country basis. Section 2.5.2 and section 2.5.5 explain the methods to calculate wind speeds at hub height and the calculation of the amount of full load hours. See Figure-3-3 for the results of this analysis. The estimated technical potential for wind energy on land is about 52 000 TWh in all EEA countries together. More than half the technical potential is generated in classes with average wind speeds of 5.4 m/s and 5.7 m/s.

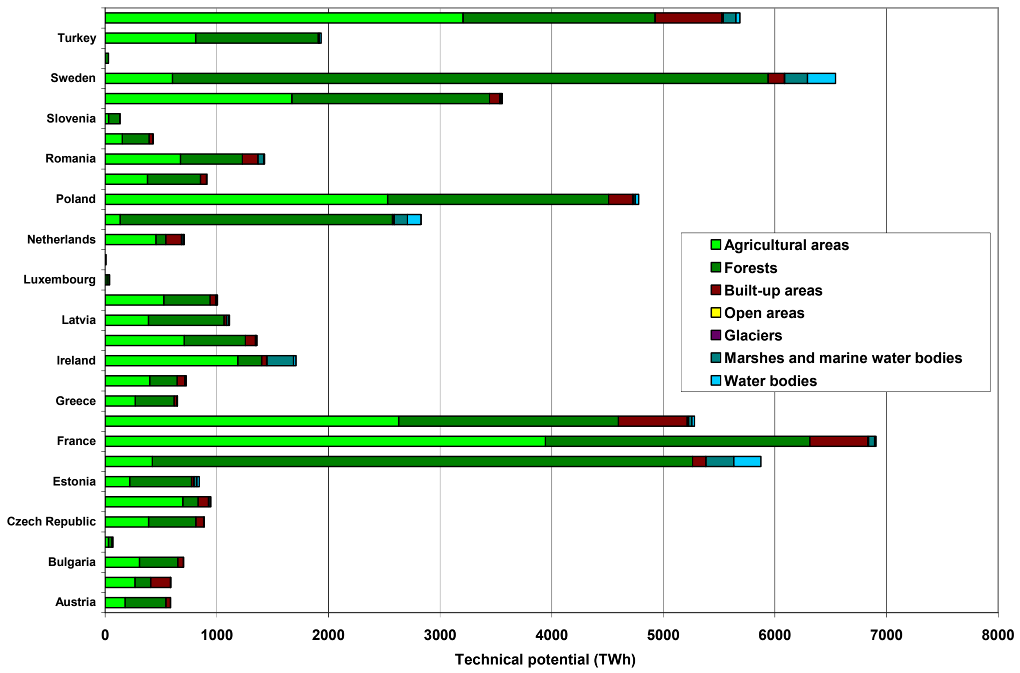

Figure-3-3: Unrestricted technical potential for onshore wind energy in 2030, based on average wind speeds 2000-2005

3.2.2 Mountainous areas

In section 2.5 of this report wind energy development in mountainous areas has been discussed. When mountainous areas are defined as areas above 600 meters, 33% of the total land area in EEA countries falls in this category. Switzerland, Turkey, Austria and Spain have largest shares of mountainous areas. In Switzerland, 74% of the total land area is mountainous area, for Turkey, Austria and Spain it is respectively 71%, 59% and 57%. The technical potential for wind in mountainous areas where we assume a lower power density of 4 MW/km^2 is just over 3200 TWh in all EEA countries together (approximately 6% of the total potential). The wind energy potential in mountainous areas is given in Figure 3-4.

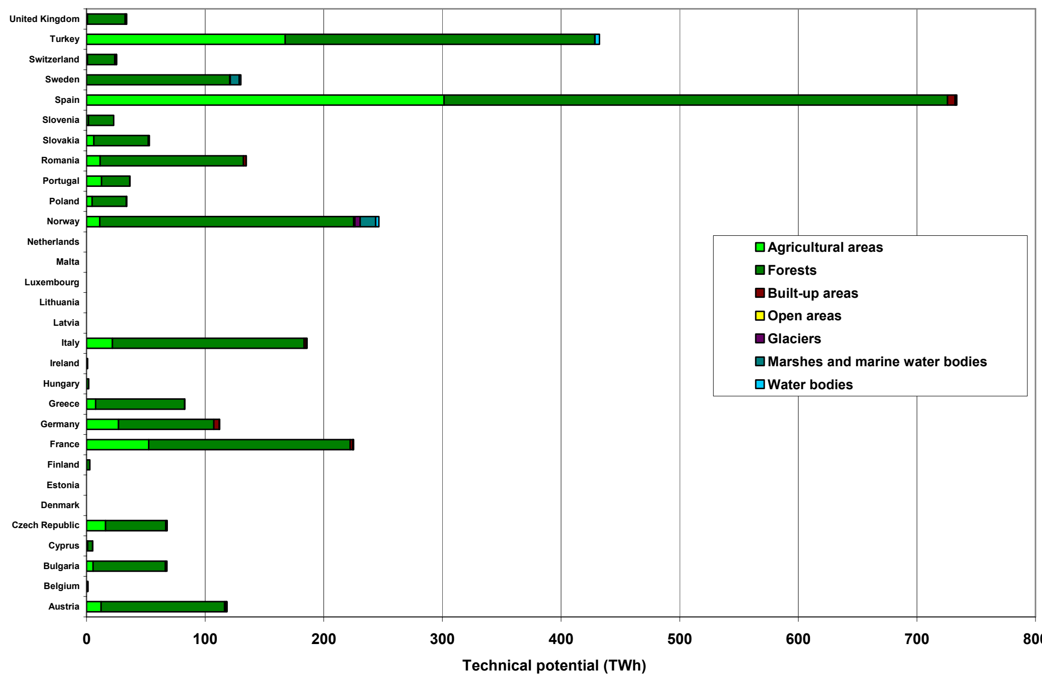

Figure 3-4 Potential for wind energy in mountainous areas in 2030 (TWh)

3.2.3. Offshore

As explained in section 2.5, Economic Exclusive Zones have been used to allocate offshore areas to the different countries. The United Kingdom (114 000 km^2) and Norway (88 000 km^2) have most offshore area available, which is not surprising since these countries have a long coastline. Offshore areas are split into categories according to the distance to the coast; 0-10 km, 10-30 km, 30-50 km and >50km (see Figure 3-5). These categories are selected to provide some information about the relationship between the potential and the distance to the shore.

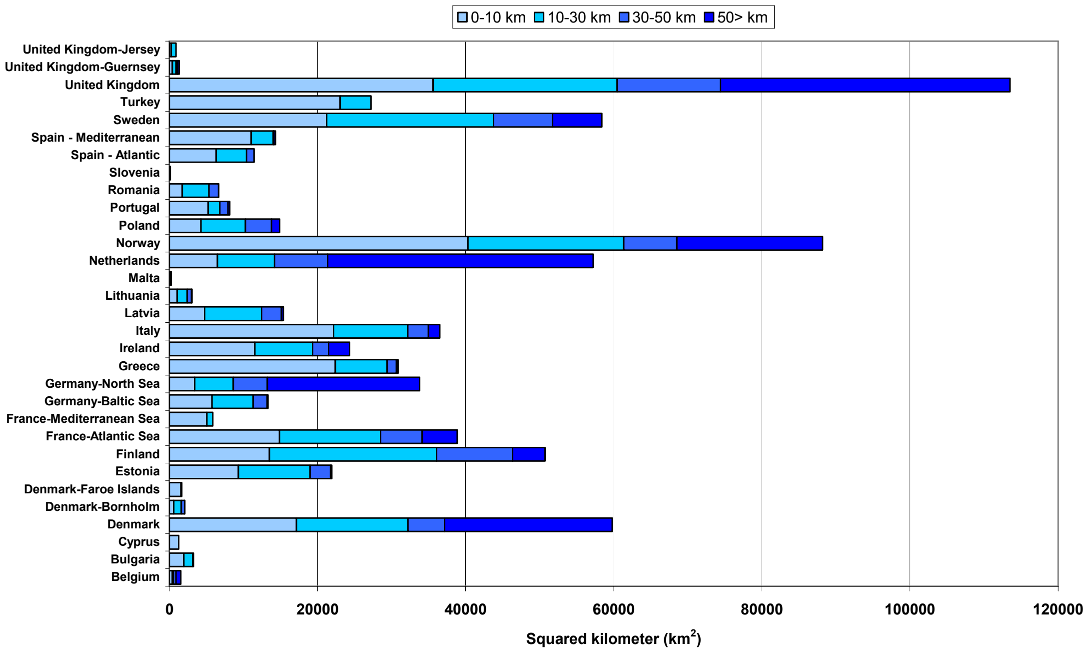

Figure 3-5: Available offshore area per sea (km2) per Economic Exclusive Zone

Current wind energy technology and its anticipated future developments set limits to the unrestricted potential for offshore. First, no wind speed data have been collected for offshore areas with a depth of more than 50 meters. These areas are excluded from the technical potential estimation, because wind turbine developments in such deep waters are considered not to happen within the limits of current technology. These days, wind farms are placed in shallow waters up to about a depth of 25 metres water depth.

The offshore (unrestricted) technical potential in 2030 is estimated at 23 000 TWh for all EEA countries together (Figure 3-6). This is just below half the onshore (unrestricted) technical potential (52 000 TWh). This study includes 5 000 000 km^2 land area and 750 000 km^2 sea area, which explains that the offshore (unrestricted) potential is lower. The potential estimation for 2030 is based on the technical limits of offshore wind technology by 2030 and related energy density (in MW/km^2) combined with average wind speed data from the years 2000 to 2005. When calculating the technical potential for these years separately, large inter-annual variability in potential is seen. The estimated technical potential in 2004 was about 11% higher compared to 2003, because of large differences in wind speed. Some individual countries show inter-annual variabilities of almost 30%, e.g. in Denmark (North Sea) and Germany (the Baltic and North Sea).

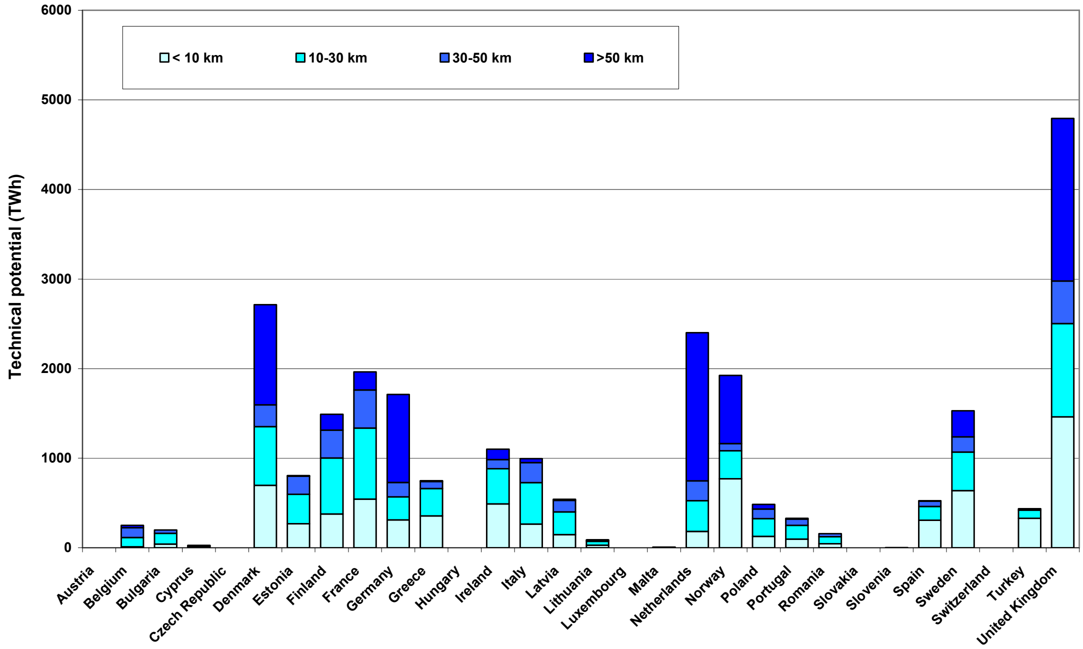

Figure 3-6: Unrestricted technical potential for offshore wind energy in 2030, based on average wind speed data

Of the distance classes studied for offshore wind, wind turbine developments at 10-30 kilometres from the coast are considered most appropriate. The impact of the visibility of wind farms is significantly less compared to a distance of 0-10 kilometres from the coast and the sea depth is often still appropriate to site wind turbines without significant additional costs. Figure-3-7 shows that the offshore wind energy potential between 10 and 30 kilometers from the coast is concentrated in the Baltic, the North Sea (incl. the Channel), and the Mediterranean. Respectively, 29%, 25% and 20% of the total offshore wind potential at 10 to 30 kilometers from the coast (7 100 TWh) can be found in these areas. Although the potential for offshore wind in other areas seems to be quite small, in some small areas interesting potentials may be found. Some offshore areas in this distance class are already deeper than 50 meters (see *Figure 3-8*) and therefore not suitable for wind energy developments.
Further out at sea, at 30 to 50 kilometers from the coast, 30%, 30% and 20% of the wind potential can be found in the Baltic, the North Sea (incl. the Channel) and the Mediterranean respectively. The total potential for this distance class is estimated at 3 300 TWh.

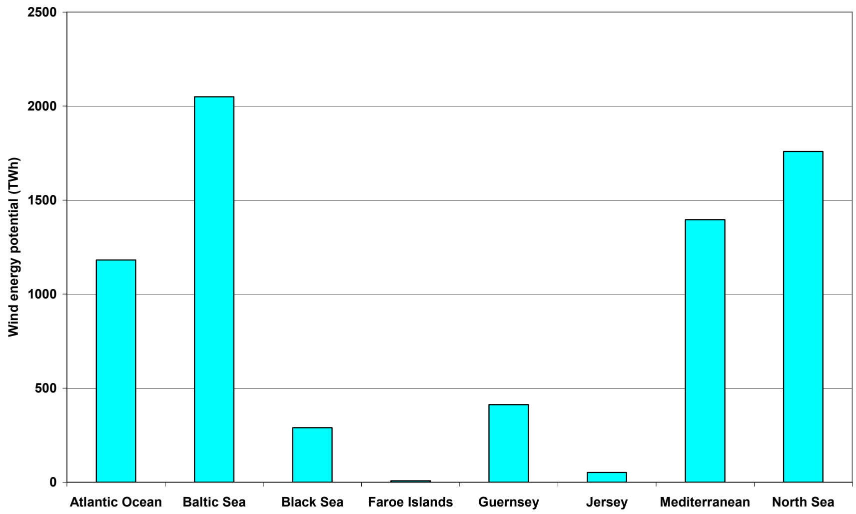

Figure-3-7 Unrestricted technical offshore wind potential in offshore area at 10 to 30 kilometers from the coast

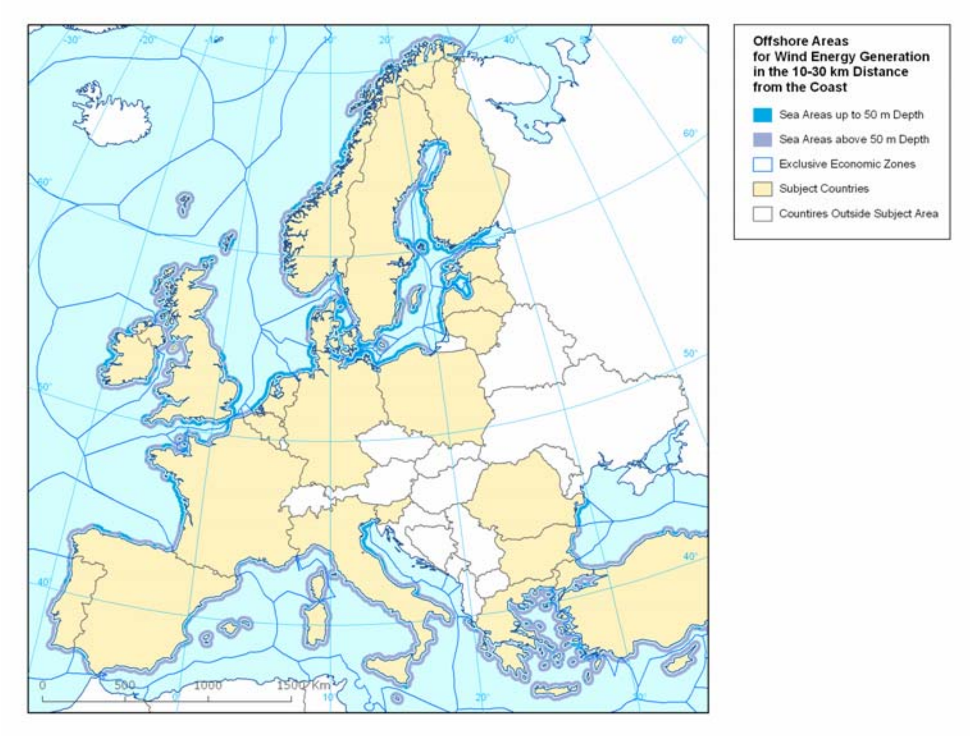

Figure 3-8 Offshore areas for wind energy generation at a distance of 10 to 30 km from the coast

3.3. Distribution of the wind energy potential

Offshore resources tend to be better than onshore resources, because on average they are characterised by higher load hours. Water has less surface roughness compared to land (especially deeper waters), which results in considerable higher wind speeds offshore and consequently higher load hours. In this study, offshore electricity production has been included from 5.0 m/s at a hub height of 120m; onshore production takes off at 4.3 m/s at a hub height of 80 m. *Figure 3-9* makes visible that offshore resources are better, in the way that wind turbines experience higher wind speeds and therefore higher annual load hours. On land only 5 % of the technical potential is realised in areas with over 3 000 full load hours, while at sea this percentage is over 40 %. These very windy land areas are mainly located in parts of the United Kingdom, Scotland and Ireland (see Figure 3-10 and *Figure 3-11*). On land there is no resource potential in the load class >4 000 hrs.

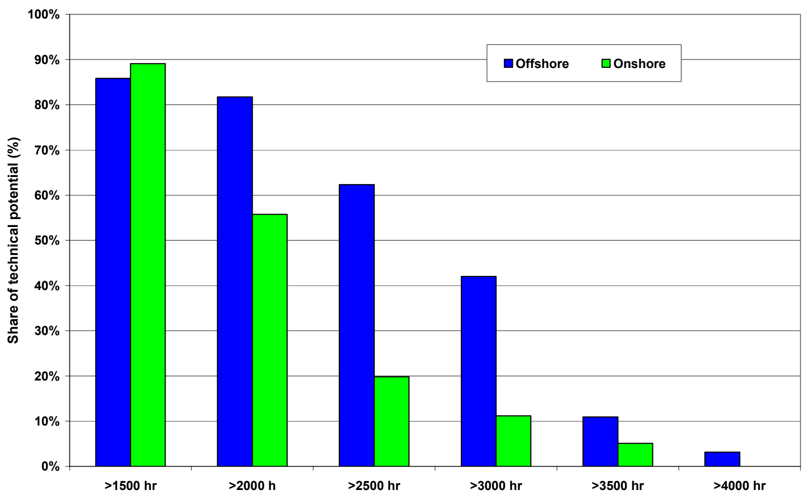

Figure 3-9: Share of the technical potential realized in different load hour classes; all distance classes are included for offshore

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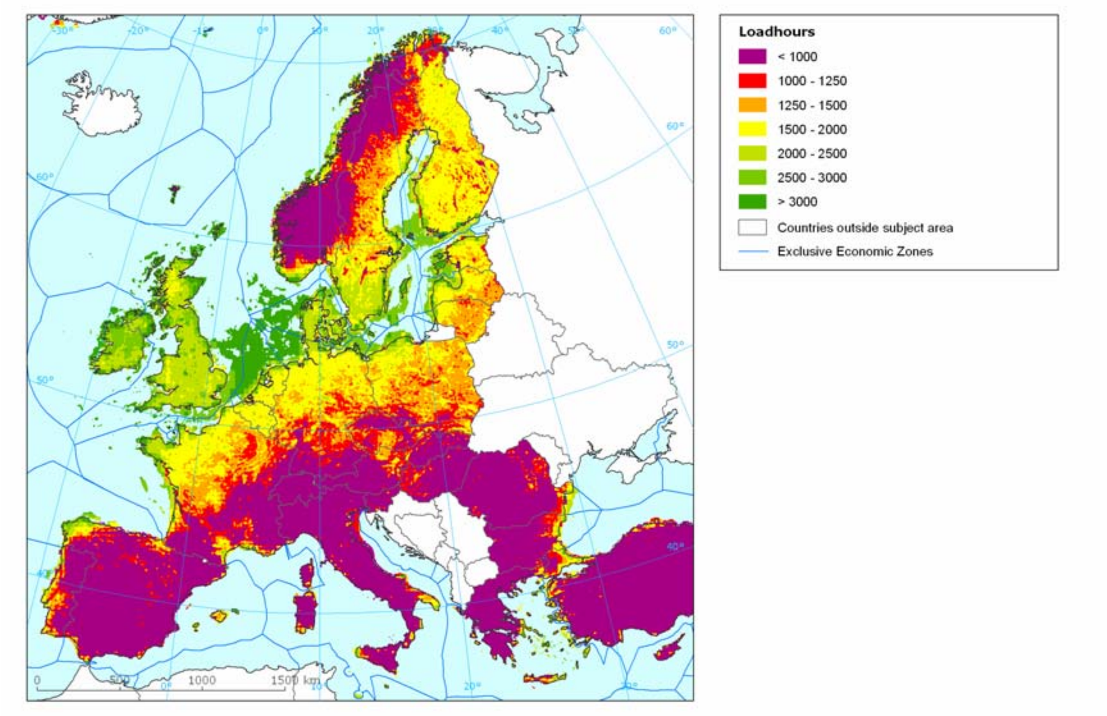

Figure 3-10: Distribution of full load hours (80m hub height onshore, 120m hub height offshore) over Europe

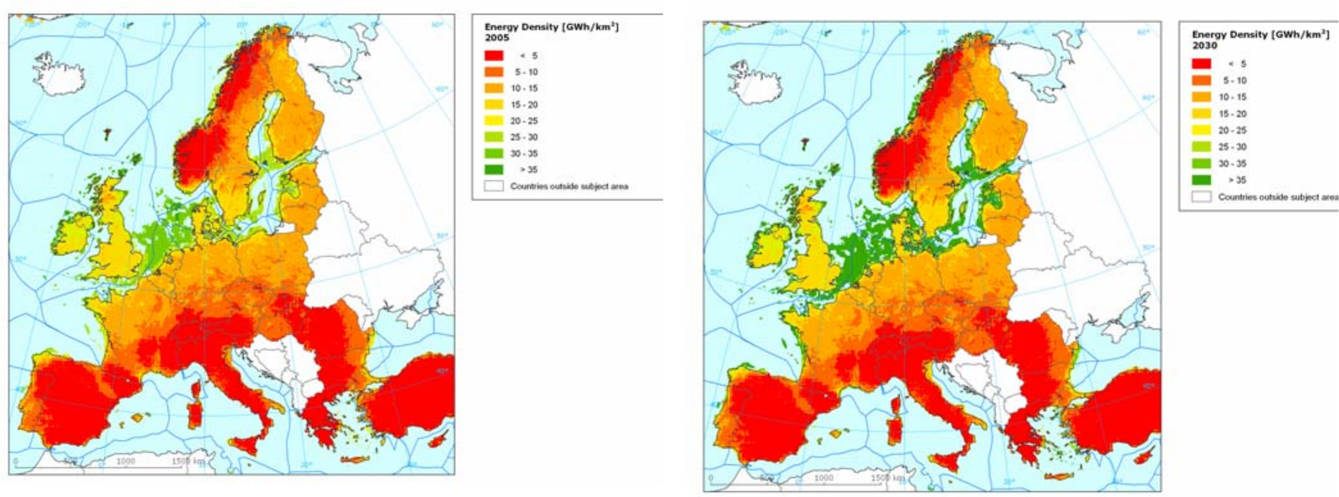

Figure 3-11 Distribution wind power energy density (GWh/km^2) for 2005 and 2030 (80m hub height onshore, 120m hub height offshore) over Europe

3.4. Socially and environmentally compatible technical potential

On land, environmental and social constraints might limit the potential for wind energy developments. In this chapter, we analyse to what extent the potential for wind energy might change when biodiversity constraints are taken into account. For offshore wind, we address spatial planning and visibility issues that might affect the offshore area available for wind energy developments.

3.4.1 Onshore: Biodiversity constraints

Chapter 8 on biodiversity constraints will elaborate on the need for proper siting of wind farms as a key to avoid or minimise adverse biodiversity effects. Poorly sited wind farms can have significant negative impacts on certain species, in particular birds and bats. As a starting point to addressing the issue of biodiversity, the wind energy potential is recalculated excluding wind energy developments in Natura 2000 areas and other designated areas.

Table 3-1 Natura 2000 and designated areas in Europe

	Total area		Natura 2000 and CDDA		Land excluded from wind energy development as a percentage of total	
	km^2	km^2	km^2	km^2	%	%
	Total	> 4m/s	Total	>4 m/s	Total	>4 m/s
Austria	83931	0	0.0	0	-	-
Belgium	30642	5427	5192	390	16.9%	7.2%
Bulgaria	110915	1980	0	0	-	-
Cyprus	8921	860	1142	0	12.8%	
Czech Republic	78754	0	0	0	-	-
Denmark	41318	41317	4949	4949	12.0%	12.0%
Estonia	44850	11232	0	0	-	-
Finland	333409	32942	53006	2162	15.9%	6.6%
France	547344	79737	146819	15632	26.8%	19.6%
Germany	356869	38857	129987	7372	36.4%	19.0%
Greece	127212	16158	25313	3862	19.9%	23.9%
Hungary	92975	0	22905	0	24.6%	0.0%
Ireland	68722	68715	0	0	-	-
Italy	298560	9582	64332	1839	21.5%	19.2%
Latvia	64381	11700	11945	1986	18.6%	17.0%
Lithuania	64955	3348	11415	333	17.6%	9.9%
Luxembourg	2580	0	0	0	-	-
Malta	240	240	60	60	24.9%	24.9%
Netherlands	34880	18973	4684	2265	13.4%	11.9%
Norway	320856	37048	0	0	-	-
Poland	311553	13509	0	0	-	-
Portugal	88451	4097	0	0	-	-
Romania	237247	2552	34044	2449	14.3%	96.0%
Slovakia	48912	0	18132	0	37.1%	-
Slovenia	20418	0	8215	0	40.2%	-
Spain	497332	20993	0	0	-	-
Sweden	443664	52489	86148	4709	19.4%	9.0%
Switzerland	41488	0	0	0	-	-
Turkey	779966	11336	0	0	-	-
United Kingdom	239986	240633	50998	50998	21.3%	21.2%
Total	**5421331**	**723725**	**679287**	**99006**	**12.5%**	**13.7%**

For this purpose, Natura 2000 and nationally designated areas (CDDA) are aggregated. In Figure 3-12, both Natura 2000 areas and CDDA areas and their intersection are mapped for different parts of Europe. A relatively large area where Natura 2000 and CDDA overlap is along the coast of the Netherlands, Germany and Denmark. In Figure 3-13 the same areas are mapped, but with full load hours as background. The surface area that combines Natura 2000 and CDDA is given in Table 3-1. Some remarkable situations happen to occur in Germany and Romania. The figures for Germany show that over 80% of the aggregated Natura 2000 and designed areas have wind speeds below 4 m/s. Wind speeds at which it is not favourable for wind farm developments. In Romania we see the opposite, 96% of the excluded Natura 2000 and designated areas have wind speeds above 4 m/s and are in principle suitable for wind developments.

When the aggregated Natura 2000 areas and CDDA areas are shielded from wind energy developments the available land decreases by 13.7 %. If we assume that the excluded areas are spread equally over all land cover classes the technical potential decreases to 43 000 TWh. Since Natura 2000 and CDDA areas are expected to be found in CLC class agricultural areas with better wind conditions in preference to forest areas, it is expected that the technical potential of 43 000 is underestimated.

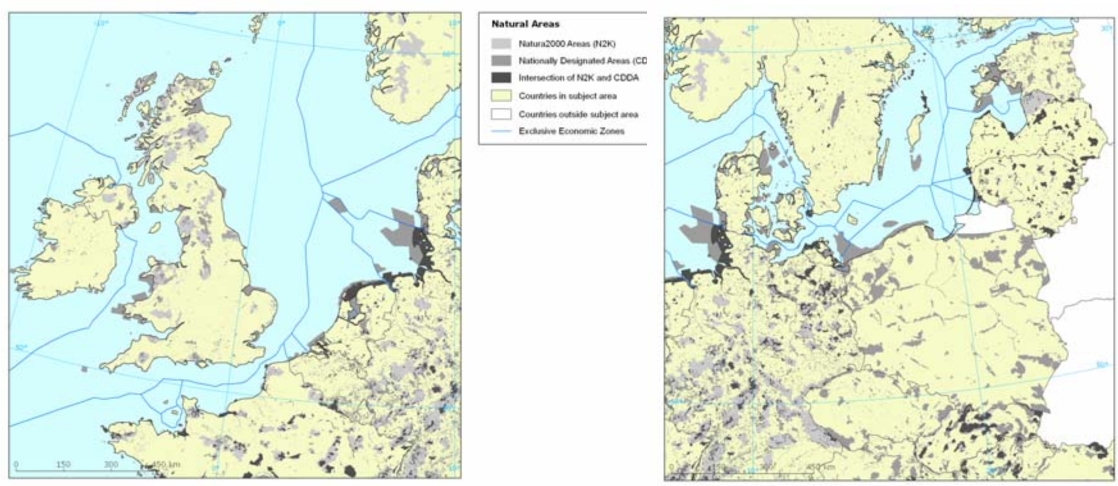

Figure 3-12: Natura 2000 areas, Nationally Designated Areas and their intersection for different parts of Europe

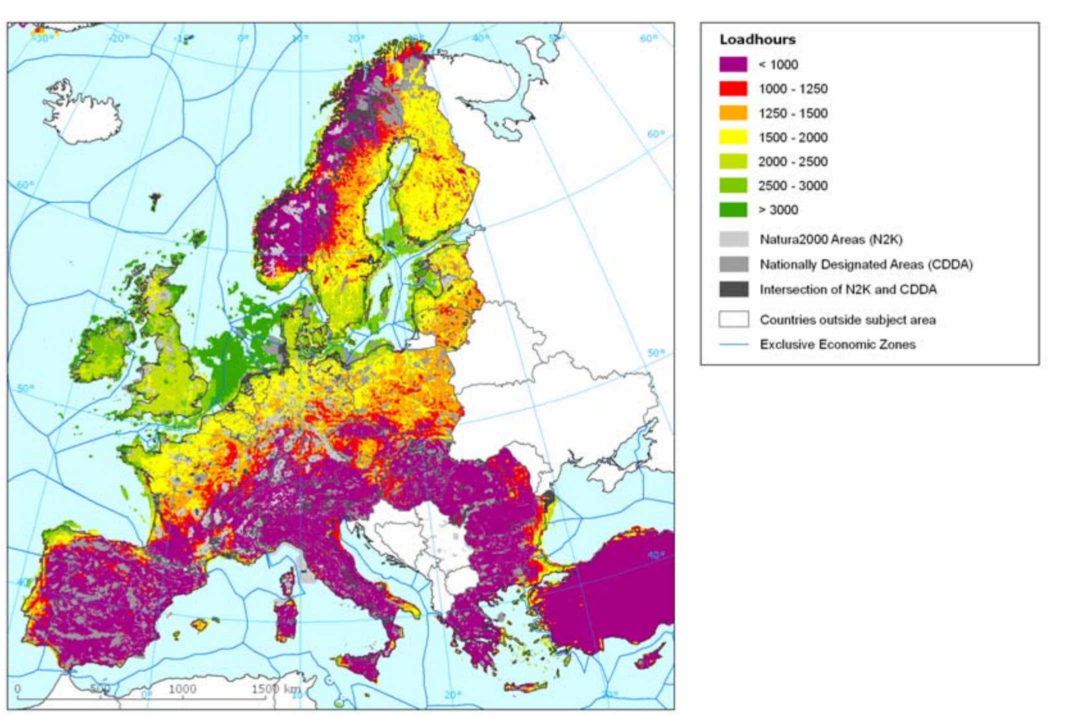

Figure 3-13: Union of Natura 2000 and CDDA areas in Europe with overlay showing full load hours

3.4.2 Offshore

The unrestricted technical potential for offshore wind does not take into account that other uses of the sea area might limit the potential for offshore wind developments. Other uses comprise for example shipping routes, military platforms, oil and gas exploration, touristic zones. Spatial planning policy is very important to guide a proper use of the available sea

area. Also 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 aspects of wind turbines play an important role, because the wind farms can be seen from the coast (see chapter 6 on social constraints). In some countries, the Netherlands for example, it is prohibited to build wind farms within 12 nautical miles from the coast (about 22 km), mainly due to the visual impacts. In the United Kingdom too, it is expected that in the next round of tenders for wind farms only locations beyond the 12 mile zone will be designated.

Taking the above considerations into account there seem to be good reasons to include some limitations to the unrestricted technical potential to arrive at a more realistic offshore technical potential estimation. Therefore, we assume that wind farm developments within 10 kilometres from the coast suffer most from spatial planning and social restrictions. We assume that in practice only 4% of the offshore area in this distance class might be available for development of offshore wind farms. For the distance classes ’10-30 kilometres’ and ’30-50 kilometres’, in our opinion, the area that can be used for wind farms can reach higher levels without spatial planning or social limitations, namely 10%. For distances to the coast above 50 kilometers it seems that a larger fraction could be utilized, because this area is relatively large and other functions like shipping e.g. are less concentrated. If these restrictions are applied the unrestricted technical potential for offshore wind drops from 25 000 TWh to 3 000 TWh (see Figure 3-14). To put this figure in perspective, this amount of electricity from wind would be be sufficient to fulfil about 60% of the energy demand in Europe in 2030 (5 100 TWh).

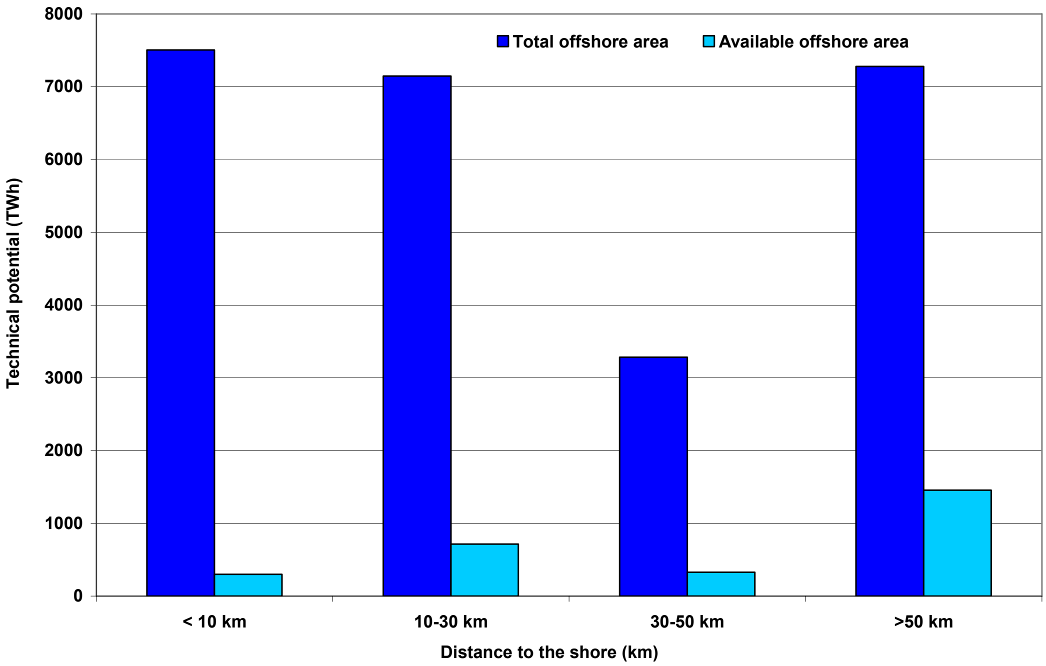

Figure 3-14 Estimated technical potential of offshore wind in Europe with restricted offshore areas available

3.5. Economic potential

In the definition of the economic assessment of wind energy we assume that the costs should reflect a societal/government perspective. Therefore, a 4.0% social discount rate is applied. In the market potential the perspective of the investor (which will include the effect of policies such as subsidizing wind energy) is added. Other economic assumptions used for this analysis e.g. the share of private capital and loans for onshore and offshore wind are summarized in table 3.2. The generation costs for wind electricity based on this discount rate can be found in Figure 3-15.
Figure 3-16 shows the electricity production costs for both onshore and offshore wind in 2005 and 2030. One can see that in 2030 production costs for offshore wind are almost at the

same level of 2005 costs for onshore wind. At average electricity production cost of 5.7 €/kWh in 2005, onshore wind energy starts to be profitable at 2300 full load hours, while offshore wind at 3700 full load hours. In the year 2030 onshore wind will be already profitable just over 1000 full load hours and offshore wind above 1750 full load hours (based on average production cost of 6.9 €ct/kWh, see table 3.2.

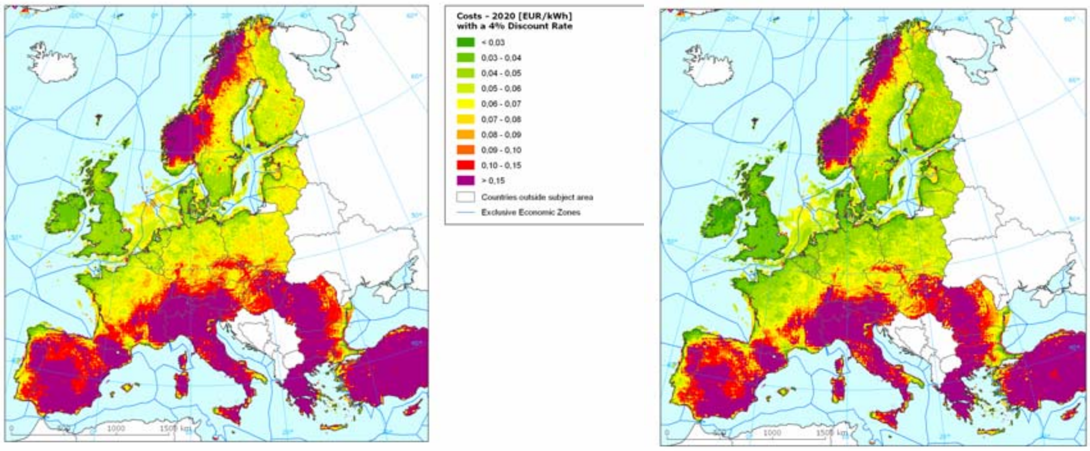

Figure 3-15: Generation cost for wind energy in Europe, left: 2020, right: 2030, 4% discount rate

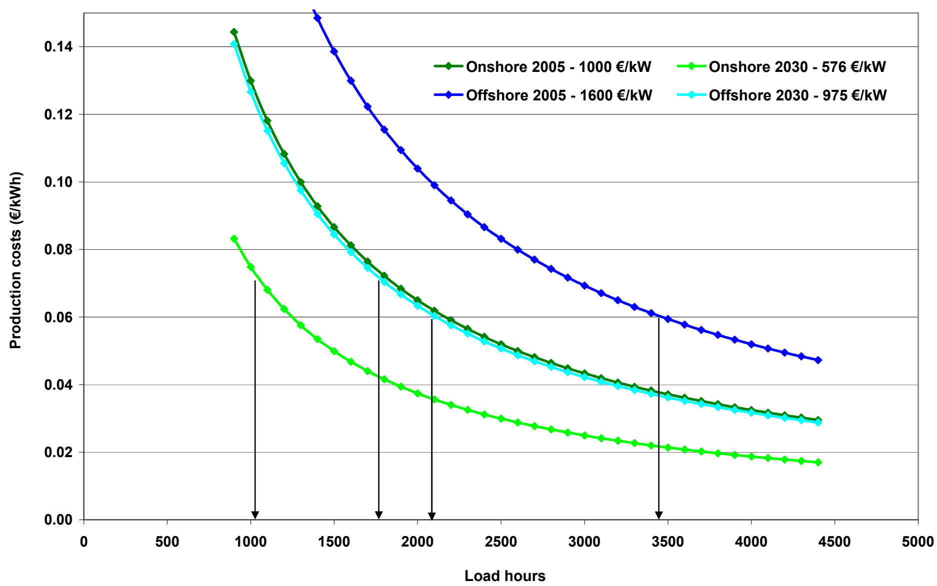

Figure 3-16: Electricity generation costs for onshore and offshore wind in 2005 and 2030; discount rate of 4%

3.6. Market potential

According to the definition of the IPCC, the market potential of wind energy is based on private costs and private discount rates. The market potential shows to what extent the available wind energy resources (technical potential) will be exploited under market conditions. Areas with estimated wind speeds below 4 m/s are excluded from the analysis. First, the estimation of wind speeds at hub heights of 80m is not accurate for low wind speed areas and secondly, electricity generation from wind in low wind speed classes is not economic exploitable.

The cost of the technology which to a large extent makes up the electricity generation costs can be a limiting factor for further implementation of wind power. In 2005, there were hardly any wind resource areas with generation costs below 10 €ct/kWh according to Figure 3-17. The effect of decreasing costs of wind turbine technology will result in lower electricity generation costs in 2020 and 2030. Figure 3-18 gives the electricity generation costs from wind in Europe in 2020 and 2030. The red coloured area, which represents electricity generation costs above 10 €t/kWh shrinks significantly between 2005 and 2030. Countries in the Southern part of Europe, where relatively low wind speeds prevail, still have generation costs in the highest category (above 10 €t/kWh).

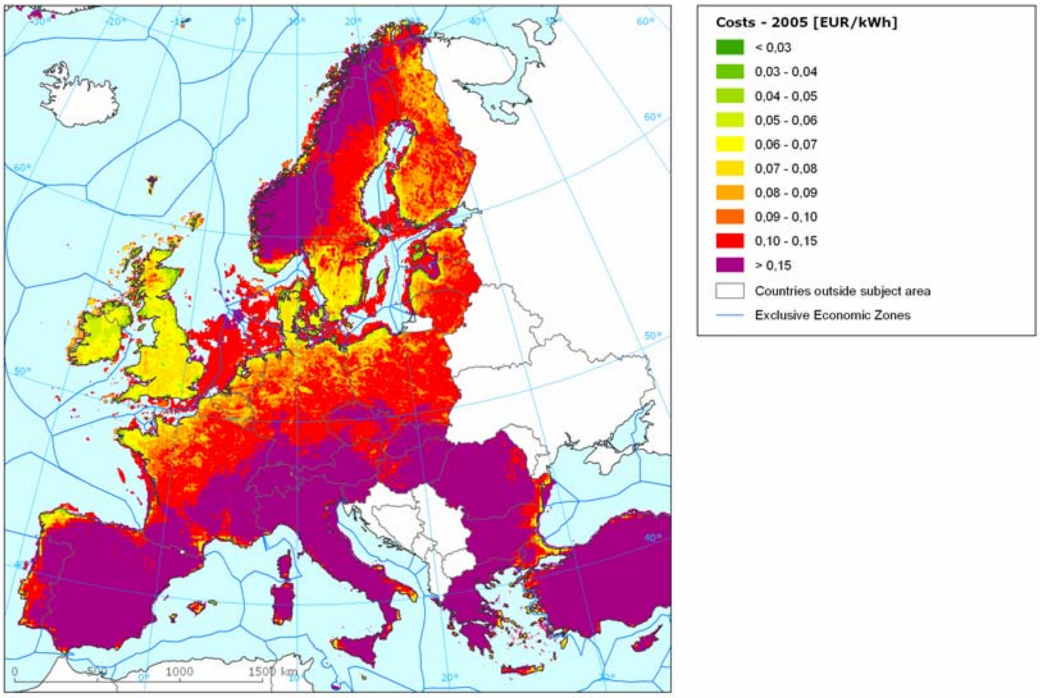

Figure 3-17: Generation costs for wind energy in Europe, 2005

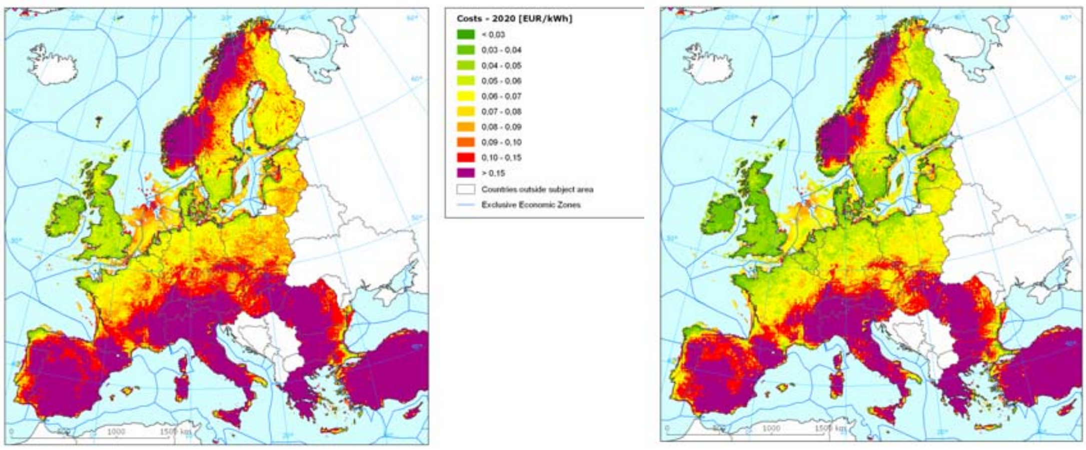

Figure 3-18: Generation costs for wind energy in Europe, left: 2020 costs, right: 2030 costs,

The extent to which new wind energy capacity will be constructed in Europe strongly depends on the development of electricity tariffs and average electricity production costs in the target years 2020 and 2030. Wind electricity production costs in relation to electricity tariffs show at what costs it is still possible to make profit. Comparison of the wind electricity generation costs to average electricity production costs shows at what costs wind becomes competitive to other electricity generation options. Together, average electricity generation costs and electricity tariffs indicate a range for estimating the market potential.

Electricity tariffs are derived from the sustainable emission pathway scenario of PRIMES and amount to 8.3 €ct/kWh in 2020 and 9.2 €ct/kWh in 2030 in the EU-25. On a country basis the electricity tariffs cover a broad range in 2005, but will converge in the years to 2020 and 2030 because of the existence of European electricity markets and grids. The grid costs, which are included in the electricity tariffs, are subtracted from the electricity tariffs to make a fair comparison with electricity generation costs. The costs of connection to the grid are estimated at 2 €ct/kWh.

The cost competiveness of wind power with other types of electricity generation is a good indicator for possible future deployment rates of the technology. Average generation costs of electricity will achieve levels of 6.0 €ct/kWh in 2020 and 6.9 €ct/kWh in 2030 under the PRIMES sustainable emission pathway scenario. Under scenarios without climate policy both electricity tariffs and electricity production costs will turn out to be lower in 2020 and 2030 compared to the costs under the sustainable emission pathway scenario. Implications are that the wind energy is less competitive without targeted renewable energy or climate policies which result in lower implementation rates of the technology.

Table 3-2 Overview of average electricity tariffs and average production costs used in the calculations of market potential for wind energy, source PRIMES[5]

	Base year - 2005	Target year - 2020	Target year - 2030
	€ct/kWh	€ct/kWh	€ct/kWh
Electricity tariffs	8.2	8.3	9.2
Grid costs (own estimate)	2.0	2.0	2.0
Average production costs	5.7	6.0	6.9

3.6.1 Onshore

The potential of onshore wind energy that can be generated at average production costs of 6.0 €ct/kWh in 2020 is about 9 600 TWh, which is 20% of the unrestricted technical potential (see Table 3-3). The wind energy potential in the different cost classes is defined as either 'not competitive', 'most likely competitive' or 'competitive'. The cost class defined as 'most likely competitive' includes part of the potential will be generated at higher production costs than 6.0 €ct/kWh. The wind energy potential that is generated at average costs of 6.7 €ct/kWh and higher will not be competitive at average generation costs of 6.0 €ct/kWh. Up to 2030, the economic potential for onshore wind will increase to over 27 000 TWh. This corresponds to almost 60% of the total unrestricted potential. The wind energy potential that cannot be exploited at these average production costs of 6.9 €ct/kWh comes to 7 000 TWh. In Figure 3-19 the resulting cost-supply curve for onshore wind energy in 2020 and 2030 is given. The most remarkable development is in the Eastern part of the EU ("EU10"), where the economic competitive potential increases more than 10-fold (400 to 4 400 TWh) from 2020 to 2030. In the EU-15 we still see a doubling (8 500 to 21 000 TWh) of the economic competitive potential.

[5] as published in the EEA report "Technical Report on Scenario test run results for Climate Change and Air Pollution SoEOR2005 (Part 1)"

Table 3-3 Generation potential of wind energy on land in different cost classes, TWh

TWh	Not competitive[6]	Most likely competitive[7]	Competitive[8]	Not competitive	Most likely competitive	Competitive	Total
	2020	2020	2020	2030	2030	2030	2030
Austria	463	3	0	199	211	56	466
Belgium	371	53	12	0	12	425	436
Bulgaria	540	14	34	309	167	112	587
Cyprus	48	8	4	20	14	25	59
Czech Republic	687	1	0	169	434	85	687
Denmark	0	65	687	0	0	751	751
Estonia	419	111	142	0	75	597	672
Finland	4016	204	198	7	1052	3359	4418
France	3951	733	576	736	1409	3115	5260
Germany	3376	384	258	344	1206	2467	4017
Greece	261	54	251	123	71	372	566
Hungary	557	0	0	343	213	1	557
Ireland	0	7	1308	0	0	1315	1315
Italy	983	57	112	571	247	334	1152
Latvia	614	154	85	0	260	593	853
Lithuania	703	13	30	0	305	442	746
Luxembourg	30	0	0	0	20	10	30
Malta	0	0	7	0	0	7	7
Netherlands	217	158	158	0	0	533	533
Norway	1517	191	528	616	527	1094	2236
Poland	3437	134	112	39	1035	2609	3682
Portugal	601	13	63	209	316	152	677
Romania	1103	19	38	690	371	99	1160
Slovakia	323	0	0	184	128	11	323
Slovenia	106	0	0	87	17	2	106
Spain	2316	170	263	1050	1018	682	2749
Sweden	3900	528	620	487	2021	2539	5048
Switzerland	42	0	0	39	3	1	42
Turkey	1264	89	123	757	296	421	1475
United Kingdom	0	447	3961	0	0	4409	4409
EU15	20485	2875	8467	3725	7582	20520	31827
EU10	6894	421	379	842	2480	4372	7694
EU2	1643	33	72	999	538	211	1747
EU27	29021	3329	8918	5566	10600	25102	41268
NO,SW,TU	2823	280	650	1413	825	1516	3754
Total	31844	3609	9568	6978	11425	26618	45021

6 ‘not competitive’ are cost classes with average production costs 0.173, 0.095, 0.080, 0.071, (€/kWh)

7 ‘most likely competitive’ is cost class with average production cost of 0.062 (€/kWh)

8 ‘competitive’ is cost class with average production cost of 0.048, 0.040, 0.032, 0.023 (€/kWh)

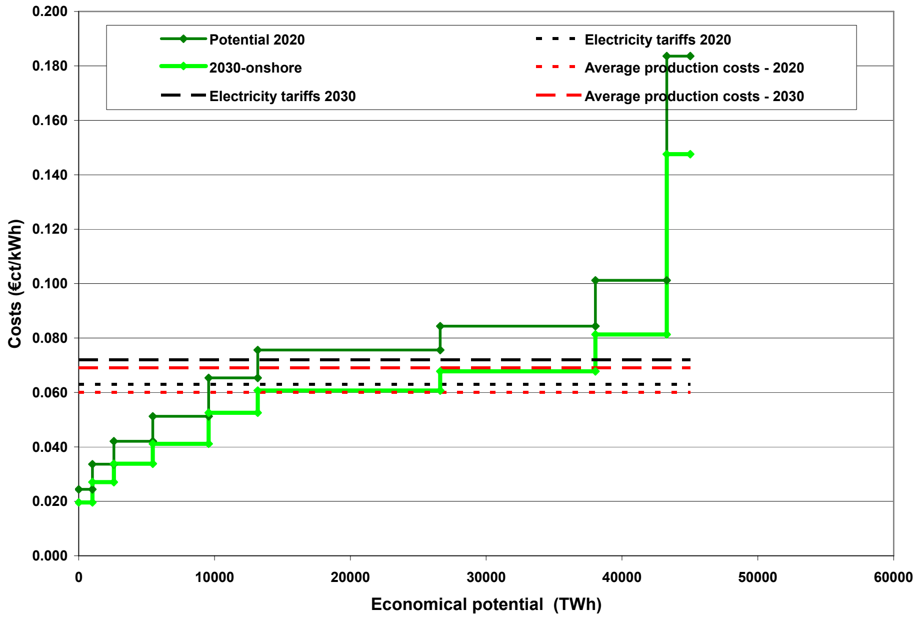

Figure 3-19: Cost supply curve for wind energy on land in Europe

3.6.2 Offshore

The market potential for offshore wind is, like land-based wind, estimated by comparing the generation costs for offshore wind to both 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 will decrease to below 1000, which are considered economic not exploitable conditions for offshore wind.

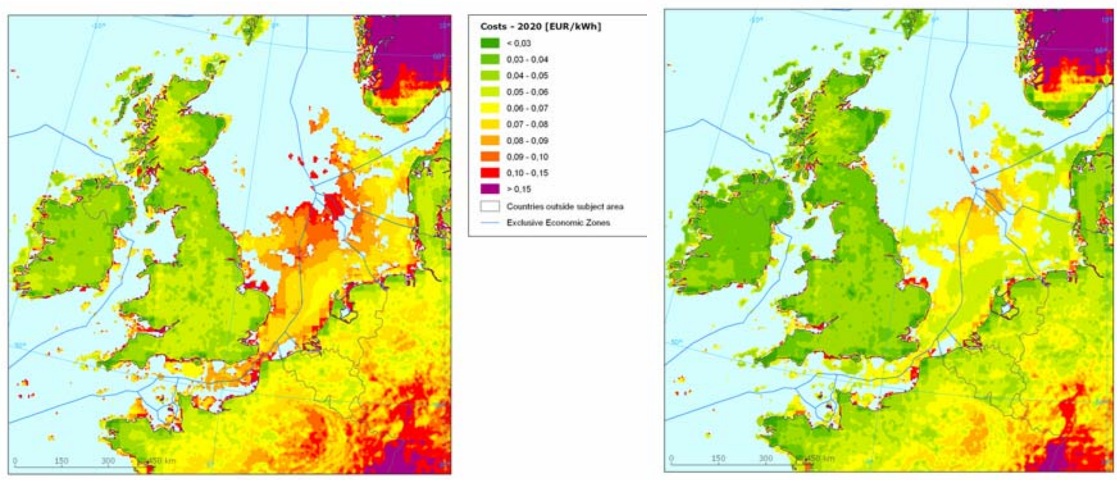

Figure 3-20: Offshore costs 2020 North Sea, market based discount rate (left, 9,6%) and social discount rate (right, 4%)

In general, production costs of electricity from offshore wind are higher compared to electricity from onshore wind (see Figure 3-20), mainly because of higher capital investments and finance costs (9,6% discount rate offshore 2020 against 7,8% for onshore projects). Production costs for offshore wind are calculated as a function of water depth and distance to the coast according to the methodology explained in section 5.2. The potential for wind energy developments in the different water depth classes is presented in Figure 3-21. At average production cost of 6.9 €ct/kWh in 2030 about 17 000 TWh (6000 GW) of offshore wind can be developed. Deep seas at 40-50 meters have highest potential of 2100 GW,

followed by 1500 GW at 30-40 meters, 950 at 20-30 meters and 1300 at 0-20 meters. Around production cost of 5.0 €ct/kWh there is more potential in areas with a depth up to 20 meters than areas at depths of 20-30 meters.
The most optimal wind locations in waters up to 20 meters depth can be found in the United Kingdom and Ireland (see Figure 3-22). The market potential of offshore wind in the United Kingdom is about 165 GW at average production cost of 6.9 €ct/kWh in 2030. In Ireland most of the potential can be developed at low production cost in the range of 3.0-5.0 €t/kWh.

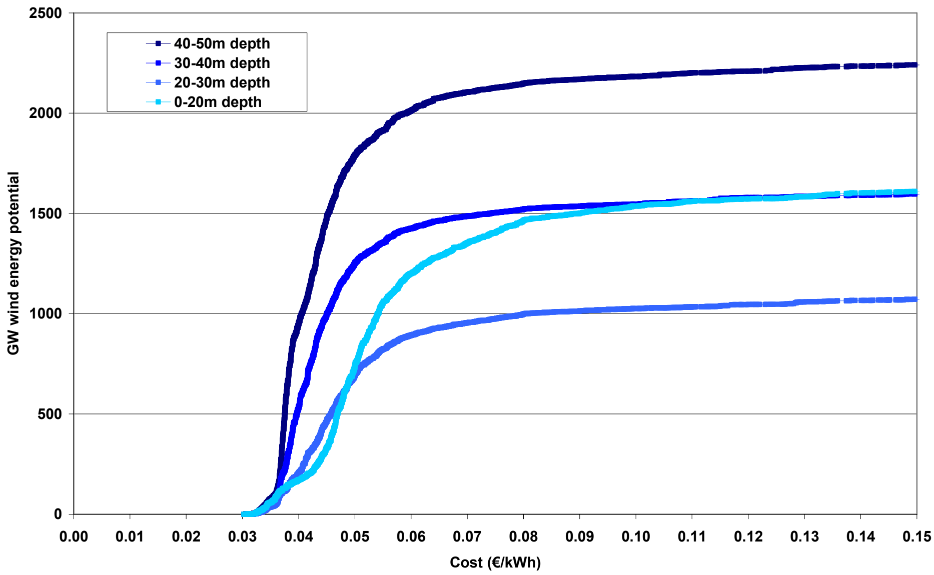

Figure 3-21 Potential for wind energy at different water depths

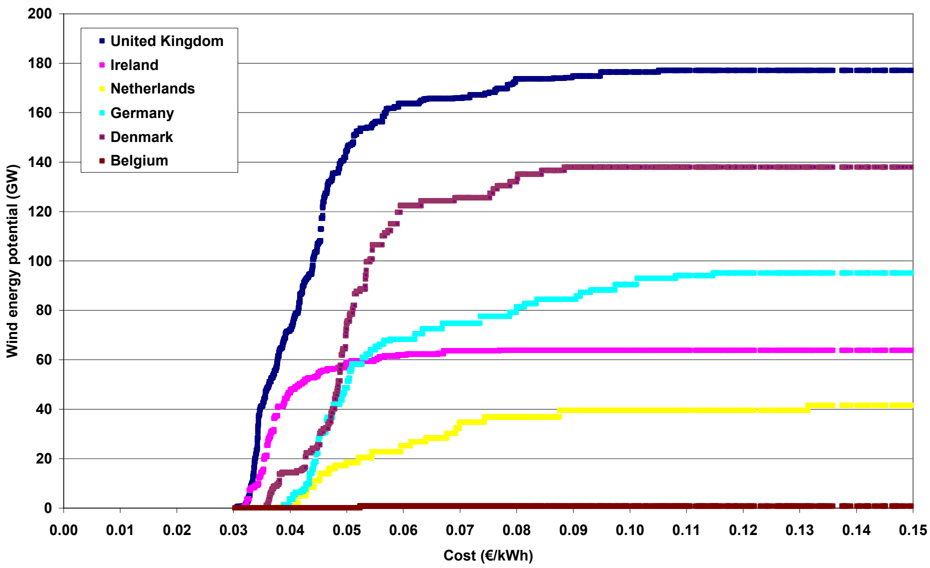

Figure 3-22 Wind energy potential in the North Sea area at 0-20 meters depth

3.7. Wind enery developments on a country level

Without any restrictions to the maximum penetration level of wind, the potential of wind energy exceeds the electricity demand in 2030 many times in most countries. In total, the technical potential of wind power in Europe exceeds the electricity demand in 2030 by a factor 14. There are however significant differences among the individual countries. For some inland central European countries (such as Austria, Czech Republic, Hungary, Slovakia, Slovenia, Luxembourg and Switzerland, but also for Turkey) wind energy is not a very significant option to satisfy the national domestic electricity demand. The wind potential in these countries is not able to supply more than 5% of the electricity demand in 2030 in these countries. Other countries that have more suitable locations to develop wind energy, but whose wind energy potential is still less than the national electricity demand in 2030 are Romania, Slovakia and Spain. About 75% of the land wind resources in Spain are below 1600 full load hours and not included in this analysis.

In a number of countries the offshore technical potential exceeds the domestic electricity demand in 2030 by more than 10 times: Denmark, Estonia, Ireland and Latvia. When restricting offshore wind developments to areas with a minimum of 2500 full load hours and to areas within a distance of 10 to 50 kilometers from the coast, the offshore potential still exceeds the electricity demand by a factor of almost 10 in these countries (see Figure 3-21). But even using their onshore wind energy potential only, these four countries can theoretically produce more than 10 times their electricity demand in this scenario.

Another group of countries in Northern and Western Europe, including Finland, Sweden, United Kingdom, the Netherlands, Lithuania and Norway can also easily meet their domestic electricity demand in 2030 assuming a minimum of 2 000 full load hours for onshore wind resources and including the offshore potential at 10 – kilometres from the coast. The combined onshore and offshore wind energy potential exceeds the electricity demand in 2030 by 2 to 7 times.

3.7.1 Grid integration

Although it seems that the wind energy potential in most countries is large enough to fulfil the national electricity demand in 2030 there are restrictions to the amount of wind electricity that can be coped with by the national electricity grids. 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 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 2008, Denmark's electricity will be supplied for 20% from wind. Andersen (2007) estimated that the penetration of wind energy on a large grid can be as much as 15% to 20% without additional precautions being taken with respect to power quality and grid stability. A very recent Danish study concluded that even the integration of 50% wind power into the Danish electricity system is technically possible without threatening security of supply (Ea Energy Analysis, 2007). TENNET (2005) in the Netehrlands concluded in 2005 that 15% could be integrated in the existing network (2012 configuration) without losses and that at a penetration of 30% approximately 15% of generated wind energy could not be absorbed by the network. In the sensitivity analyse the two most important constraints were the existing combined heat-power generation plants and the assumptions on import/export (that could absorb an overflow of electricity generated by wind power)

To put the figures in perspective, we assume a maximum penetration level of 25% wind and calculate the amount of suitable land area that would be required to achieve this. Table 3-4 suggests that in order to satisfy 25% of the electricity supply by wind power in 2030 would require on average 8% of the suitable national land and sea area in the low-greenhouse gas emissions scenario. Restrictions applied to the available wind resources are that only land areas with more than 2 000 full load hours and offshore areas with more than 2 500 full load hours and between 10 and 50 kilometres from the coast are included. In a number of countries the amount of land required is less than 4%, a level that is already achieved in Germany. When we assume this level of land and sea use together to be a socially accepted minimum Switzerland, Finland, Ireland, Denmark, Latvia and Estonia are able to fulfil 25% of their electricity demand at these minimum conditions.

A further analysis has been done on the amount of agricultural land required to achieve a maximum penetration level of electricity from wind of 25%. Previous chapters have already indicated agricultural land as being most appropriate for siting wind turbines. The feasible penetration analysis for agricultural land in chapter 3 revealed feasible penetration percentages of wind on agricultural land of 1.26% in Denmark, 1.13% in the Netherlands and 10.73% in Germany. Based on these countries the average feasible penetration of wind turbines is calculated at 4.4%. This percentage is used as an approximation of the minimum share of agricultural land that could be used across Europe for wind turbines. Figure 3-23 shows to what extent it is possible to fulfil 25% of the electricity demand in 2030 with wind turbines on agricultural land. With the restriction that only 4.4% of the available agricultural land can be used for the siting of turbines only Denmark, Estonia, Latvia and Lithuania have sufficient land available.

Table 3-4: Summary table of the potential of wind energy in relation to the electricity consumption in 2020 and 2030[9]

	Electricity consumption			Onshore		Offshore		Combined	
	TWh	TWh	TWh	Electricity from wind (%)		Electricity from wind, depth < 50m (%)		onshore: >2000 hr, offshore: >2500 hr, 10-50km	25% electricity, % suitable land required
	2000	2020	2030	>1600 hrs	>2000 hrs	>2500 hr, Economic zones	>2500 hr, 10-50 km		
Austria	60	81	90	0%	0%	0%	0%	0%	-
Malta	2	3	4	268%	0%	0%	0%	0%	-
Slovenia	14	19	18	67%	0%	0%	0%	0%	-
Turkey	125	272	429	0%	0%	5%	4%	4%	669%
Czech Republic	73	92	97	28%	4%	0%	0%	4%	614%
Spain	223	360	391	1%	0%	16%	9%	9%	284%
Romania	52	87	108	152%	63%	18%	18%	81%	30.8%
Slovakia	30	46	47	228%	88%	0%	0%	88%	28.5%
Germany	569	644	685	490%	91%	162%	40%	131%	19.1%
France	536	702	751	482%	28%	166%	122%	150%	16.7%
Belgium	83	103	110	55%	0%	203%	179%	179%	14.0%
Norway	142	163	171	337%	100%	717%	97%	197%	12.7%
Netherlands	90	140	157	5%	5%	848%	205%	210%	11.9%
United Kingdom	372	517	591	77%	22%	574%	188%	210%	11.9%
Bulgaria	41	50	56	819%	24%	197%	197%	221%	11.3%
Portugal	43	71	85	3324%	142%	113%	113%	255%	9.80%
Poland	143	240	270	436%	210%	90%	62%	272%	9.19%
Sweden	146	171	178	413%	159%	441%	219%	379%	6.60%
Italy	270	363	412	344%	342%	79%	79%	421%	5.94%
Greece	53	87	100	2667%	278%	243%	175%	454%	5.51%
Hungary	35	53	58	695%	469%	0%	0%	469%	5.33%
Luxembourg	0	4	6	8402%	571%	0%	0%	571%	4.38%
Cyprus	3	5	7	1799%	542%	75%	75%	617%	4.05%
Lithuania	11	16	20	3165%	455%	231%	166%	620%	4.03%
Switzerland	66	91	97	2823%	689%	0%	0%	689%	3.63%
Finland	70	91	96	673%	160%	793%	540%	700%	3.57%
Ireland	24	38	40	1%	0%	2455%	1209%	1209%	2.07%
Denmark	36	44	50	183%	0%	5376%	1487%	1487%	1.68%
Latvia	4	8	10	3781%	1268%	3370%	2805%	4073%	0.61%
Estonia	9	12	12	6671%	6098%	3986%	3222%	9320%	0.27%
EU15	2574	3418	3740	591%	244%	354%	149%	393%	6%
EU10	324	495	542	869%	75%	203%	159%	235%	11%
EU2	93	137	164	139%	47%	79%	79%	126%	20%
EU27	2990	4049	4446	609%	216%	325%	148%	364%	7%
NO,SW,TU	333	525	696	235%	101%	179%	26%	127%	20%
All	3324	4575	5142	558%	201%	306%	131%	332%	8%

9 Electricity consumption figures are derived from the PRIMES "Climate action" scenario published in (EEA, 2005)

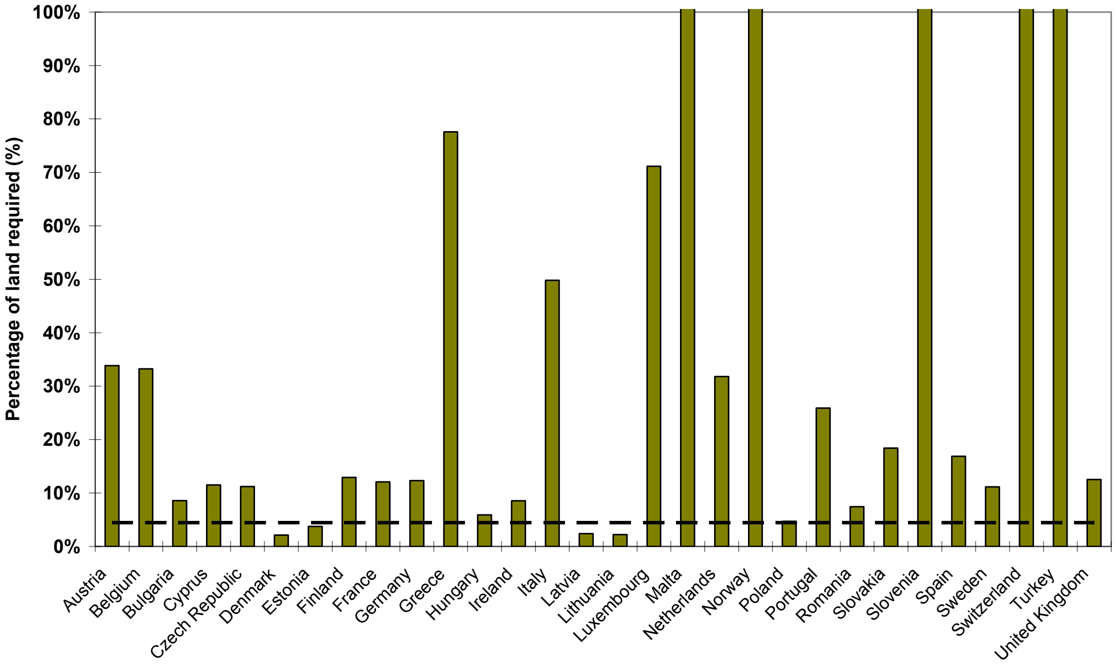

Figure 3-23: Percentage of agricultural land required to fulfill 25% of the electricity demand in 2030

3.8. Conclusions

The maximum technical wind energy potential in the EU-27 (and the EU-15) would be about 15 times the total electricity demand by 2020 in a low-greenhouse gas emissions scenario that is consistent with the EU's long-term climate change objectives[10]. Whereas the electricity demand is projected at about 5 000 TWh, the wind potential is estimated at 75 000 TWh for offshore and onshore resources together with the only restriction being the availability of wind. If the load hour threshold for onshore areas is increased to 2000 full load hours and only include the parts of the economic zones within 10 – 50 kilometres from the coast for offshore areas the available potential drops to 17 073 TWh.

The results show that the differences in wind energy potential between countries are significant. While this result is not unexpected, it is more interesting to note that different countries use their theoretical wind resources to a very different extent. Some countries have a very marginal potential of both onshore and offshore resources, like Austria, Czech Republic, Hungary, Luxembourg, Slovakia, Slovenia and Switzerland. On the other hand, there are also a number of countries that have wind potentials being many times higher than the national electricity demand in 2030 under the low-greenhouse gas emission scenario. In Latvia, Estonia, Ireland and Denmark the domestic electricity demand in 2030 is exceeded by a factor 10 if only offshore wind resources would be exploited.

While the technical potentials are interesting, they may paint a misleadingly rosy picture, even if through the load hour threshold also economic factors are taken into account. Various constraints have been introduced to arrive at a more realistic potential for wind, the so-called "socially and environmentally compatible" technical potential.
Following the recommendations from chapter 8 on "Biodiversity constraints", the union of Natura 2000 and other designated areas is defined as no-go area for the siting of wind turbines as a first attempt to include biodiversity constraints in the potential estimation for wind on land. As a consequence of considering these areas as no-go areas for wind developments the onshore technical potential drops to 43 000. TWh when the union of Natura

[10] The EEA renewables variant of the Climate Action scenario in EEA (2006); the renewable variants are not included in any EEA publication in any detail; I suggest to take the main Climate Action scenario instead

2000 and other designated areas are considered as no-go areas for wind developments. In reality, in some cases wind turbines could be installed in Natura 2000 or protected areas, while in other cases biodiversity constraints would also apply in areas other than these formally protected sites.
The offshore technical potential is restricted by both economic and social constraints. The visual aspect of offshore wind farms close to the shore limits the potential of wind that can be exploited in these areas. Also other functions of the sea area might limit the practical implementation of wind. Offshore areas with low wind speeds and with a distance to the coast beyond 50 kilometres are excluded because of economic reasons. Considering these limitations the offshore potential for wind drops from 25 000 TWh to 2 000 TWh.

The 2030 market potential, based on private costs and private discount rates, is estimated at 17 000 TWh for wind onshore and at 18 000 TWh (6 000 GW) for wind offshore.

Further analysis included the fact that not all types of land are equally suitable to site wind turbines on. Inland countries have to rely on land based wind energy resources, with agricultural land being the most appropriate to place wind power on. With the restriction that only 4.4% of the available agricultural land can be used for siting of turbines only Denmark, Estonia, Latvia and Lithuania still have sufficient land available to cover 25% of their domestic national electricity demand in 2030.

Of course, our calculations involve many subjective assumptions and uncertainties, but we believe that the general conclusions are robust: there is very large wind energy potential in Europe, and tapping only part of it on a relatively small land and sea area can make a major renewable contribution to the European electricity supply. The potential is however very different between countries: for some northern countries it is very large and wind energy can theoretically cover the total electricity demand many times over, while in other countries it can only play a marginal role. It depends on economic, political and practical constraints which share of the potential will eventually be captured.

4. Model calibration and feasible penetration evaluation

4.1. Annual wind speeds in Europe

The wind speed value of 4 m/s is of particular interest for this study since it is typically only for wind speeds beyond this threshold that wind turbines can operate effectively. Model calculations (ECMWF, 2007) show that surface (10 m above ground level) wind speeds across the majority of the Europe are less than 4 m/s. Annual mean wind speeds greater than 4 m/s are expected to occur 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 shows the most important Corine land classifications for Europe, in terms of area, these are:

- Non-irrigated arable land, permanently irrigated land and rice fields (CL 4);
- Pastures (CL 6);
- 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);
- Broad-leaved, coniferous and mixed forests (CL8);
- Natural grasslands, moors and heathland, sclerephyllous vegetation and transitional woodland shrub (CL9).

The method that we used in this study generates gridded information on wind velocities, based on spatially averaged ECMWF data. A key uncertainty is 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.

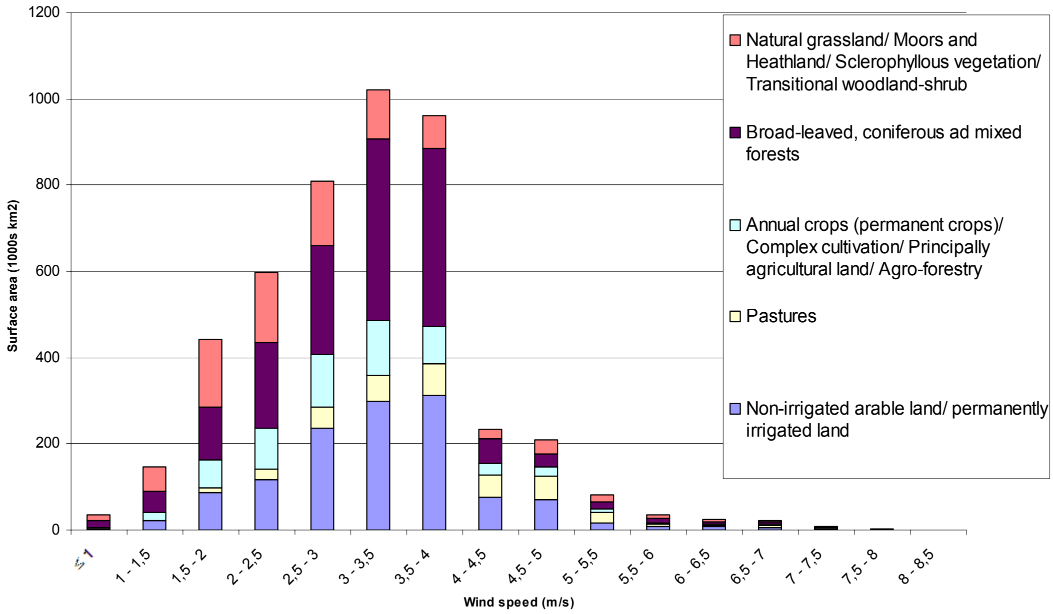

Figure 4-1: The land surface area, distributed between different Corine land classifications, plotted against model predicted surface wind speeds for 2001

4.2. Surface observations at European meteorological stations

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 this year.

4.3. 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).

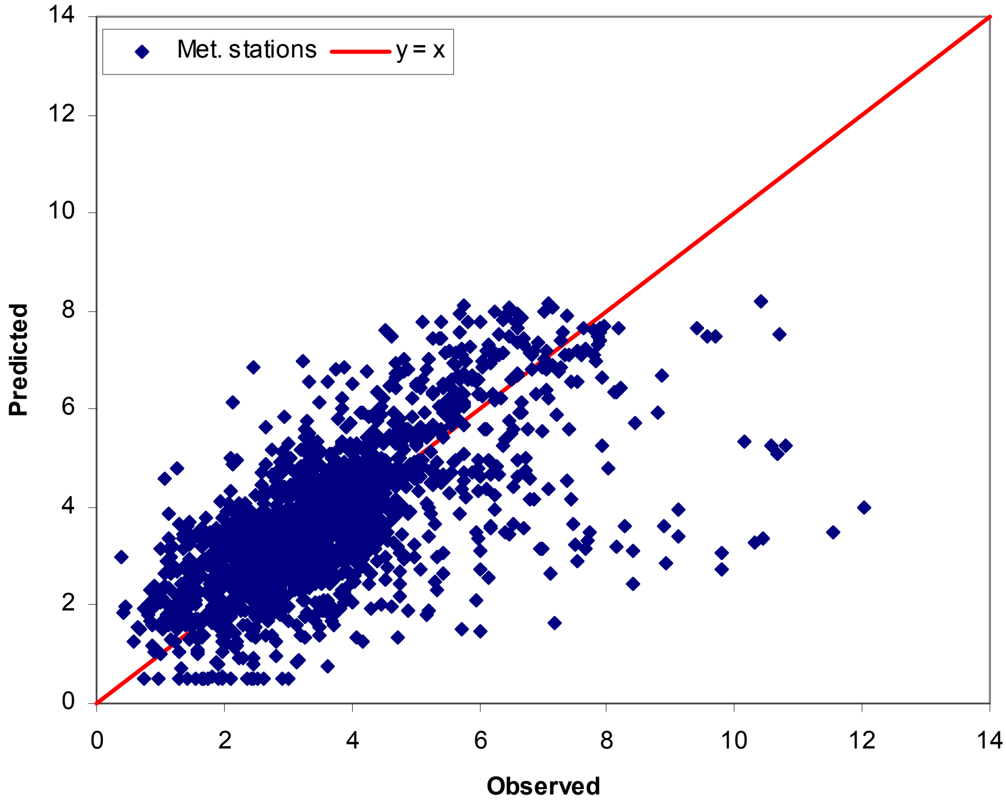

Figure 4-2: The relationship between observed and predicted 2001 mean daily wind speeds (using the methodology) for all European meteorological stations

For wind speeds less than 5 m/s the model shows reasonable agreement with surface observations (Figure 4-2). 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[11], taking y = x as the regression line. The standard error of

[11] 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.

prediction, the standard distance of the prediction from the y = x line, is 1.35 m/s. However, there are a number of locations, 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 this disagreement is analysed further. The following section will investigate geographical influences on the model versus monitoring comparison.

4.4. Geographical differences

Topography and prevailing meteorology vary significantly across Europe. It is therefore important to consider if there are any geographical differences in the relationship between predicted and observed wind speeds. Table 4-4-1 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.

Table 4-4-1: 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: Norway, Sweden and Finland	3.832	1.881	3.839	1.878	0.007	1.450	0.999	1.455
C: France, Spain and Portugal	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

The model compares well also for region B (Norway, Sweden and Finland), for which the mean predicted wind speeds are 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, Spain and Portugal), 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 model-predicted wind speeds and observations for region D (Austria and Switzerland). The mean predicted wind speed is 18% below the observation 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). Considering Figure 4-3d, it is obvious that the relationship between observed and predicted wind speeds lies some way from a y = x regression line, particularly for higher observed wind speeds.

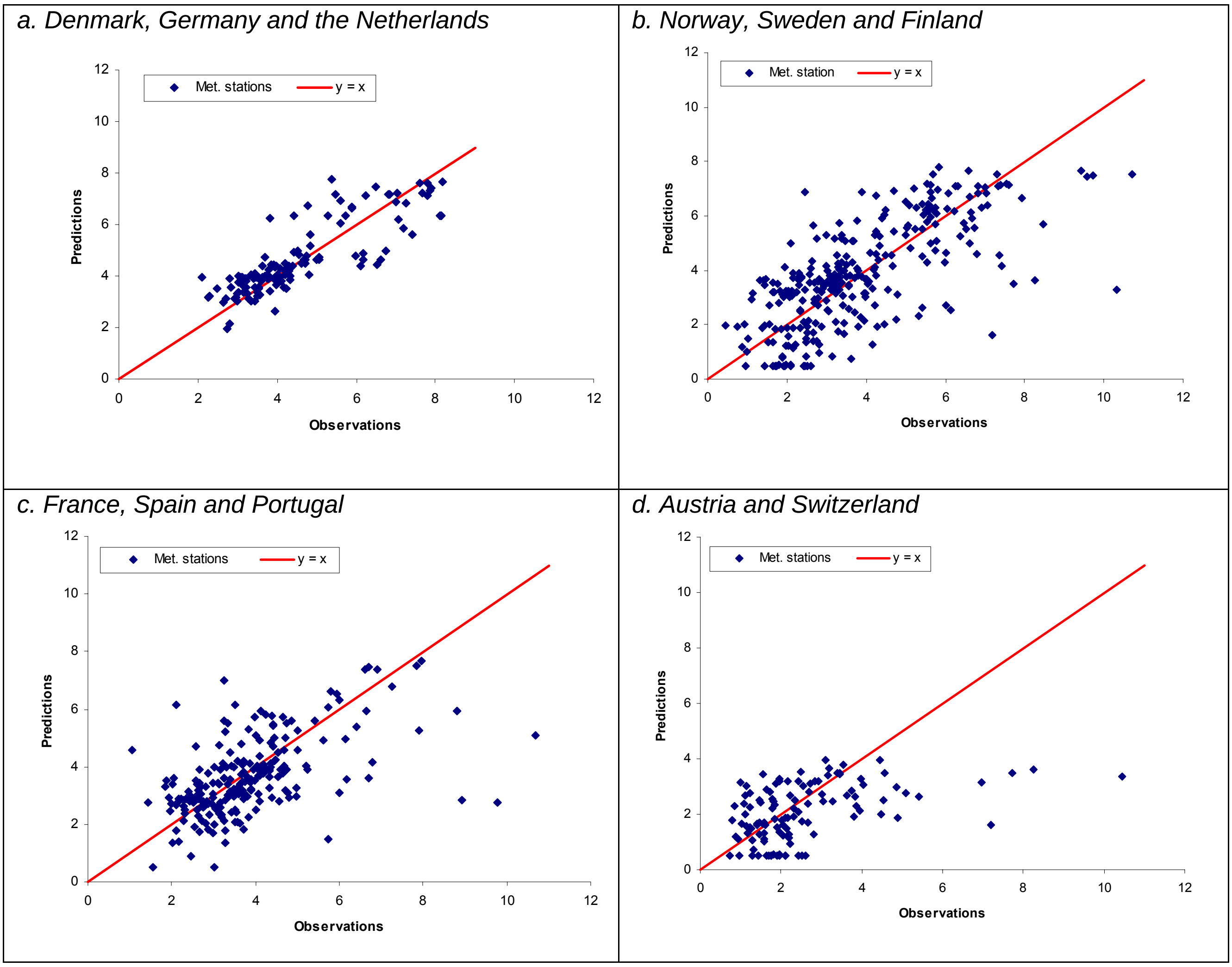

Figure 4-3: The relationship between observed and GIS-calculated 2001 mean daily wind speeds for the four geographical regions listed in Table 4-4-1.

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°×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.

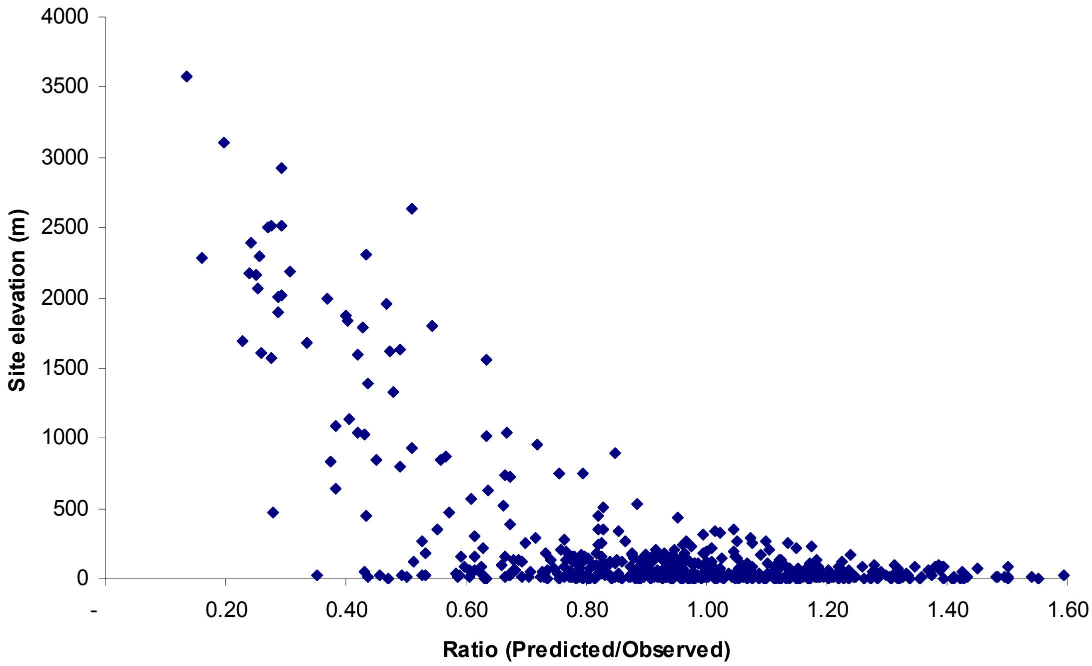

Figure 4-4: The ratio of predicted to observed wind speeds plotted against station elevation

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

Based on the results as presented in Figure 4-4, it was decided to use a height dependent correction factor for the ECMWF wind fields as shown in Table 4-2.

Table 4-2: Height dependent correction factors for ECMWF windfields as derived from figure 4-4

Altitude	correction factor windspeed
100	1,47
250	1,54
500	1,7
750	1,8
1000	2,0
1250	2,2
1500	2,5
1750	2,9
2000	3,3

The impact of the height dependent correction factors can be seen in Figure 4-5, which plots again the ratio of predicted to observed winds speeds against site elevation. Again, for sites below around 250m elevation, predicted to observed wind speed ratios cluster around 1 but spreading from 0.6 to 1.4. As site elevation increases, the model still tends to underpredict wind speeds but this effect is reduced compared to Figure 4-4.

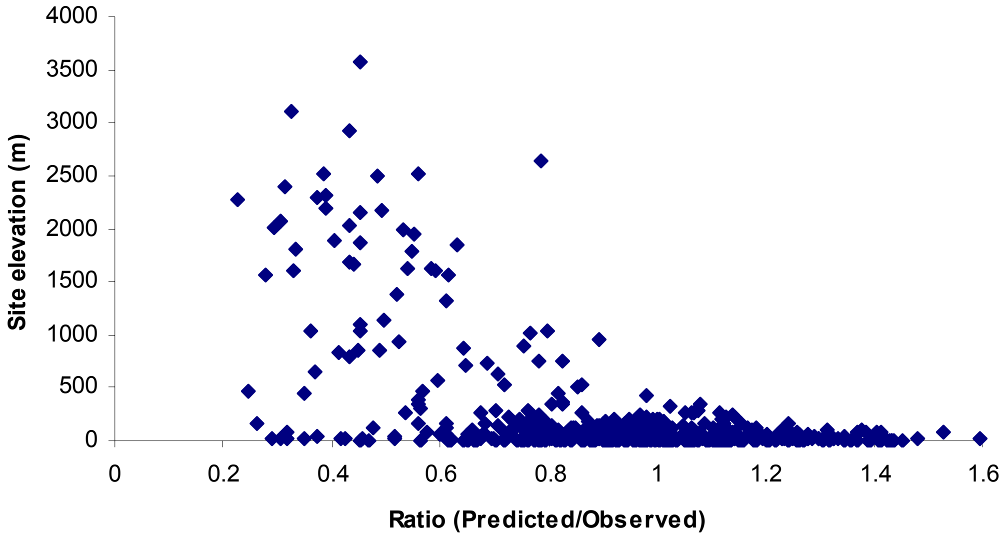

Figure 4-5: The ratio of predicted (including height dependent correction factors) to observed wind speeds plotted against station elevation

It would appear from the results shown in Figure 4-5 that the impact of spatial averaging in regions of high topographic variability can therefore explain some of the poor model performance discussed above for Austria and Switzerland. Similarly, this reasoning can be applied to explain the good agreement, broadly speaking, between predicted and observed wind speeds in Denmark, Germany and the Netherlands since the topography of this region is well represented by a spatially averaged value. However, an additional factor affecting the agreement between model predicted and observed wind speeds is the land cover type.

Figure 4-6 shows the relationship between observed and GIS-calculated wind speeds for meteorlogical 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 agreement 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 how representative those mean quantities are 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 class 4, which has a surface roughness of 0.03 – 0.17 m. The surface roughness range for land class 8, however, is 0.75 – 1.0 m. Therefore, for surface measurements at meteorological stations in forested areas (CL8), there is a greater likelihood of an observed wind speed lying further from the area mean.

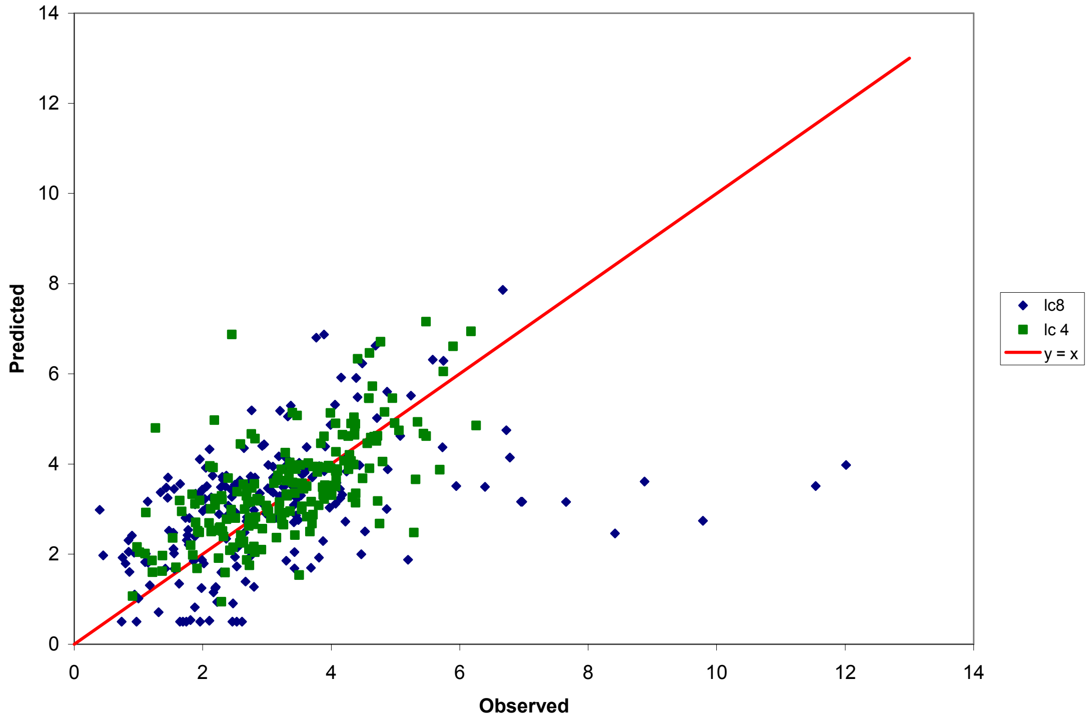

Figure 4-6: The relationship between observed and predicted 2001 (according to methodology) mean daily wind speeds for met stations within Corine land classification areas: non-irrigated arable land, permanently irrigated land and rice fields (CL 4); and broad-leaved, coniferous and mixed forests (CL 8)

4.5. 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.

4.5.1. 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 4-7. Taking 4 m/s as the threshold wind 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 4-7a) This is reversed for stations with an observed wind speed greater than 4 m/s (shaded region of Figure 4-7b). As a percentage of all the European meteorological stations 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.

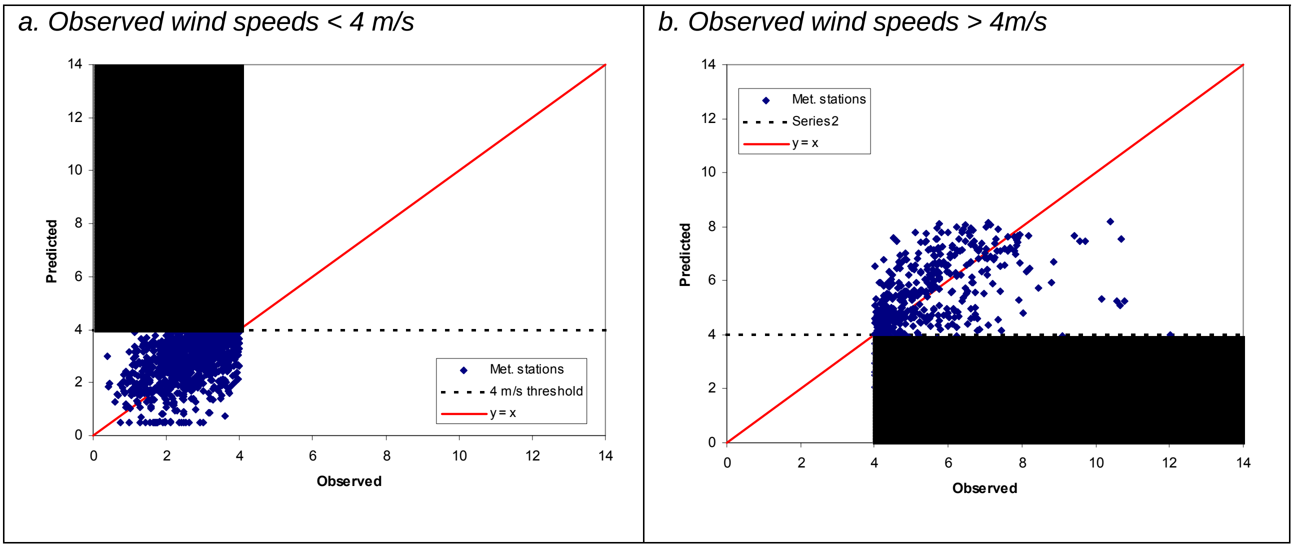

Figure 4-7: Illustrations of over- and under-prediction (grey areas) of wind speeds in the model at low and high observed wind speeds

4.5.2. Upper and lower wind speed intervals and implications for full load hours

Figure 4-8 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 ±1120 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 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 agreement 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.

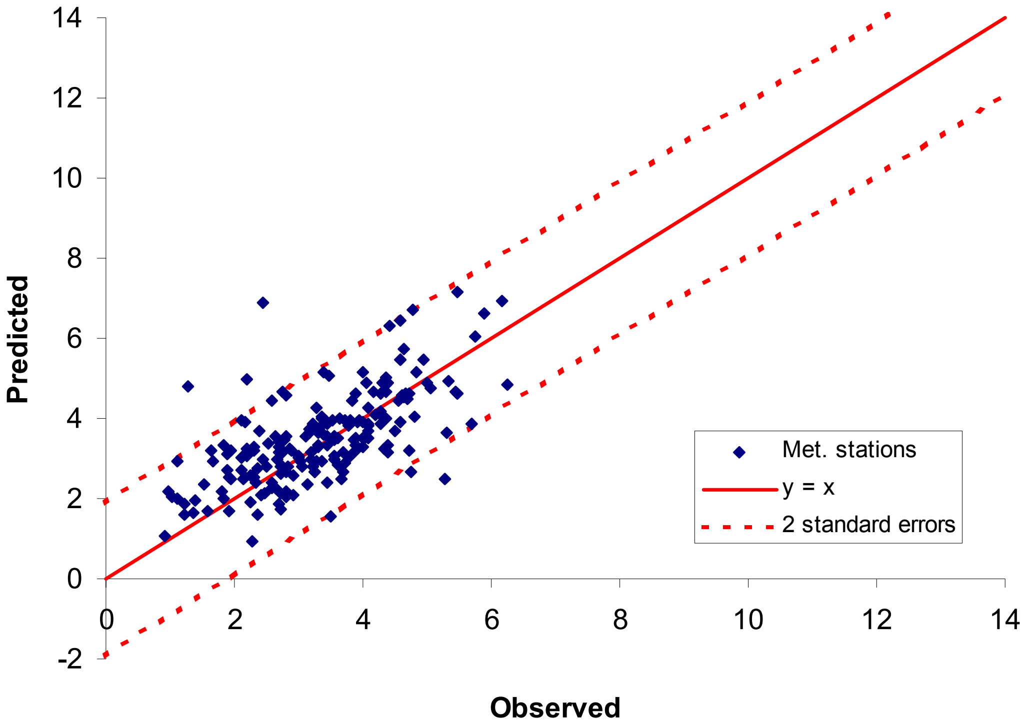

Figure 4-8: The relationship between observed and methodology-calculated 2001 mean daily wind speeds for met stations contained in Corine land classification 4 (non-irrigated arable land, permanently irrigated land and rice fields)

4.6. Analysis of feasible penetration in Denmark and the Netherlands

Denmark has the third highest penetration of wind turbines in Europe, behind Germany and Spain with 3,122 MW installed capacity at the end of 2005 (EWEA). The total surface area of Denmark is greater than that of the Netherlands, but in terms of Corine land classification make-up, it is similar to the Netherlands, being extensively pasture or arable land with a low surface roughness (Figure 4-9). This section aims to analyse the penetration of wind turbines in Denmark, based on area coverage, and to investigate: (i) the effect on Danish national wind energy capacity of 'repowering' all the wind turbines in Denmark to a 2 MW capacity; (ii) the potential impacts for installed capacity in the Netherlands if the penetrations achieved in Denmark were applied there. This analysis can give some idea of the 'feasible penetration' levels of wind energy in Europe. We put 'feasible penetration' between quotes, because the current levels are likely not to be definite, but can change, e.g. through changes in society's perceptions and preferences and through government policies, as discussed in later chapters. In Denmark's particular situation, the national average wind power density is approximately 0.06 Mw/km^2 of total land area. However, there are several municipalities in which the power density is close to or greater than twice this national average. A situation can be conceived where the national average power density is raised to that shown by these municipalities. For this reason we do to 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.

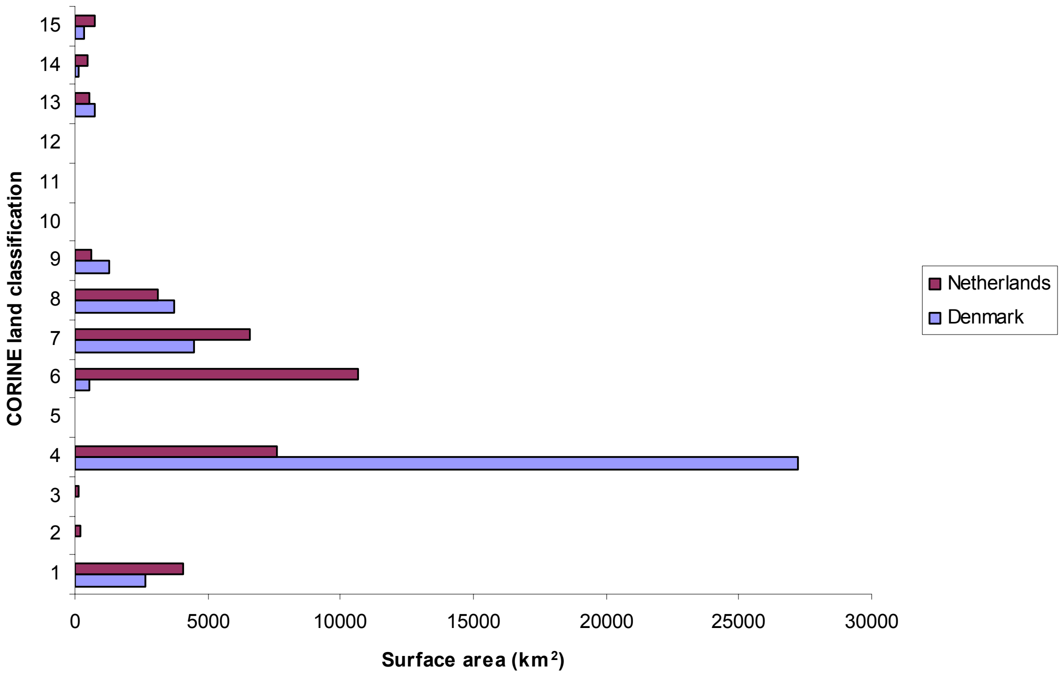

Figure 4-9: Land surface area within the 15 Corine land classifications for Denmark and the Netherlands

Data on the location of all wind turbines existing in Denmark for the years 2000 to 2005 was gathered from the Danish Wind Energy Agency (DWEA, 2007). 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 within wind farms or wind parks of 10 MW/km^2 achieved with five 2 MW turbines. The total land 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 to 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 1840 turbines and hence an installed capacity of 3680 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 4-3 andTable: 4-4 for Denmark and the Netherlands, respectively.

It can be seen from Table 4-3 that the greatest 'feasible penetrations' of wind turbines in Denmark occur for:

- CL 3, wind speed range 7 – 7.5 m/s;
- CL 4, wind speed ranges 5.5 – 6 and 7.5 – 8 m/s;
- CL5 wind speed range 4.5 – 5 m/s.

No wind turbine penetration is calculated for CL 2, 10, 11, 12, 14 or 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, 7 and 13.
In the Netherlands, wind speeds are typically lower than in Denmark, as illustrated by Figure 4-10, which shows the surface area of Denmark and the Netherlands in 0.5 m/s wind speed intervals, expressed as a percentage of the total land area of each respective country. For the period 2000 to 2005, an average of 45% of the Netherlands surface area shows wind speeds

of less than 4 m/s, whilst 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. Considering Table: 4-4,, it can be seen 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 is seen easier in Figure 4-11. This figure shows 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 areas 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 'feasible penetration' levels achieved in Denmark were to be exactly replicated in the Netherlands, but 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 1500 MW to nearly 1200 MW. If Danish penetrations were applied only to those land class and wind speed categories where the penetration is greater than 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 penetrations greater than those in Denmark, would cause the installed capacity in Denmark to increase to nearly 5000 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.

Table 4-3: Penetration of wind turbines in Denmark: the 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

Corine Land Class	Land type description	Wind speed (m/s)									Wind Turbine area in each land class (% of national total area)
		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 & 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 & berry plantations; Olive groves	-	-	4.05%	-	-	-	-	-	-	-
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 & 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	-	-	-	-	-	-	-	-	-	-

Table: 4-4: Penetration of wind turbines in Netherlands: the 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

Corine Land Class	Land type description	Wind speed (m/s)									Wind turbine area in each land class (% of national total area)
		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	0.01%	0.09%	0.12%	0.38%	0.29%	1.04%	–	-	-	0.08%
2	Road/rail networks & 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 & 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 & 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%

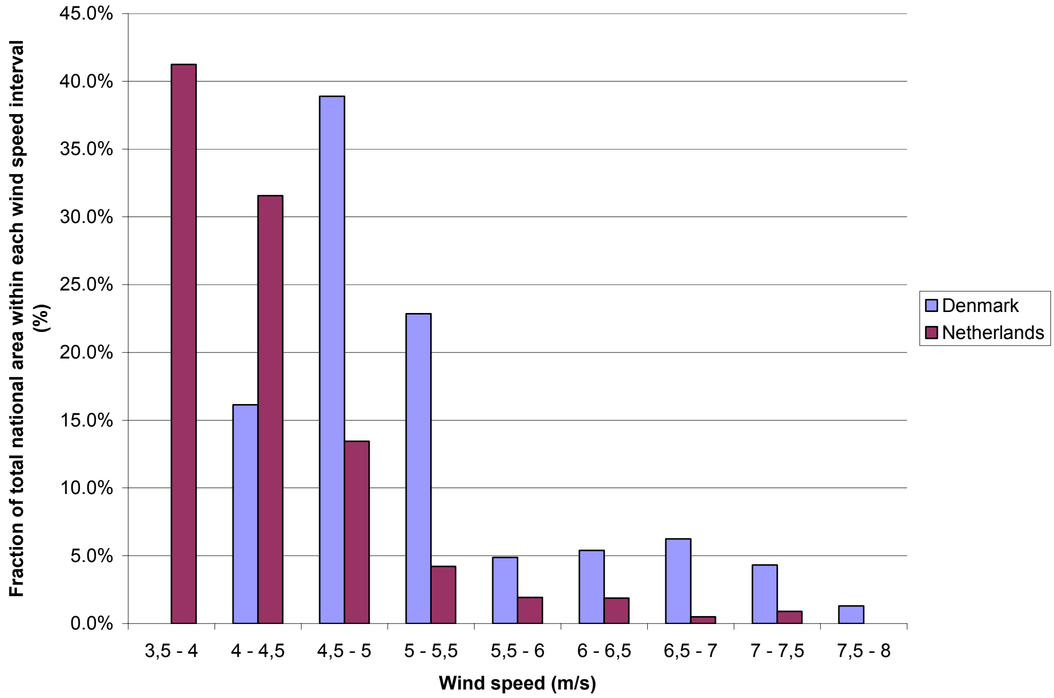

Figure 4-10: Surface area of land in Denmark and the Netherlands for all Corine land types in each wind speed interval expressed as a percentage of the total national area

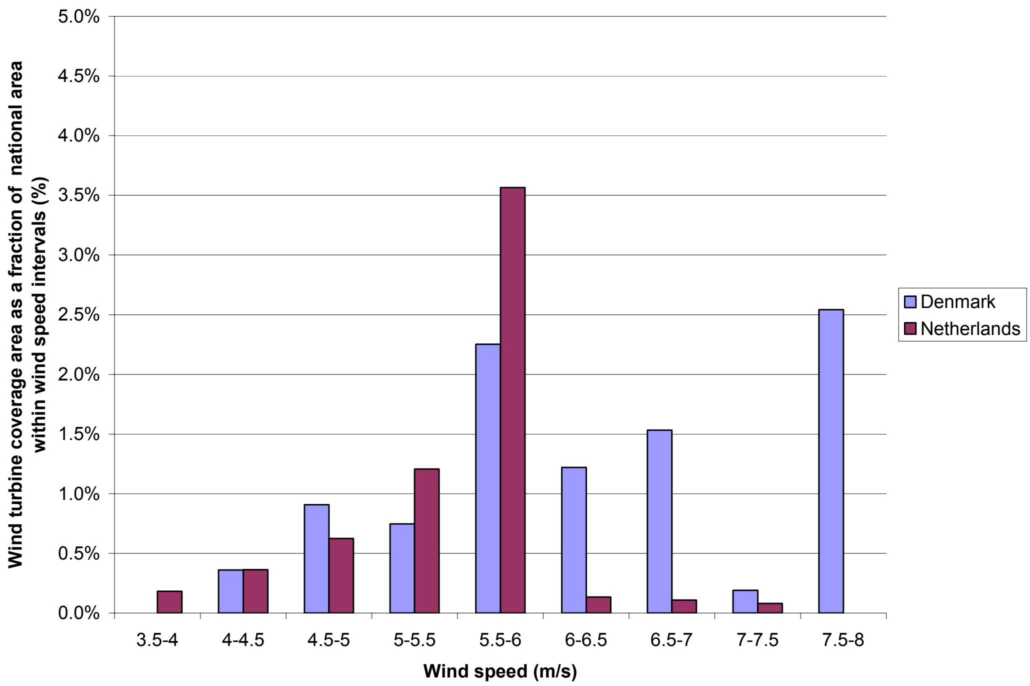

Figure 4-11: Penetration area of wind turbines in a range of wind speed intervals expressed as a percentage of the area within each wind speed interval across all Corine land classifications

Considering
Table 4-5, 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 greater than 4m/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 %. Assuming that the 2005 installed capacity has a mean energy density of 10 MW/km^2, the total national 'feasible penetration' level for Germany is 0.52 %. A similar fraction of land area in Germany experiences wind speeds below 4 m/s as compared to Denmark and the Netherlands. Assuming that all German wind turbines are installed within areas experiencing wind speeds above this threshold, the 'feasible penetration' value is large (4.74 %) in comparison with Denmark and the Netherlands. As a lower boundary estimate, it can be assumed that the proportion of the total coverage of wind turbines within areas of wind speed greater than 4 m/s is the same as in the Netherlands (81%), leading to a 'feasible penetration' for viable wind speed areas of 3.84%. From the total area of wind speed viable land, it is of interest to consider the 'feasible penetration' level for agricultural land since this is likely to represent the major land type for wind turbine installations.

Figure 2-1 gives the full load hours in agricultural areas. The 'feasible penetration' levels of wind on agricultural land and for land types 4 (non-irrigated arable land, permanently irrigated land and rice fields), 6 (pastures), and 7 as a whole, and for CLC 4 on its own, are given in
Table 4-5 Land type 7 is characterised by annual crops associated with permanent crops, complex cultivation patterns, and land principally used for agriculture, with significant areas of natural vegetation and agro-forestry. 'Feasible 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 CLC 4 on its own, 'feasible penetration' levels are higher still: i.e. 1.26 % in Denmark and 1.13 % in the Netherlands. Maximum 'feasible penetration' levels for agricultural land as a whole (6.15%) and for CLC 4 only (10.73 %) can be calculated if 100 % of the wind turbine coverage is assumed to be found in CLC 4. Alternatively, it can be assumed that the same proportion of wind turbine coverage in Germany is valid for agricultural land. Furthermore, the assumption is that the same proportion of this area falls within CLC4) as is found in the Netherlands Using this assumption, estimates for lower boundary 'feasible penetration' levels of 4.78 % and 4.73 %, are valid for agricultural land and CLC 4 land, respectively.

The assumed energy density for Germany of 10 MW/km^2 can be compared with the energy density found in Denmark and the Netherlands, calculated using the 2005 installed capacity in each country. This is then divided by the area covered by wind turbines calculated with the methodology discussed at the beginning of this section. For Denmark, the calculated energy density is 8.5 MW/km^2 and for the Netherlands, 11.2 MW/km^2. The average energy density for the whole of Denmark and the Netherlands is therefore 9.85 MW/km^2, demonstrating the assumed energy density of 10 MW/km^2 used for Germany in
Table 4-5 to be reasonable.

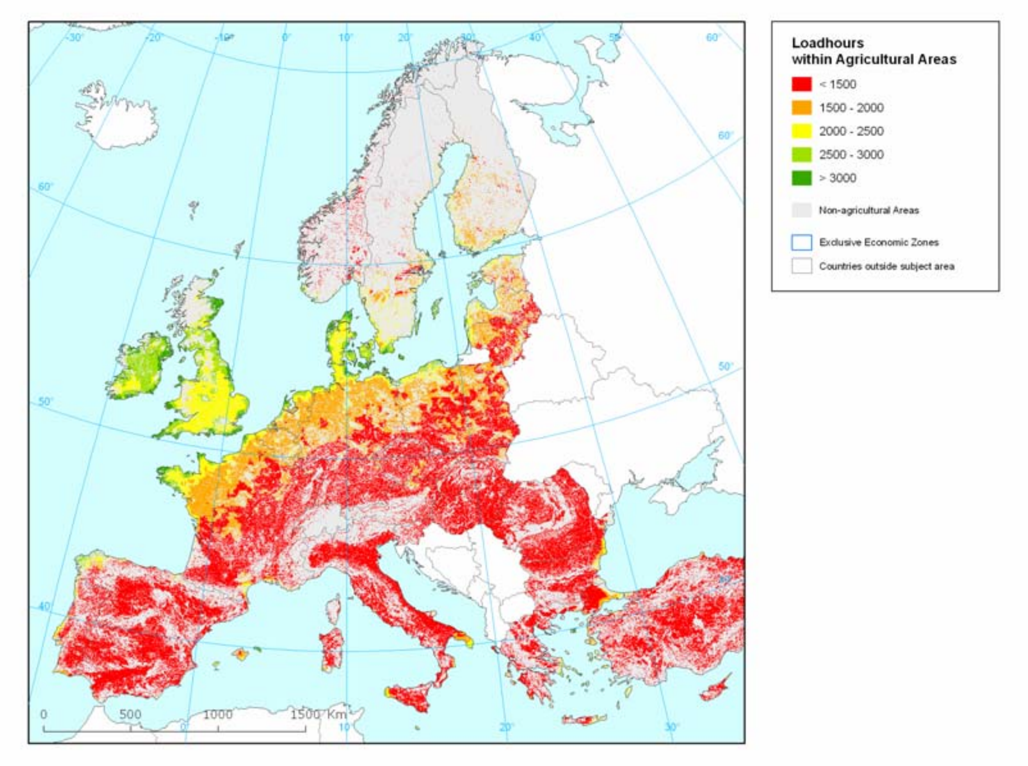

Figure 4-12: Full load hours in agricultural areas only

Table 4-5: A comparison of'feasible penetration'levels for Denmark, the Netherlands and Germany, considering total national land area as separate from agricultural land.

Nation	Variable	Total	With wind speeds > 4 m/s		
			Total	CLC 4, 6, 7	CLC 4
Denmark	Area of turbines (km^2)	368	368	362	342
	Total land area (km^2)	41118	41118	32116	27111
	Penetration	**0.90%**	**0.90%**	**1.13%**	**1.26%**
Netherlands	Area of turbines (km^2)	138	112	87	61
	Total land area (km^2)	34880	18973	13978	5420
	Penetration	**0.40%**	**0.59%**	**0.62%**	**1.13%**
Germany	Installed capacity 2005	18428			
	Surface area, assuming 10 MW/km^2 (km^2)	1843			
	Total land area (km^2)	356870	38857	29968	17176
	Penetration	**0.52%**	**4.74%**	**6.15%**	**10.73%**
	Penetration (lower boundary)[1]		**3.84%**	**4.78%**	**4.73%**

Table footnote:

[1]Lower boundary calculations assume wind turbine distributions as found in the Netherlands:

Total < 4 m/s	Assumes, using the Netherlands example, that 81% of the total area covered by wind turbines receives wind speeds > 4 m/s
> 4 m/s CLC 4, 6, & 7	DK, NL and DE all have a similar proportion of land (~76%) in CLC 4, 6 & 7. For NL 78% of wind turbine area falls into these categories compared to 98% for DK. Therefore assume here that a lower limit of 78% of Germany's wind turbine area is comprised of these land types.
> 4 m/s CLC 4	44% of wind turbine area in NL is comprised of CLC 4 land. For DK, that value is 93%, therefore for lower limit assume here that 44% of Germany's wind turbine area is CLC 4.

4.7. Conclusions

Sections 4.3 – 4.5 established that wind speeds predicted using the model methodology employed for this study generally showed agreement with observations of surface wind speed at European meteorological stations. Good agreement with a y = x fit between observed and predicted values was found for geographical regions, where low surface roughness land types are extensive, for example, across Denmark, the Netherlands and Germany.

At the surface level, somewhat better agreement was found for Corine land type 4 (agricultural lands) than land type 8 (forests). Better agreement is argued as being due to the low surface roughness that characterises this land type, 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 model-predicted wind speeds show poor agreement at meteorological stations that are not representative of the 15 km by 20 km grid average value provided by the ECMWF data used to drive the model, for example, in forested area (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, a discussion arose on the methodology used here, which takes into account the surface roughness to calculate wind speeds at 80 m above ground level. Better agreement might be more possible at this height than for surface readings. However, it is important that further analysis of the uncertainty at 80 m, the hub height elevation, should be included in any future investigation using this methodology.

On balance, the uncertainties have been found to be smallest for the areas that generally are most suitable for establishment of wind energy turbines, 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, even if wind speeds can be high, because of landscape, biodiversity and other concerns (see the following chapters).

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.

Section 4.6 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 3200 MW to nearly 3700 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, the Netherlands and Germany. Relatively low saturation levels were found in Denmark and the Netherlands for viable wind speed land of 0.9 and 0.6 %, compared with Germany (3.84 – 4.74%). '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 but still lower than the 'feasible penetration' level in Germany, which was based on the Netherlands distribution of turbines results at a value of 4.74 %.

5. ECONOMIC AND TECHNOLOGICAL CONSTRAINTS

5.1. Technological development

When assessing wind energy potential up to 2020 and 2030, assumptions on the technological and economic developments of wind turbines are required, such as rated power, hub height and turnkey investment costs. This chapter summarises the background for main parameters that are used in the EEA project on the European wind energy potential assessment.
For assessing the future output of a wind farm, assumptions on the future parameters of the following factors are required:

- the rated power[12] of wind turbines;
- the size of the diameter, or swept area;
- the hub height of wind turbines.

Below, we describe the historical and future developments of these technical parameters of wind turbines.

5.2 Onshore wind turbines

Historically, wind turbine size has increased significantly, from an average rated power in the beginning of the 1980s of less than 50 kW to over 1 MW in 2005 (Danish Wind Energy Association, 2006). The commercial-size range sold today is typically 750–2 500 kW (GWEA, Global wind energy outlook, 2006). While the average size in past years has slightly decreased, it is expected that rated power will increase in the future, although at a lower rate. In this study we assume that the rated power will level off at 2 MW. Various other studies assume a rated power of onshore wind turbines at a level of 2 MW for 2020 and 2030 (EWEA, 2006a; Greenpeace & EWEA, 2004; Greenpeace & GWEC, 2006).

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, 2003). EWEA showed that there is a relation between the rated power of turbines and the rotor diameter. The rated power increases as a power of the rotor diameter with an exponent of around 2. This implies that a diameter of 100 m is related to a rated power of around 3 MW, and 70 m for a turbine of around 1.5 MW (EWEA, 2003). For the average turbine of 2 MW, the related rotor diameter, according to the relationship found, would be 80 m. Based on this relationship between the rated power and the rotor diameter, the average rotor diameter has been estimated and presented in **Error! Reference source not found.**.

[12] The 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 winds).

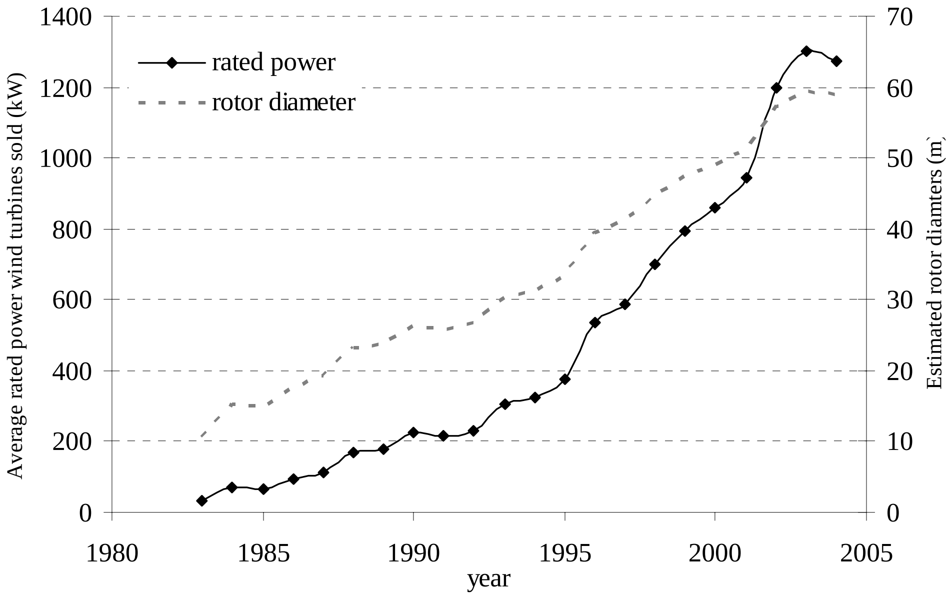

Figure 5-1: Historical development of onshore wind turbine size, in rated power and estimated rotor diameter. Source: Danish Wind Energy Association, 2006.

The hub height is only 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 (2003) indicates that for larger onshore turbines, the hub height equals almost the rotor diameter. The average hub height relates to the wind speed. By varying the hub height and the generator, an optimal output of the power can be generated. Here, for reasons of simplicity, we assume that the hub height equals the rotor diameter.

5.3 Assumptions on future characteristics

The assumptions on the wind turbine technology made in this study are summarised in Table 5-1.

Table 5-1: Summary of the assumptions on the 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

Offshore wind turbines

There is not as much experience with offshore wind energy projects. An overview of planned or installed wind farms within Europe was made by Van Hulle et al., 2004 and IEA, 2005 (see Table 5-2).

Table 5-2: Overview of some planed or installed European offshore wind farms. Source: Van Hulle et al., 2004; IEA, 2005, Papalexandrou (2008).

Project name	**Country**	**Total wind farm area**	**Nr of WT**	**WT rated power**	**Power density**	**WT rotor diameter**	Costs
		km^2		MW	MW/km^2	m	**M€/MW**
Middelgrunden	DK	3	20	2	13		
Horns Rev	DK	20	80	2	8	80	1.9
Nysted	DK	24	72	2.3	7	82	1.7
North Hoyle	UK	5.4	30	2	11	80	1.8
Scroby Sands	UK	4.3	30	2	14		1.8
Kentish Flats	UK	10	30	3	9		
Barrow Offshore Wind	UK	10	30	3	9	90	
DOWEC	NL	45	80	6	11	129	
Egmond aan Zee	NL	30	36	3	3.6		
Princess Amalia Wind farm (Q7)	NL	10	25	2	5		
C-power	BE	14	60	3.6	15	104	

Because of economies of scale, turbine sizes may further increase. EWEA (2006a) has assumed an average wind turbine size of 10 MW in their briefing paper 'No Fuel'. The rotor diameter of such large turbines, when using the relationship for onshore turbines, would be around 150 m. However, as indicated earlier, rotor diameter also relates to hub height. For offshore wind turbines, 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).

5.2. Cost development of wind energy

Main parameters determining the cost of wind energy are investment costs (i.e. turbine costs, foundation, electrical installation, grid-connection, consultancy, land costs, financial costs, security, road construction) and operation and maintenance costs (O&M). As costs depend on various factors, they also vary significantly among various countries. In this paragraph, future investment and O&M costs are mainly based on studies that have an international scope.

5.2.1. Investment costs

5.2.1.1. Current levels and historical development

Current turnkey wind energy costs are estimated to be around EUR 1 000/kW for onshore and EUR 1 200–1 850/kW for offshore wind farms (Junginger, 2005). For Germany, Spain and Denmark, EWEA (2003) presented a cost distribution for onshore farms as indicated in Table 5-3.
This table also indicates average shares of offshore plants according to Junginger, 2005. It is evident that onshore wind energy costs are dominated by turbine costs. For offshore wind, the costs for foundation and grid connection can make up a significant share of investment costs. Current levels of investment cost for offshore wind are significantly higher. Offshore wind costs have increased considerably over the last years due to the bottleneck in the supply chain and in particular the lack of offshore wind turbine availability. In this study we assume that current high prices for wind turbines are short-term increases and that the market will converge as over time to price levels that better represent real costs. The situation might improve already after 2010 when new manufacturers will enter the market (Papalexandrou, 2008).

Table 5-3: Overview of cost estimates of onshore and offshore wind farms

	Onshore [a]	**Onshore** [a]	**Offshore** [b]	**Offshore** [d]
	Share of total investment costs (%)	**Typical share of other costs (%)**	**Share of total investment costs (%)**	**Share of total investment costs (%)**
Total turnkey investment costs	800–1100 €/kW[b]		1200–2000 €/kW[b,c]	2300–3300 €/kW[d]
Turbine	74–82		30–50	30–50
Foundation	1–6	20–25	15–25	20–35
Installation	1–9	10–15	0–30	5–20
Grid–connection	2–9	35–45	15–30	10–20
Consultancy	1–3	5–10		
Land	1–3	5–10		
Financial costs	1–5	5–10		
Road construction	1–5	5–10		
Others			8	5

EWEA, 2003 [a)] Junginger, 2005 [b)] ECN, 2004 [c)] Papalexandrou, 2008

Wind turbine costs are the lion's share of onshore wind energy investment costs. We therefore focus on these costs. Wind turbine costs have decreased significantly over time (Figure 5-2). Wind turbine costs between EUR 750–1 000/kW were reported at the beginning of this century (e.g. Junginger, 2005; Neij et al., 2005). The largest historical factor behind wind turbine price reductions has been increased turbine size (Junginger, 2005; Coulomb and Neuhoff, 2006).

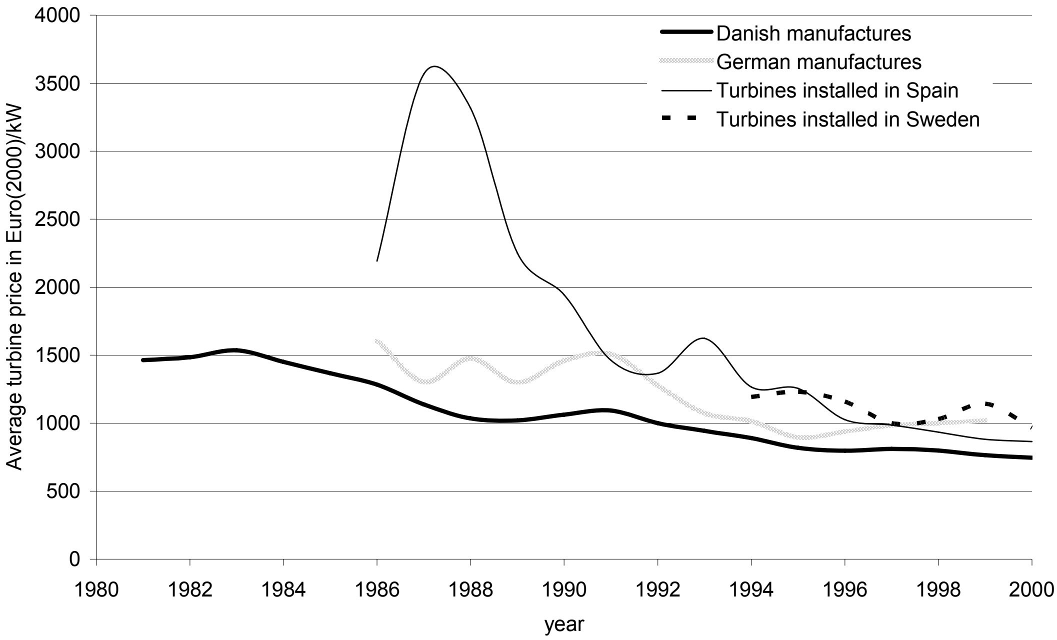

Figure 5-2: Historical development of wind turbine investment costs in various countries. Source: Neij et al., 2005

5.2.1.2. 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 they add to their portfolio (EWEA, 2003). Another, more conservative estimate, applied by Garrad Hassan in their global wind energy potential study, is a decrease of investment costs of 1– 2.2% per year (Fellows, 2001).

Whereas historical developments originated mainly from up-scaling, future cost reductions are expected to come from mass production and improved design (Junginger, 2005; EWEA, 2003). Increasing experience and mass production are expected to also reduce other costs, such as grid connection, foundation and planning. These costs have already decreased significantly over the past few years (EWEA, 2003).

One of the methodologies that is often used to estimate future investment costs of wind energy is the concept of learning-by-doing expressed by a learning or experience curve (e.g. EWEA, 2003; Junginger, 2005; Neij et al., 2005). The experience curve used for wind turbines indicates the decrease in capital costs per unit of capacity with an increase of produced capacity. It incorporates up-scaling as well as mass production. The most important parameter in the learning curve is the progress ratio (PR). The progress ratio is a measure of the relative investment cost reduction per unit of capacity when doubling production. Typical PRs for wind turbines are found in the range of 80–95 % (Junginger, 2005; Neij et al., 2005) meaning that wind turbine costs decrease by 5–20 % when doubling the total installed wind capacity.

Several studies indicate that to analyse the future costs of wind energy or wind turbines by applying learning curves, a global scope is preferred. 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 on a global scale rather than focus on wind energy penetration in a European context.

Table 5-4 presents an overview of wind energy contribution in three global energy scenarios for the target years 2020 and 2030. In addition, the number that the capacity has doubled (cumulative installed capacity for these targets years) is indicated. Using a range for the progress ratio of 80 – 95%, a doubling of two would imply a wind turbine cost reduction of 10–40 %; a four-time doubling results in a cost reduction of 20– 60%. The highest cost reduction ranges are expected to be only a theoretical number. We use a more moderate cost reduction estimate of 25% for 2020 and 40% for 2030. Assuming costs of EUR 800/kW now, the costs would become EUR 600/kW in 2020 and EUR 480/kW in 2030.

Table 5-4: Overview of contribution of wind energy capacity (GW) in various global energy scenarios

Reference	**Name scenario**	**Cumulative Installed Capacity (GW)**					**Number of doublings**	
		Current[a]	**2010**	**2015**	**2020**	**2030**	**2020**	**2030**
Greenpeace & GWEA, 2006	Reference	59			231	364	2	2.5
	Moderate	59			560	1129	3.2	4.3
	Advanced	59			1073	2107	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	

[a] ‘‘current’’ means between 2003–2005

Above we discussed wind turbine investment costs. As can be seen from Table 5-3, turbine costs are around 80 % of the total turnkey investment costs of onshore wind farms. The other costs can also be expected to decrease because of more experience. Due to lack of data, we assume the same relative cost reductions for the other costs as for the turbine costs. In addition, the share of turbine costs is assumed to remain constant over time.

For offshore scenarios, no experience curve can be constructed as there is insufficient experience. Junginger (2005) estimated cost reductions for the year 2020 based on cost reductions from separate parts of the wind farm (e.g. foundation, grid connection, cable, installation) and concluded that the cost of electricity from wind farms offshore could be reduced by almost 40% by 2020. Assuming average turnkey costs of EUR 1 800/kW this results in EUR 1 080/kW by 2020. For the year 2030, we used a conservative estimate of 1 % cost reduction per year, resulting in turnkey costs of about EUR 975/kW.

5.2.2. Operation and maintenance costs

Based on experiences from Germany, Spain, the United Kingdom and Denmark, EWEA (2003) reports that O&M costs are, in general, estimated to be at a level of approximately EUR 0.012 – 0.015/kWh of produced wind power, over the total lifetime of a wind farm. As a share of total turnkey investment costs, O&M costs are between 2–3% in the early years of the farm and around 5% of total investment costs at the end of the lifetime (EWEA, 2003). O&M costs for offshore wind farms are estimated to be in the range of 2–4.4 % of the 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 constant and in absolute terms, therefore, they decrease over time at the same rate as wind turbine costs.

5.2.3. Estimation of investment cost of offshore wind as a function on ice, water depth, distance to coast, military zones and offshore platforms.

The overview of investment cost of offshore wind in Table 5 5 clearly shows that the investment costs are dominated by turbine (30 – 50%), grid connection (15 – 30%) and foundation cost (15 – 25%). Current high price levels of wind turbines give a different picture on the split up between the different cost elements. The turbine costs have a larger share in total costs (see Table 5 5). The construction of offshore wind parks at locations further from the shore often goes along with the placement in deeper waters and changed conditions. This section investigates how investment costs of offshore wind parks might change when the distance to the shore and the water depth increase. The base case includes a 200MW wind farm using 2 MW turbines, 5km from shore in water depths of 15 meters.

Distance to the coast

Of the cost items listed in Table 5-3 installation costs and grid connection cost are affected most when offshore wind parks are located at greater distances to the shore. At larger distances installation costs increase because installation times are affected due to the greater travelling time needed from the holding port to the site. Another important factor that should be kept in mind is weather restrictions, as the further offshore the worse usually the weather conditions to install. A factor used to represent the weather restrictions is the weather downtime. It is an additional factor acquainting the real time needed to install offshore and usually is between 20-30%. The effect on installation costs is low for wind turbines and foundations as the cost share of the travelling to site compared to total installation costs of the above components is relatively low. The main effect in installation costs is found in cable installations as the distance to shore plays key role on the total electrical installation costs. ECN (2003) analysed the influence of the distance to the shore on transport and installation costs. A cost relation was derived based on the scheduled cycle time for the installation of the wind turbines 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 0 – 60 kilometers.

Another cost item that is affected when the distance to the shore increases is the export cable supply. The export cable connects the wind farm with a suitable connection point on land. Other factors that affect the height of the grid connection costs are the cable size, sea bed conditions and the possible need for transformer stations. Experts estimate current grid connection cost (excluding transformator stations) at 0.5 - 1 million Euro per kilometre offshore cable (International Association of Engineering Insurers, 2006). Another study estimates costs of supply and installation of export cable at 1 million Euro per kilometre offshore cable (Papalexandrou, 2008). The share of grid connection cost in total investment cost increases with decreasing size of the wind farm.

Another important parameter that affects investment cost for offshore wind farms is the onshore distance to the grid. According to (Papalexandrou, 2008) onshore cable cost is equal to € 0.65 million per offshore cable used (export cable) per km of onshore cable.

Based on above information from literature it is assumed that:
- o The weather downtime is 25%
- o The export cable cost is equal to 1 Million Euro per km including installation. The relationship between distance from shore and grid connection cost is expected to be linear.
- o Installation costs are linear till 50km as travel time for installation vessels is not affected significantly and when going further offshore they increase more sharply.

Based on these assumptions the overall cost increase of investment costs is indicated in table 5.5. It shows that offshore investment cost might increase from 1800 € to 2878 €/kW as a function of distance to the coast.

Table 5-5: Qualitative and quantitative increase in offshore investment cost as function of distance to the coast

Distance to coast			**0 -10**	**10 – 20**	**20 – 30**	**30 -40**	**40-50**	**50-100**	**100-200**	**>200**
Cost component		**€/kW**	**km**	**km**	**km**	**km**	**km**	**km**	**km**	**km**
Turbine	43%	772								
Foundation	20%	352								
Installation	26%	465	465	476	488	500	511	607	816	964
Grid connection	7%	133	133	159	185	211	236	314	507	702
Others	4%	79	79	81	82	84	85	87	88	89
Total		1800	1800	1839	1878	1918	1956	2131	2534	2878
Scale factor			1	1.022	1.043	1.065	1.086	1.183	1.408	1.598

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) the foundation costs may account for up to 30% of the total cost in deeper waters (Nikolaos, 2004). In a report published by Greenpeace (2000) the relation 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 317 kEuro at 8 meters depth to 352 kEuro at 16 meters depth; a cost increase of 11%. Finally, according to Papalexandrou (2008) foundation supply costs can differ from 300 kEuro/MW at 15 meters till 1000 kEuro/MW at 40 meters using monopiles. Currently, offshore wind farms have not been built in waters with depths above 30 meters, but in the future this will change. Design and cost restrictions lead to usage of new designs different than monopiles for water depths above 30-35 meters. Tripods, quatropods, jacket and floating structures are under consideration. The cost of these structures remains uncertain. Installation cost will increase as well because there is a need for vessels that are capable of installing wind turbines in greater water depths. Besides, the installation vessels probably need to be capable of installing larger turbines and blades.

Based on above information from literature it is assumed that the estimation of foundation supply costs as a function of water depth follows the cost relationship as found in Papalexandrou (2008), adjusting the prices for the base case at 1800 Euro/kW. The relationship for foundation supply costs is expected to be exponential.

Table 5-6: Increase offshore installation costs as function water depth

Water depth			**10 - 20 m**	**20 - 30 m**	**30 - 40 m**	**40 - 50 m**
Cost component	**Share**	**€/kW**	**€/kW**	**€/kW**	**€/kW**	**€/kW**

Turbine	43%	772				
Foundation	20%	352	352	466	625	900
Installation	26%	465	465	465	605	605
Grid connection	7%	133				
Others	4%	79	79	85	92	105
Total		1800	1800	1920	2227	2514
Scale factor			1.000	1.067	1.237	1.396

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 of Table 5-7 to derive offshore investment costs as a function of both distance to the coast and water depth. The combined scale factor is derived by multiplying the scale factor for distance to the shore with the scale factor for water depth.

Table 5-7: Scale factors costs increase as function of water depth and distance to coast

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

5.3. High wind energy penetration levels, implications for the grid

Recent European studies have concluded that large penetration levels of wind power in the generation of electricity can be achieved in several countries, even up to levels of 40 %. 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 extension of 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:

- Grid upgrade and extension; both of the distribution and transmission grid;
- System balancing and additional reserve capacity required for system balancing.

When focussing only on these aspects, the costs for discarded wind electricity (overproduction of wind due to a mismatch between demand and supply) are neglected. We think that this is acceptable for our study because, first, it is expected that this will not occur widely in the timeframe we are considering and second, additional grid extensions will be implemented first and will further reduce the risk of discarded wind electricity.

5.3.1. Grid upgrade and extension

Wind turbines are often installed in distant regions far away from major electricity consumption. Large portions of the electricity produced must therefore be transported over large distances to load centres[13]. This could lead to congestion of the 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. EWEA reviewed several country specific studies and concluded that for these studies (both onshore and offshore) the grid extension and/or reinforcement costs caused by additional wind generation are in the range of EUR cents 0.1–7/MWh for penetration levels up to 30 %. Other sources mention costs for grid extension in the range of EUR cents 1–10/kWh (Burgers, 2007), or EUR cents 0–5/kWh for various countries and different wind energy penetration levels as implemented (GreenNet, 2004).

[13] A load centre is a large switch with smaller switches serving as circuit breakers. These will protect the wires and equipment from potential short circuits or overloads.

5.3.2. 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.

Related costs for this additional reserve are estimated at a level of EUR cents 2–4/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 (2006) shows the improvement and current state-of-the-art in country wide forecasting for Germany. The Root Mean Square Error (RMSE) decreases from about 10% in 2001 to about 6% in 2006, with more improvements in the pipeline, see figure 5-3. Their competitor energy&meteo systems claims in 2008 a yearly average error of below 5% for all of Germany.

Single wind farms however will probably also in the future only in some cases (simple terrain, not too close to the shore) be forecasted below 10% of installed capacity. The other aspects vary significantly per country. Interconnection is expected to increase over time, which would improve the grid's capacity to accommodate larger proportions of wind energy without additional costs.

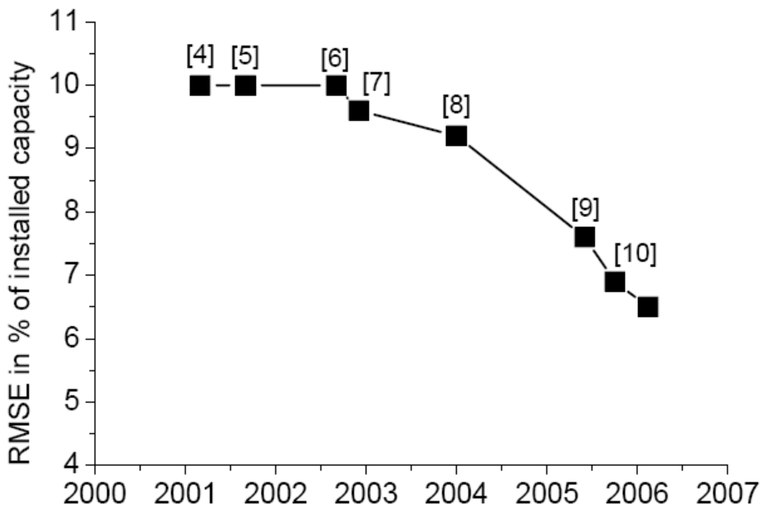

Figure 5-3: Wind power forecasting, Reduction in prediction error in the period 2000-2006 (source Lange et.al,2006)

5.4. Additional costs at high penetration levels

The previous section already presented some indications for additional costs related to higher wind energy penetration levels. In summary, we can state that depending on wind penetration level, geographical distribution and forecasting techniques, the additional costs for grid extension are about EUR cents 0–10/kWh and for additional reserve capacity EUR cents 2–4/kWh.

However, at issue is whether all costs should be allocated to wind power because the extension of the grid and the additional reserve capacity has benefits for the entire system — not only for wind energy. In the debate, this is often referred to as ''deep'' or ''shallow'' grid connection costs (Resch, 2005). In this report we limited ourselves to the costs of wind turbine construction. For comparison with energy prices, we assumed a flat grid connection and/or transport cost of EUR cents 2/kWh.

5.5. Additional cost for wind farms in mountainous areas

In addition to the lower suitable areas, the costs of wind farms are expectedly higher. There is limited research conducted on costs. The data presented below are based on a survey among project developers of wind farms in alpine areas reported in the project Alpine Windharvest in 2004, see e.g. Winkelmeier and Geistlinger (2004). For cost increase following reasons were mentioned:

- Reduction of output
- Increased investment costs of turbine and foundation
- Increased construction costs
- Increase of operation and maintenance

Increased investment costs of turbine and foundation
The costs of the turbine increase because of measures to limit the ice on the blades, the nacelle or the monitoring equipment as anemometer. Further, there can be an increase of grid connection costs due to the roughness of the terrain and an increase of costs of foundation for the same reason. 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. The survey reported did not quantify the additional costs.

Increased construction costs
The construction costs can increase because of additional roads or extension of roads. Construction costs may also increase because of special vehicles that are required. From the thirteen project developers included in the survey (Winkelmeier and Geistlinger, 2004) six of them reported to have moderate to extraordinary additional construction costs. Further quantification is not presented.

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 safety of the specialists responsible for the maintenance. No quantification of the additional costs is given.

Treatment of mountainous areas in this study
In this study we have included the restrictions as explained above in following assumption:

- A restriction to wind farms below 2000 m
- A reduction of the power density at areas above 1000 m
- An increase in the investment and O&M costs.

A restriction to wind farms below 2000 m
For this study it is assumed that wind turbines will not be installed at altitudes above 2000 m. It is assumed that at areas above 2000 m the limitations of access to roads and grid connection are that high that there is very limited area suitable. The value of 2000 m is rather arbitrary as the highest large-scale wind farm is installed at 2330 m (see above), but the remaining current large-scale wind farms are all below 2000 m.

A reduction of the power density at areas above 1000 m
It is assumed that between 1000 and 2000 m there are areas available that are suitable for wind farms. However some areas might be more isolated. The terrain may be more complex for large wind farms. In addition, as wind turbines have to be connected to low-voltage grids, the scale of the wind farms can be expected to be lower. Therefore, the maximum power density at areas between 1000 and 2000 m is assumed to be lower. The quantification of the reduction of power density cannot be founded due to lack of data. Ignoring the effect would result in an overestimation. Therefore the power density for wind farms in mountainous areas between 1000 and 2000 m is reduced with 50%. For this study it implies that the power density of 8 MW/km2 applied to all types of land uses is set to 4 MW/km2 for mountainous areas. This assumption on power density in mountainous areas is in line with an Italian study on analysis of power density of a sample area in the Apennine mountaines. It turned out that the power density in that area at heights around 800 – 1000 meters was on average 4.2 MW/km2 (CESI, 2003).

An increase in investment and operation and maintenance costs
As explained above, there are limited arguments for an average cost increase of wind farms in mountainous areas and most of the data derive from one wind farm in Austria (Tauern park). Based on the survey referred to, it can be expected that the cost increase is moderate. Where

figures are mentioned they are all in the order of < 10%. As the factors may cumulate it is expected that the total investment costs increase with 10%. The O&M costs are expected to increase only with 1%. For the offshore investment costs used in this study it means an increase from 1800 €/MW to 1980 €/kW.

5.6. Power density in relation to different land use types

Different types and sizes of wind farms can be placed in a suitable area. The design, siting and size of a wind farm is determined by aesthetic considerations, obstacles on the terrain, wind direction and, of course, financial considerations.

In areas without obstacles, wind farms can be designed in the most optimal way and can have a power density of about 10–15 MW per km^2. The layout is restricted by interferences of the turbines that reduce wind farm efficiency.

However, for most wind farms, aesthetic considerations and obstacles that reduce the power density also should be considered. In particular, aesthetic considerations are based on different values and are difficult to quantify. Several governments have prepared guidelines for the planning, siting and design of wind farms that include aesthetic considerations (e.g. SEI, 2006). These guidelines aim to assist wind project developers in achieving ''reasonable objectivity'' on the aesthetic aspects of placing wind farms in the landscape. These guidelines are used here to quantify the power density for different land use types.

5.6.1. Design and siting of the wind farm

When considering aesthetic aspects, it is mentioned that the wind farm should be balanced, that is, in harmony, within the landscape. The topographic and sectional profile are important, as are the composite relationships with the surroundings (e.g. large entities close to the built environment or forestry areas). Typical examples are situations close to roads or water ways in which a regular, linear layout is more in harmony than a matrix layout.

This results in a more restricted choice of wind farm design and size in more complex and rugged land-use scenarios, such as close to the built environment, forestry areas, areas with tourism activity or close to infrastructure.

5.6.2. Scale and size of the wind farm

The scale of the wind farm and the size of the turbines are partly determined by the layout or design (see above) but also imply individual aesthetic considerations (see Chapter 4). The spatial extent, the area covered by the wind farm, should also be in harmony with the landscape, that is, appropriate to the scale of its panoramic setting. Next to that, the spacing of the turbines is important, that is, the area between the turbines. Regular spacing is more appropriate in landscapes with a clear and orderly land-cover pattern. Whereas, irregular spacing is considered more appropriate in landscapes of varied land cover or hilly landscapes. In addition, if in the panoramic scene other wind farms are visible, it is important that the spacing is comparable between wind farms.

5.7. Discussion and conclusion

In this chapter, the main technical and economic assumptions required for the wind energy potential assessment were summarized. Assumptions are made for the time frame 2020–2030. In this section, we discuss data quality and the main uncertainties, and we summarise the main conclusions.
Because of the long time period used in the project, the large geographical scope and the yet relatively limited experience with large-scale wind farms, most of the assumptions that we made are very uncertain. It is also noted that we found relatively few independent assessments of wind energy potential, in the sense that most of the data come from studies and reports by wind energy associations and environmental NGOs, which might provide relatively optimistic results. Therefore, an extensive sensitivity analysis would normally be required.

In the assessment of onshore wind energy potential, a sensitivity analysis was possible for some factors because different data sources were available. For offshore wind energy however, very limited information is available and often simple rules of thumb were required. In the sensitivity analysis, the offshore data should therefore require additional attention. Because of resource and time constraints, a comprehensive sensitivity analysis for all factors was not feasible, but we have selected a few important ones that were distinguished in the calculations and can be included or omitted in the results: distance to shore (offshore: 0–10 km, 10–30 km, 30–50 km, >50 km); different land cover classes (on-shore, land cover types, CLC); and different cost categories. The potential for six different years (2000-2005) gives a sense for the inter-annual variations.

The data are based on single-wind turbine costs. The prices of wind turbines in the context of orders for larger wind farms are different. On the one hand, they decrease because of larger quantities, which may reduce the price between 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.

We have focused on wind energy investment and operation and maintenance costs only. The costs of wind energy when penetrating the electricity system (e.g. transmission, back up, spinning reserve, storage, imbalance) should be considered in the context of an electricity model and a penetration scenario. Studies have shown that at high penetration levels, indicatively above 20-40 %, the cost reductions due to technological learning might be offset by the additional costs of system integration (e.g. Hoogwijk et al., 2006). Main assumptions of the parameters are summarised in Table 5-8.

Table 5-8: The main conclusions on the assumptions of the future technological and cost development of wind energy

		2005			2020			2030		
	Unit	Offshr	Onshr	Mount.	Offshr	Onshr	Mount.	Offshr	Onshr	Mount.
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
Turnkey costs	Euro/kW	1600[1]	1000	1100	1080	720	792	975	576	632
O&M costs	%	4	4	5	4	4	5	4	4	5
private capital (at 15%)	%	50	20	20	40	20	20	30	20	20
loans (at 6%)	%	50	80	80	60	80	80	70	80	80
finance costs	%	10,5	7,8	7,8	9,6	7,8	7,8	8,7	7,8	7,8
1600 Ldhr	Euro/Kwh	0,175	0,097	0,12	0,10	0,07	0,082	0,099	0,056	0,065
2500 ldhr		0,112	0,062	0,077	0,065	0,045	0,052	0,063	0,036	0,042
costs (C/loadhr)	C	280	155	193	182	112	131	158	90	105
Costs (C/loadhr))	C (4% discount)	208	130	154	140	94	105	127	74,9	88,4
Fdi	Scale factor distance coast: 0,00285*distance (km) + 0,972									
Fde	Scale factor 15-50m depth: -0,0125*Fd +0,812 (i.e depth as negative number (-25m)									

[1]Cost within 10 km of the coast and less then 15m deep water, see last two rows for increase cost as function of distance to coast and increasing water depths

6. Social constraints

Social acceptability is a key aspect to be considered in addressing the potential for deployment of wind energy. Whereas the economic potential takes into account costs as a limiting factor for the development of wind capacity, estimating the social potential of wind energy implies that public acceptance is taken into account. Section 4.1.1.1 considers the impact of visual aspects and noise on the public perception of wind power. Other factors, regarded as being less important for wind on land, are briefly touched upon. For offshore wind power, concerns arise about the effects of wind farms on the marine environment and biodiversity. These aspects are dealt with in chapter 7 (Biodiversity constraints).

6.1. Public acceptance

6.1.1. Factors underlying opposition to wind power

6.1.1.1. Visual impact

The visual impact of wind turbines on the landscape is one of the most important reasons for people to oppose to wind power. It is also the factor that is most studied. The visual impact refers to the effect of the siting of wind turbines on the visual or aesthetic properties of the surroundings (EWEA, 2004). The fact that wind turbines are dominant structures in the landscape often leads to 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 also play an important and, sometimes, dominant role, since wind turbines appear in an otherwise structureless landscape (Henderson et al., 2001). However, the visual impacts of offshore wind farms can generally be mitigated easier than for onshore wind farms by siting the wind farms further away from the shore or coastal area. The visual impact of offshore turbines diminishes with the distance to the shore; 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 (Garrad Hassan, 2001). 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 is one emphasising bigger turbines and larger projects. As a consequence, also the visual aspects also change with respect to increase dominance in the landscape, increased spacing between individual turbines and lower operational speeds (EWEA, 2004). People’s opinion 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 in a calmer manner by the viewer compared to smaller turbines.

In general, public acceptance increases when turbines – of all sizes– are sited with 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, simple geometrical wind turbine patterns are often not suitable and it is more feasible to site wind turbines in such way that the contours of the landscape are followed (Danish Wind Industry Association, 2007). 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 in to the different parties involved in wind power developments. The next chapter on institutional aspects will more closely look at such planning rules and guidelines on a country basis.

6.1.1.2. 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 frequency of a blade passing the tower is once very second.

It is a difficult task to define how noisy wind turbines are. An important factor in defining whether the sound power level from wind turbines is perceived as ‘noise’ has to do with the background noise level. In rural or low-density areas sounds from wind turbines become annoying at lower sound power levels than in urban areas, because in rural areas the background noise tends to be less. 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 night-time, noise problems with wind turbines can become more prominent. Under the specific 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 metres from the turbine this is 50–60 dB (A), which is the same level of having a conversation. At a distance of 500 metres 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 (personal communication, 2007). In Table 6-1 lists comparative noise levels from different sources.

Table 6-1: Comparative noise levels from different sources (Sustainable Development Commission, 2005)

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

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 nights 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 to 400 metres from wind turbines will not be enough to ensure sound-power 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 from 500 m to 1000 m (Van den Berg, 2003). Experiences from the past learn that noise problems depend on a number of local factors that can change over time.

The most common method for dealing with a potential noise issue is to require a minimum distance between the 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 45 dB (Danish Wind Industry Association, 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. For

night-time periods the established threshold values are lower and range from 30 dB (A) to 45 dB (A).
However, after extensive measurements, G. P. Van den Berg, a physicist at the University of Groningen in the Netherlands, discovered in 2003 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. According to the research of Van den Berg, 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 potential significant source of negative reactions of the public towards 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 basis of such studies the distance required to other objects can be the defined.

6.1.1.3. Other concerns

Besides noise and visual impact of wind turbines, which are among the most important factors that influence public opinion on wind turbine developments, there might be other concerns. These include environmental effects such as shadow casting or reflected light on the rotating wind turbine blades, and the impact on birds (chapter 8) and land use (EWEA, 2004). Some people also fear the impact of wind turbines on residential property values. In this section, we discuss these aspects briefly.

At times when the sun shines wind turbines cast shadows on the ground. Another effect caused by the sunlight is the flickering of turbine blades. This shadow casting and flickering effects can be perceived as annoying for residents living close to the wind turbine(s). Careful planning of the wind turbine site can avoid these problems very well. Currently, rules for avoiding shadow casting and flickering are not yet explicitly regulated by planning authorities.

Wind turbines are tall structures, with a tower base of approximately 8 metres and 250 metres between each turbine. The spacing between wind turbine rows is about 500 metres. An entire wind farm including towers, substation, and access roads uses only about 5% of the allotted land (CWEA, 2007). Wind turbines themselves occupy only 1% of the land area reserved for the wind energy project. 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.

The negative impact of wind turbines on residential property values is often put forward as well. 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 beyond a one-mile (1.6 km) distance 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).

6.2. Onshore versus offshore

As already expressed earlier in the text, onshore and offshore wind have different impacts on the environment and humans. There is no univocal answer to the question whether people have preference for either onshore or offshore wind. The answer to this question might change over time, as preferences could change due to increasing numbers and sizes of wind turbines, policies or other reasons.

When considering offshore wind turbines, visual and noise impacts from wind turbines are easier to mitigate when they are placed offshore. The problem of visual pollution becomes less important when wind turbines are placed further from residents' living areas, which is often the case for offshore wind farms. Experiences from two Danish offshore wind farms (Horns Rev and Nysted) showed a clear willingness to pay more via electricity bills to reduce visual impact of the wind farms (Danish Energy Authority, 2006).

An US opinion survey showed that specific local circumstances can lead to a preference for onshore wind as opposed to offshore wind (Hingtgen, 2006). Community representatives of the lakeshore communities along two of the Great Lakes in the Upper Midwest were asked about the public opinion on whether their communities would support or oppose an offshore wind farm in any of the five Great Lakes. The majority of the respondents thought that offshore wind farms would be perceived as a negative aesthetic element in the landscape. In fact, these view-related issues turned out to be the apparent cause of the majority's preference for onshore farms. It also turned out that acceptance would be higher if coastal areas are used for agricultural or industrial activities.

6.3. Results of public attitude surveys in the EU-27

Over the years a large number of studies have been done to investigate the public attitude of people towards wind energy (and especially the turbines). The previous section focused on the analysis of most important factors influencing public opinions on wind energy. This section discusses the public attitude in countries where wind energy is developed most extensively, notably, Denmark, Germany and Spain.

In general, public opinion towards wind energy is quite positive. Obviously, the percentage of people in favour of the implementation of wind power differs from country to country. In the countries that currently exploit the largest wind power resources, the support for wind power is relatively high. To the question: 'would you welcome increased use of wind power for climate protection reasons', 92% of 1 003 interviewed people in Germany answered positively. In Spain, a number of surveys were conducted in three regions where large wind farms had already been constructed. In a 2001 study, 85% of the respondents in the Navarra region were in favour of implementing wind farms and 1% opposed to this (EWEA, 2003). Another result from this study showed that public opinion of wind farms starts to grow once they are installed. Also in that year, 68% of the Danish people answered 'yes' to the question, should Denmark continue to build wind turbines to increase wind power's share of the electricity production (Sustainable Development Commission, 2005).

The opinion polls are most detailed in the United Kingdom. The UK public is not yet used to high penetration levels of wind energy, but measurable support is on average 80%. Over the past 13 years the support has been relatively stable. The results of UK and Scottish studies performed in the 1992–2005 period show an average support of 80% (Sustainable Development Commission, 2005).

Obviously, there is a difference between people being asked about their opinion of wind energy in general and people being asked about constructing a wind turbine close to their homes. However, and maybe counter-intuitively, a general finding taken from local resident surveys is that people living near wind farms are more in favour of the wind turbines than the general public. In Scotland 85% of the general public supports wind energy, while 94% of the people that live close to the wind farms are positive about it (TNS, 2003). These are general findings and individual projects might give a totally different picture.

In general, it appears that among the general population the minority opposing wind energy is primarily concerned about the visual impact of wind turbines. Not surprisingly, people that live closest to wind farms are the people that could react strongly against wind energy proposals in the area when experiencing noise, shadow flickering or sunlight reflections. Noise seems to be the most annoying problem if it persists. People visiting a wind park may not experience the noise problem in its full proportion if there is only one wind turbine and if the noise occurs on quiet nights with little wind at ground level. People living close to wind farms often positively change their attitude when it turns out that there are no problems with noise or light flickering. Noise and visual impacts as well as other negative impacts can very well be avoided with careful siting of the wind turbines.

6.4. Winning public acceptance

Among the most important factors in lowering the barriers so as to stimulate people to judge wind energy more positively is public participation. Soerensen et al. (2003) identified that three ways of getting the public involved in a project are through information about the ongoing development, through involvement in the decision-making process and through financial involvement in the project. The confidence of the public can be increased when the means to get the public involved are utilized. Among the number of examples of successful public involvement is the role of 'community wind' in Germany and Denmark. 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). The general partnerships (co-operatives) have played an important role in Denmark, especially by providing acceptance at local level, where the possibility of resistance is otherwise high due to visual or noise impacts (Soerensen et al., 2003). Other countries that pursue community wind are the United Kingdom and Sweden.

In Spain, efforts to minimise impacts and integrate wind parks into the landscape in an aesthetic way, combined with local participation, have yielded good results (EWEA, 2004). The next section covers national policies and institutional conditions that could influence public attitudes.

6.5. Summary and conclusions

This chapter addresses the social factors that are of importance high importance for the exploitation of the wind energy potential. Social acceptance of wind projects often has to do with the visual impact of wind turbines on the landscape, both for wind turbines on land and offshore. In Europe, one needs to consider this aspect when future wind farms are scheduled for construction, because it often hampers wind power implementation. Offshore wind power might be part of the solution to the negative visual aspects if wind farms are located further from the coast, which makes them less visible. For offshore wind power too, there are strong public concerns about the visual impact of the wind farms. In the end, visual impact is a matter of taste and therefore wind projects will probably continue to meet resistance. It is therefore not likely to fully prevent public resistance to wind power, but there are a number of ways to reduce the public resistance related to visual aspects. For both offshore and land-based wind power wind turbines should be sited where the impact on the landscape is minimised. In general, offshore wind farms should be located as far away from the coast as possible. Furthermore, recreational areas and coastal settlements should be avoided as much as possible. For wind turbines on land, landscape architecture can overcome many of the barriers to visual impact. Furthermore, local resistance can be lowered by local ownership structures, where residents experience 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 very well be overcome by careful siting of wind turbines and considering minimum distances to nearby residents. By means of a noise analysis the impact of the wind turbine(s) on the sound level can be determined.

With the number of wind farms increasing and visual and noise impacts being major concerns of the population, an important task for national governments will be to develop a clear vision on the future implementation of wind farms in existing landscapes. Studying the suitability of different types of landscapes for the implementation of wind turbines will become an important topic for research.

7. Effects of National Legislation, Planning rules and Support Instruments on the Development of Wind energy.

In the development of wind energy a number of potential restraining elements are related to legislation, planning rules or support instruments. This chapter reflects upon these elements in the context of four typical EU member states in case studies. A second part reflects on the European perspective on these elements.

7.1 Introduction

The political attitude towards wind energy is positive in many EU countries resulting in sometimes ambitious targets for wind energy. In order to reach these future targets it is as important to implement suitable regulations, planning rules and instruments supporting market introduction. This chapter reflects on- and analyses legislation, planning rules and support instruments for onshore and offshore wind in the Netherlands, Spain, Hungary and Denmark.

These four countries each represent a different and typical approach regarding the promotion of renewable energy and wind energy in particular. An analysis of their approach and government (policy) measures determining the factors for success or failure can be divided in the three components legislation, planning rules and support instruments. To what extend these components are interrelated will also be discussed.

In order to structure the energy sector and prevent proliferation, governments will usually regulate initiatives through legislation. Where on the one hand governmental support instruments will promote initiatives, on the other hand legislation offers a restrictive institutional framework. Because promotion (policy) and restriction often form anti-poles, the development of wind energy will depend on the balance between these two. With a rapid growth of wind energy however, discussion has started whether the slow development of the institutional framework is too restrictive for the rapid growth of wind energy.

The promotion of wind energy is done with various but basically financial support instruments to attract investments in wind energy.. (Restrictive) legislation originates from a variety of economic, social and geographic interests. Main drivers are sustainable development and environmental protection. Compared to support mechanisms, legislation is generally more embedded in the institutional system. Because of this characteristic, legislation is a potential bottleneck for the development of wind energy.

A third component that can either act as support instrument or restrictive legislation are planning rules designed to regulate the siting of wind turbines. In many EU countries, the popularity of this measure increases due to spatial feasible penetration and a growing social resistance (Dinica 2003).
To gain insights in how any of these three components can influence the development of wind energy, their characteristics per country will be discussed. Country case studies try to answer the following question:

What (inter)national legislation, planning rules and support instruments are relevant for the development of wind energy and to what extend do these act as a constraint or support?

As mentioned earlier the different components are means to different goals and subsequently might interfere with each other, at the same time hampering the development of wind energy.. With a focus on all components in the development, a fourth section in the case studies addresses a second question:

To what extend are (inter) national legislation, planning rules and support instruments in harmony with the progressive wind energy policy goals as stated by the EU and can one identify crucial 'bottlenecks' that might slow down wind energy development?

Since this report aims to determine the wind energy potential for Europe, it is important to realise that social factors in these are increasingly important and hence qualifying for the outcome. However, social factors are difficult to integrate in the current modelling system because of their qualitative nature. In this chapter an attempt is made to translate qualitative information concerning legislation, planning rules and support instruments into numeric values in order to contribute to determining the wind energy potential in Europe. By comparing the analysis of the case studies, it's possible to differentiate in 'likelihood' of development of wind energy per country and the chance of achieving the EU goals regarding renewables.

An estimated detail like 'likelihood' of development consists of an array of qualitative and quantitative data that is being processed twice. First relevant data is categorised where one describes and values conditions that are to a certain extent in favour of or restraining development. This results in a number of criteria that can be valued per spatial unit by assigning them to one of the predetermined categories. Secondly the relative importance of each individual criterion within the array of data is determined to subsequently contribute proportionally to the (indicative) 'likelihood' of development of wind energy. It is important to realise the subjective character of both processes.

This chapter functions as an outline for further research on this subject and proposes the following criteria:

Legislation
Nr. of necessary permits: based on the information supplied by Ministries from the country in question. If possible it differs between onshore and offshore permits and maximum and minimum permits. It can be regarded as indicator for the complexity of a system.
Appeal procedure: binary data. Does the legislative procedure include the opportunity to lodge an appeal and thus slow the process?

Planning rules
Effectiveness planning rules: a characteristic that is given the score low, medium or high based on the results of the current planning rules. Results are evaluated and valued relative to the other case studies.
Social involvement: the index score low, medium or high values the social involvement during the procedural process preceding a new wind energy project. The score is based on information of current and past projects. The score is relative.

Support instruments
Effectiveness support instrument: a characteristic that is given the score low, medium or high based on the results of the current policy of support instruments. Results are evaluated and valued relative to the other case studies.

Consistency of support: national policy regarding wind energy is either consistent and support instruments offer a good incentive to invest in wind turbines or wind farms or policy is inconsistent and offers unreliable perspectives for investors to step in.

7.2 Case study 1: Netherlands

The development of wind energy in the Netherlands started in the 1970's as a consequence of the '73 oil crisis. Nowadays wind energy contributes 3-3.5 % to the Dutch electricity demand Onshore development is currently characterized by the development of the largest Dutch wind farm to be built in the Noordoostpolder while offshore wind energy is characterized by two developments, the Offshore Wind Farm (Egmond aan Zee) and the new Princess Amalia Wind Farm, operational since June 2008. The current technical- and political developments feed the discussion regarding the development of offshore wind parks because onshore wind parks meet increasingly resistance by the public.

Legislation

Legislation concerning wind energy can be divided in onshore and offshore legislation. Most relevant legislation for offshore wind farms appears to be “Wet Beheer Rijkswaterstaatwerken” (WBR, 1996) that includes an environmental impact assessment report (M.e.r.). The WBR applies for the whole exclusive economical zone (EEZ), including the 12 mile territorial waters and defines the regulations to which a wind farm should comply to.

The WBR is the single law that is relevant for wind energy development on the North Sea. However, the permit procedure involves a large number of authorities, each processing the application individually. Because of the complicated process and the abundance of (common) interests in the area, it is very difficult to get a permit for wind energy development.

In contrast to offshore, there is more and more diverse onshore legislation. Government agencies involved are Provinces, Regional Water Boards, the Ministry of Agriculture, Nature and Food safety (LNV) and the Ministry of Transport, Public works and Water management (V&W). Relevant legislationis:

- Nature conservation Act[14] : for the protection of nature in general.
- Law Management of Water State Activities: concerns North Sea and IJsselmeer.
- Flora and Fauna Act[15:] concerns protected flora and fauna.

Apart from this legislation, numerous other laws affect the development of wind energy in some way. Relevant legislation differs per site. Currently the Dutch wind energy development seems to get frustrated because of the long time span of up to five years to receive the necessary permits and subsidies. This is primarily due to the large amount of Government agencies involved and the fact that every procedure includes appeal procedures which tend to be very time consuming. This is a consequence of the large number of stakeholders and the high social and political involvement in the Netherlands.

Planning Rules

Because wind energy is one of the main topics in the renewable energy debate in the Netherlands, spatial planning of wind energy is no longer in an early stage of development. Starting with the BLOW-agreements in 2001, currently the National Implementation Plan Wind Energy[16] aims at developing planning rules for wind turbines. The National Implementation Plan Wind Energy includes all stakeholders in the process for reaching consensus on the future locations of wind turbines. Wind projects after 2011 can benefit from this and, pursuant to streamlining of procedures, the planning will contribute to achieving the EU goals for renewables.

Although the Netherlands is working on planning issues currently a mere 36% of onshore wind projects are actually being realised (personal communication, Ministry of Housing, Spatial Planning and Environment[17]). This rather low percentage of success is primarily caused by the large number of government bodies on different levels that are involved in the development of wind energy and the lack of support by local authorities. By crossing the plans for regional or national wind development municipalities form an important bottleneck in the development of wind energy (questionnaire, EEA, 2006). At local level the social involvement plays an important role as is the NIMBY-effect (not in my backyard), a widespread phenomenon that people are positive towards wind energy as long as wind turbines are not present in the near vicinity.

The development of offshore wind energy falls behind on onshore wind energy because of unfavourable planning conditions. Various authorities have interests in the area so planning remains difficult. Awareness raising by the Government soon results in the 5th Policy Note on Water Management[18], including a National Water Plan covering these issues. The National Water Plan will become an outline for the Dutch policy concerning the North Sea and assign specific areas for wind farms.

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14 Natuurbeschermingswet, 1998
15 Flora en Faunawet, 2002
16 Nationaal Plan van Aanpak Wind Energie
17 Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM)
18 Nota Waterhuishouding (Ministerie Verkeer en Waterstaat)

Support instruments
The Dutch government is ambitious in promoting wind energy hence provides the market with a subsidy. The Dutch Ministry of Economic Affairs initiated the Regulation Promotion of Renewable Energy production[19] (SDE) that compensates for the still economical unattractive conditions for current wind energy production.
At the moment there is no subsidy arrangement for offshore wind energy production although current development is promising. Two offshore wind farms for the Dutch coast, Windpark Egmond aan Zee and the Princess Amalia Wind Farm received financial supported from the Government.

The fact that the Netherlands has had an unstable policy regarding wind energy in the last years had a negative influence on its development (especially offshore) since uncertainties concerning Government support tempered investments (Dinica 2003). Countries like Denmark and Germany that initially started at the same time made significantly more progress.

Conclusion
Dutch wind energy conditions regarding legislation, planning rules and support instruments are yet not favourable when considering the EU goals for renewable energy. Legislation forms a bottleneck since too many authorities are involved in the decision-making process, planning issues are progressing but yet remain under discussion (both onshore and offshore) and the support-instruments provided by the Dutch government are considered insufficient for entrepreneurship due to its changing nature in previous years (questionnaire, EEA, 2006).

However, the Dutch conditions for wind energy development are expected to improve as a variety of stakeholders is being involved in the policy process. Where procedural and planning bottlenecks still exist in 2008, new policy and regulations in 2009/2010 might promote more effective procedures and a subsequent accelerating wind energy development. Facing the EU goals for renewable energy, this might be the best alternative for the Dutch Government since the three main ingredients for wind energy development legislation, planning and support instruments cannot be regarded in harmony with each other nor with EU goals.

Table 7-1: Score criteria of 'likelihood' of development of wind energy in the Netherlands

Legislation	
Nr. of necessary permits	onshore 3-6, offshore 1 (WBR)
Appeal procedure	Existing
Planning rules	
Effectiveness planning rules	Low
Social involvement	High
Support instruments	
Effectiveness support instrument	Medium
Consistency of support	Low

7.3 Case study 2: Spain

Spain is one of the most successful countries regarding the promotion of electricity from renewable energy sources (RES-E), particularly wind energy. The share of wind energy in the electricity market has increased 16 fold since 1990 to more then 13 GW in 2007 (Domínguez et al., 2007) and accounts now for almost 10 % of the electricity demand. The majority of wind turbines is situated on shore. Two-third of the wind turbines are exploited privately on a small scale. Spain has set an example with a successful development of wind energy that is primarily due to the continuity of support schemes and the schemes themselves: the feed-in tariff (FIT) (del Río Gonzáles, 2008).

Characteristic example for development of Spanish wind energy, is the current expansion of the wind farm El Marquesado in Granada that has the potential of becoming one of the largest of its kind with an installed capacity of 500 MW. The expansion of onshore wind energy does not seem to

[19] Regeling Stimulering Duurzame Energieproductie (SDE)

suffer from any legislative hurdles. Offshore wind energy however is an issue under discussion at the moment.

Legislation
The Government of Spain approved in 2007 legislation that will allow offshore wind parks to be build off its coasts since experimental wind parks appeared to be more lucrative because the advantages of stronger, steadier coastal breezes. Concerns about the impact on Spain's tourist industry have been one reason why, until now, the construction of wind turbines has been restricted to the mainland. To allay these and any environmental concerns the Spanish Ministry of Environment currently investigates the best sites for wind parks. Potential investors will be allowed to reserve the area, provided they demonstrate that the wind turbines do not damage the environment by means of an environmental assessment study.

However the Ministry of Economy is responsible for energy policies. Its main goals are to ensure effective competition in the energy systems and to protect consumer interests. Another key actor in renewable energy promotion is the Institute for energy Diversification and Saving (IDEA) that plays a crucial role in initiating investments in renewable power plants (Dinica, 2003).

National authorities and national legislation are crucial for wind energy projects larger than 50 MW. For any wind energy project below 50 MW the regional governments of Autonomous Communities play a key role in wind energy diffusion in Spain. Their energy departments have the authority to decide on the administrative approval terms and procedures for wind energy parks and this has a very strong influence on the timetable and extent of wind energy market share increase (Dinica, 2003). It is important to mention that the majority (2/3) of windmills are exploited on a small scale thus controlled by regional authorities, offshore wind projects however are mostly larger than 50 MW and are under the control of the national Government.

Spain is among the countries with the highest dependency on imported energy resources in the EU. Towards the end of the 1990's domestic resources served just 30% of total demand. With the improvement of renewable energy technologies, its popularity increased and the aim to improve energy independency is still an important factor why the political commitment is high for wind energy. Guided by EU policy and legislation wind energy projects seldom experience legislative friction since legislation is kept up to date and well organised (questionnaire, EEA, 2006).

Planning rules
The strong influence of the Governments of Autonomous Communities in Spain also has its impact on planning issues. Besides their legal authorities, the political vision of regional Governments was a key success factor for renewables in many Autonomous Communities such as Galicia, Navarra, Castilla y Leon and Andalucia. Others however, although still politically committed towards renewable energy support were more concerned with the aspects of rigorous planning, environmental sensitivity studies and social consensus, which led to a temporary slow down of wind energy development.

Larger wind energy projects, currently offshore projects, are prone to discussions on a national and regional level. Especially the tourism sector fears the impact of large offshore wind parks. One example is the planning of the wind park outside the coast of Cabo Trafalgar where local people blame the Government's bad planning since the wind park of 2800 MW will endanger the local ecology (bird and fish) and also the sea view (Cagliani, 2008). Governmental planning is based on the conditions that initiators applying for a license to build an offshore wind farm in one of the Government-designated zones will have to show that their wind park will generate at least 50 MW of electricity and also demonstrate that the wind turbines do not ruin the environment. The people of Cabo Trafalgar demand reconsidering of the plans.

In general however, planning issues do not seem to restrain the development of wind energy in Spain since social and political influences seem to contribute to favourable conditions.

Support instruments
Spanish renewable energy policy is summarized in the Renewable Energy Plan which is complying with the European Directives and sets a wind power objective of 20000 MW for 2011and is more than 12.1 % of the current electricity demand. Like France, Denmark and Germany, Spain has an

Electricity Feed Law that permits the interconnection of renewable sources of electricity with the grid and also specifies the price paid. The continuity of the support scheme, the feed-in-tariff (FIT), throughout the development of renewable energy sources is an important factor in its Spanish success since it creates favourable conditions for investments (del Río Gonzáles, 2008). The Spanish government recognised this at an early stage and made the FIT a steady factor in RES development.

Besides the continuity of the Spanish support scheme another factor behind the success is the broad social and political coalition leading to political commitment. The fact that the FIT has been modified twice in order to accommodate concerns from different actors can be regarded as exemplary (Dinica, 2003). A result of the political commitment is that a diversity of renewable energy sources are being exploited; i.e. the Plan de Energías Renovables of 2005 sets ambitious capacity targets for not only wind energy but also PV, thermal, solar thermal electric and biomass.

Early 2007, the existing Electricity Law (1997) was reformed, and this process created significant uncertainty for the first time in the Spanish market. Finally, at the end of May a new Law on regulating the production of renewable energy[20] was published, revealing a similar structure to the old system but with less favourable tariffs and a cap and floor mechanism for the fixed premium option. With this the Spanish renewable energy market has entered a period of relative uncertainty.

Conclusion
Spain emerged to be one of the leading countries in Europe concerning wind energy development. A record of 3.5 GW was installed in 2007 representing 40% of the European total. The success results from a clear national incentive framework for renewable energy, the FIT, as well as strong national targets. The process for offshore wind energy has started recently and is rapidly progressing. Also EU-based Spanish legislation does not seem to restrain the ambitious targets Spain sets for itself.

Table 7-2: Score criteria of 'likelihood' of development of wind energy in Spain

Legislation	
Nr. of necessary permits	onshore unknown, offshore 1
Appeal procedure	Existing
Planning rules	
Effectiveness planning rules	Medium
Social involvement	High
Support instruments	
Effectiveness support instrument	High
Consistency of support	medium

7.4 Case study 3: Hungary

In 2003, renewables had a 3.6% share of Hungary's total primary energy supply, but the share of renewables in electrical power supply was only 0.5%. Hungary aims to achieve 5% of total primary energy and 3.6% of the power supply from renewables by 2010 (EREC, 2008). Currently, investment in renewable energy technology is small – the concept of environmental protection is fairly new and research funding in general is low: Hungary spent only a small amount of the GDP on research and development in past years (questionnaire, EEA, 2006).

However, new initiatives come up. Clear progress has been made. The Hungarian Academy of Sciences has for instance set up a Centre for Biological Research – Biopolis – where scientist have managed to perfect technologies that transform food industry waste into biogas for energy production, doubling the performance of the biogas-producing bacteria. The use of biomass as renewable energy source is the technique that has by far the largest application in Hungary followed by the use of geothermal energy (EREC, 2008) and subsequently in part stimulating wind energy that now seems to outgrow its infancy

[20] Real Decreto 661/2007, de 25 de mayo, por el que se regula la actividad de producción de enrgía eléctrica en regimen especial.

The focus on other renewables does not mean Hungary has no interest in wind energy. The fact that the country is landlocked means it cannot exploit offshore wind and that it can be categorized as moderately windy. Nevertheless, because of the compulsory reception (regulated by legislation) and the favourable (raised) price of electricity generated from renewable sources, and as a result of investment subsidies, construction of an increasing number of wind turbines and smaller wind farms has begun in the last couple of years in Hungary, in order to produce electricity for the national electric grid (Farkas et al., 2006). Before 2010 the plan is to have 330 MW capacity installed, primarily in the the Northwestern part of the country where the conditions are most favourable.

Legislation
One aspect that might interfere with the development of wind energy is the permission process for wind farms which is a very complex procedure involving several authorities and numerous legislations. Because wind energy and the construction of wind farms are not mentioned in the current legislation, procedures tend to be inefficient (questionnaire, EEA, 2006). The Energy Efficiency Program, initiated in 2001, offers however a concept that promotes also wind energy.

To illustrate the difficult decision process: plans existed in Hungary to develop larger scale wind parks such as 40-windmill installation near the Tés-Highland. A German company, intended to invest up to EUR 100 million, but the permit was refused for reasons of nature conservation. Assessments of investment projects that account for all potential impacts, and efforts to minimize them, are essential. Yet permitting and conflicts with nature protection significantly hinder the development of wind energy.

Typical of the Hungarian permission procedure for placing wind turbines are the six authorities involved that in total have to consider 20 National Acts, 15 Government Degrees, 26 Ministerial Degrees, 4 Government Resolutions and 12 pieces of legislation related to the climate policy of Hungary (questionnaire, EEA, 2006). Application procedures tend to be influenced by the amount of legislation in combination with authorities that are yet inexperienced with wind energy projects.

Planning rules
Hungary has no planning rules on national scale aiming at locating wind energy sites. A few wind energy projects were initiated until now in close cooperation with local authorities. One good example is the Szelero Vep Wind Project with the purpose of building 20 wind turbines with a total capacity of 330 MW to be finished 2010. To address the scepticism, all stakeholders (local authorities and population) have been involved in the wind energy project from the start, resulting in a high social involvement and acceptance. The bottleneck of this project remains the authorisation procedure and the communication with the authorities (Farkas et al., 2006).

Another issue related to planning is the state of the Hungarian electricity grid which is not expected to function optimally when renewable energy sources are to be plugged in (questionnaire, EEA, 2006). The grid does not meet the requirements and needs adjustment. To guarantee consistent delivery of electricity to the power grid Hungarian power plants using fossil fuels need to adapt to an irregular production regime to compensate for the irregular delivery of wind energy. Currently, Hungarian power plants are not suited for frequent production changes.

Support instruments
The Hungarian government introduced a support mechanism for all renewable energy systems based on investment subsidies and a feed-in-tariff. The feed-in-tariff (9.4 €ct/kWh) was adopted for inclusion in the Electricity Act in 2001. There is no differentiation among technologies. The Electricity Act does not define a time limit for the feed-in-tariff, however does guarantee this for the lifetime of the installation. The Electricity Act gives the Government the possibility to define a start date for a green certificate system to be introduced anytime after 2008, as soon as the market of renewable electricity has reached a critical mass for competition of 300-350 MW. In the transition period, there will be a fixed premium system for small-scale power plants based on cogeneration or renewables.

For the moment, the use of biomass as the largest application in Hungary mostly benefits from support instruments. The effectiveness of renewable energy policy for wind energy is unknown.

Also since renewable energy is relatively new in Hungary. It does not have the advantage of a consistent policy yet. This leads to high investment risks and low penetration of wind energy so far.

Conclusion
The few wind energy projects in Hungary are typical for the premature state of renewable energy and especially wind energy. The main bottlenecks in the development of wind energy appear to be the public procurement and the authorisation procedure. The fact that wind energy is new in Hungary may be the most important reason for the slow development (Farkas et al., 2006). Wind energy in Hungary seems to be no priority for Governmental support.

Table 7-3: Score criteria of 'likelihood' of development of wind energy in Hungary

Legislation	
Nr. of necessary permits	onshore >10, offshore n.a.
Appeal procedure	existence unknown
Planning rules	
Effectiveness planning rules	not existent
Social involvement	Medium
Support instruments	
Effectiveness support instrument	Unknown
Consistency of support	medium

7.5 Case study 4: Denmark

Soon after the '73 oil crisis Denmark started developing renewable energy facilities suited for large scale exploitation and fulfil a role as one of the frontrunners until this day, especially concerning wind energy. Currently roughly 20% of the countries electricity demand is produced by onshore- and offshore wind turbines. The Danish wind energy sector is characterized by numerous onshore projects and an ambitious development of large offshore projects like Horns Rev situated in the North Sea. Because of a long history with energy Denmark has a prominent place in (exporting) global wind technology.

The rapid advent of wind energy is primarily the result of the favourable economic conditions created by the Danish social-democratic government during the 1980's and 90's. An investment subsidy introduced in 1979 covered 30% of investment costs in wind turbines, subject to approval by the National Energy Research Centre. The investment subsidy was not only a stimulus for the construction of wind turbines but also a stimulus for market forces to better develop a wind turbine industry. By 1989 government support switched to a feed-in-tariff since private investments in wind turbines had become attractive. Small- and medium-sized wind turbines quickly became reliable and cost-effective. Due to technical problems associated with large wind turbines, economic support for large wind energy projects is still necessary.

Denmark has a strong focus on offshore wind energy since onshore wind energy soon will reach feasible penetration level. Although public support for wind energy is traditionally high in Denmark new onshore wind energy developments are coping with increasing social resistance due to the fact that the country is experienced as 'full'. The Action Plan on Offshore Windpower, 1997, set the basis for an altering government policy.

Legislation
Where Danish legislation concerning wind energy could be divided in onshore- and offshore legislation under the authority of the Ministry of Environment and the Ministry of Transport and Energy, since the last election in 2007 the only authority is now the Ministry of Climate and Energy. For either on-and offshore applications an environmental impact assessment is the first step in a legislation procedure after the general public and the authorities and organizations concerned have had an opportunity to express their opinions. Also towards the end of the procedure a public consultation represents an important element in the final approval of a permit. The high level of participatory planning tends to make procedures more successful and relatively efficient.

The Danish Energy Agency (DEA) as part of the Ministry of Climate and Energy is heavily involved in the development of offshore wind energy. For instance, the regulatory project risks are reduced to a minimum with a one-stop shop concept (IEA, 2005). All necessary permits, ranging from grid-connection to offshore activities, are to be acquired at the DEA's office. Only a few permits are needed (depending on location). They are provided by a central agency, which streamlines the procedures.

Planning rules

For the development of wind energy in Denmark, the development of models for dealing with public planning issues has been very important for the acceptance of the technology. Public planning is based on an early involvement of all stakeholders in a wind energy project. Initially public planning procedures were developed through trial and error. In 1992 more systematic planning procedures were developed at national level, with directives for local planners. In addition, an executive order from the Ministries of Environment and Energy ordered municipalities to find suitable sites for wind turbines siting throughout the country. This form of 'prior planning' with public hearings in advance of any actual applications for siting of turbines helped the public acceptance and support for the development of wind energy considerably (Krohn, 2002).

Around 1997 another set of planning regulations were developed for offshore wind parks with a central national authority, the Danish Energy Agency, being responsible for involving all interested stakeholders, public and private. This method has facilitated the planning process considerably (Devine-Wright, 2005). The effectiveness of this planning method based on involving all stakeholders prior to any planning is the reason for a high social involvement.

In Denmark, new planning guidelines had to be developed because of the increased size of modern wind turbines. New locations with a height requirement of 100–150 m must be appointed. Local authorities should have targets for wind turbine development linked to the local planning policy to make sure that the national goal is met. Up to 1 January 2007, it was the region's responsibility to identify suitable locations for new wind turbines. After this date, the responsibility was shifted to the municipalities.

Support instruments

The support of the Danish authorities was important for the development of wind energy. Investments in wind energy were stimulated by an attractive subsidy (Smit et al, 2007). The authorities' attitude was very cooperative and predictable, enabling utilities to anticipate. However the 2001 elections changed the Danish policies drastically, leading to a cancellation of three large planned projects and a more market based incentive mechanism (Roggenkamp, 2003). As a result, wind energy development suffered a setback. Only the development of the two wind farms of Horns Rev and Nystad went on. The two extensions Horns Rev II (finished this year) and Nystad II (will be build next year) represent a renewed pace in development however.

With offshore wind energy as a major renewable energy source the development suffered a significant setback and underlines the importance of a continuous and attractive support policy. Last year however, the conditions improved for Danish wind energy and recently the plan for a new wind park in the Kattegat, located North of Jutland, were permitted by Danish authorities.

Conclusion

Denmark can be considered one of the frontrunners for implementing wind energy and has a mature procedural structure. A potential bottleneck however that can restrain the development of wind energy might be the policy change and subsequent economic support scheme in 2003. This led to a steep decrease of new wind energy initiatives.

Table 7-4: Score criteria of 'likelihood' of development of wind energy in Denmark

Legislation	
Nr. of necessary permits	onshore 3-6, offshore 3
Appeal procedure	yes, by the Naturklagenævnet

Planning rules	
Effectiveness planning rules	Existing
Social involvement	High
Support instruments	
Effectiveness support instrument	High
Consistency of support	Medium

7.6 Case study comparison and discussion

This paragraph aims to identify the differences in development of wind energy between the Netherlands, Spain, Hungary and Denmark and discusses these issues where the comparison falls short due to insufficient or incomplete data.

Table 7-5: summary of criteria: 'likelihood' of wind energy development

	Netherlands	Spain	Hungary	Denmark
Legislation				
Nr. of necessary permits	onshore 3-6, offshore 1 (WBR)	onshore unknown, offshore 1	onshore >10, offshore n.a.	onshore 3-6, offshore 3
Appeal procedure	existing	existing	existence unknown	existing
Planning rules				
Effectiveness planning rules	low	medium	not existent	existing
Social involvement	high	high	medium	high
Support instruments				
Effectiveness support instrument	medium	high	unknown	high
Consistency of support	low	medium	medium	medium

Comparison of characteristics for wind energy development in these four countries shows a number of apparent differences. The Netherlands, Spain and Denmark are in an advanced stage of integrating wind energy in their electricity system but are each to a certain extent struggling with different issues to fulfil the EU goals regarding renewable energy for 2020. Wind energy in Hungary on the other hand is still in an early stage of development.

Regarding Spain as most successful in implementing wind energy, most important factors in the development of wind energy are a combination of rather effective support instruments, a high social involvement, and streamlined legislation. Similar conditions exist in Denmark and the Netherlands, however a crucial difference is that the support by the Government was not stable over the last years. This slowed down the development of wind energy.
Wind energy in the Netherlands also suffers from a complex decision making process that, although not a criterion here, has a big impact on the development. Hungary is starting the implementation of wind energy but suffers from start-up problems like unfamiliarity with the new type of renewable energy sources (RES) and subsequent procedural problems.

A striking detail is that not the amount of permits is decisive for the success of initiating a wind turbine(park) but the procedural 'fluentness' and support from (local) authorities that is determining the success of the project. Another element for success appears to be the feed-in tariff systems applied in Denmark and Spain that have been successful in the deployment of large amounts of wind power capacity. The biggest advantage of the systems as designed in these countries is the longer term certainty about receiving support, which lowers investment risks considerably. Fixed feed-in tariffs are currently used in many of the EU-25 member states (OPTRES, 2007).

Furthermore, crucial bottlenecks that might decelerate wind energy development are different per country. The impact however of the different bottlenecks are to such extent restraining that the relevance of including social data (institutions, planning and support instruments) in determining the European wind energy potential is high, but only when considering this on a inter-European scale since Institutions and policy are still only valid within national borders.

Comparison of the wind energy potential based on institutional and policy characteristics of countries can easily be regarded inaccurate due to a lack of quantitative data. Moreover, the step towards indexation the qualitative data and subsequently value the results are impossible without making assumptions. Results have to be considered indicative. In this case when comparing these 4 countries the exact relation of the criteria with the potential of wind energy is yet undefined. Also sets of clear boundary conditions have to defined, enabling quantitative scores on the criteria.

7.8 The European perspective on Legislation, Planning Rules and Support Instruments regarding Wind Energy

The development of renewable energy sources (RES) still is primarily a national issue in most EU member states leading to a significant differentiation in progress development in the European region. All case studies mentioned above are typical examples of how institutional and political conditions are major elements in how, where and when RES are implemented in the current energy system. Policy targets at EU level as well as increasing ambitions at the member states level, make clear that guidance on the development of RES (and in particular wind energy as one of the most promising sources) is needed.

Wind energy currently meets 3.7% of EU electricity demand and the European Commission's goal of increasing that share to 12% by 2020 is certainly achievable (EWEA, 2008). In 2007, wind power capacity in the EU increased by 8.5 GW, and on average, wind power capacity needs to increase by 9.5 GW per year over the next 13 years to reach 180 GW and meet 12-14% of EU power demand in 2020. 180 GW of wind in 2020 would produce 477 TWh of electricity, of which 133 TWh would come from offshore wind. This study shows that EU's ambitions could be achieved with appropriate actions.

However, a number of challenges lay ahead. Apart from the technical issues that need to be solved (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 European approach. This paragraph discusses these issues per theme.

Legislation
The European Commission proposes influential institutional developments for a new Energy Policy in the recent Green Paper: 'A European Strategy for Sustainable, competitive and Secure Energy for Europe'[21]. This Green Paper includes a Renewable Energy Roadmap[22] that proposes a binding 20% target for the overall share of renewable energy in 2020 for the EU. The Road Map provides for each Member State to adopt mandatory targets and action plans in line with its potential. Thereupon on 23rd January 2008 the Commission put forward the new energy and climate package[23] including a proposal for a directive on the promotion of the use of renewable energy, setting national binding targets for the share of renewable energy consumption aimed at together achieving the overall 20% target. The timely adoption and implementation of these two packages will form the EU's main contribution to promoting wind energy (European Commission, 2008a).

Within the context of legislation, but also planning and economic support instruments, it should be mentioned that under the Seventh Framework Programme[24] (FP7) the European Commission has given a higher priority to wind energy starting with the 2009 Energy Work Programme. The focus is on research and development.

The institutional framework offered by the EU however has yet to develop to its full potential, competing with conventional energy sources. The lack of clarity on the conditions under which wind farms can be build in or close to areas designated for protection under the EU 'Birds' and 'Habitat' Directives or other protected nature conservation areas (European Commission, 2008b) is

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21 COM (2006) 105 Final
22 COM (2006) 848 Final
23 COM (2008) 0030 Final
24 http://ec.europa.eu/research/fp7/index_en.cfm

considered an important barrier. Failure to identify such areas increases uncertainty of the potential suitability of any given site for wind farms.
Another issue is lack of clarity on the Environmental Impact Assessment (EIA) and the need for guidelines and information exchange at international level to prevent cross regional- and national obstacles. Finally the variety of authorities involved in the consenting procedures is considered an inefficient, unnecessary bottleneck (European Commission, 2008b).

While land based wind energy will remain dominant in the immediate future, installations at sea become increasingly important; this study shows the high potential for off shore wind energy. A relevant issue here is that the legislative framework and the established procedures are sometimes written with land (and not offshore) applications in mind. 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.

Besides further development of a strong European framework and European support and authority on energy development, a large number of stakeholders in this process (EC, 2008a) indicate that consenting procedures should be accelerated by streamlining and bundling procedures gathering all steps in the process. A ‘one stop shop’ was broadly suggested.

A number of challenges to be dealt with regarding onshore but also (and especially) offshore wind energy are best to be solved at European level. The need for interconnection, technology development and spatial planning cannot be solved sufficiently on a national level.

Planning Rules
Wind energy planning, in particular offshore, increasingly develops towards a European issue since the main thresholds relate to the integration in the (European) electricity grid. Onshore planning remains a national issue where physical and legislative elements are most relevant, having less of a transboundary element (like offshore wind energy).

Offshore wind energy planning is mostly related to development of the grid infrastructure and system integration. Most offshore wind resources are not equally distributed across the continent and to date most offshore wind developments have been in Northern Europe. In a scenario with large-scale development of offshore wind power, the production from off shore sites will therefore 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 (EC, 2008b). A European approach is necessary to assure interconnection and enable integration of offshore wind into the European grid.

In contrast to spatial planning on land, member states generally are little experienced in- and sometimes have inadequate governance structures and rules for integrated planning in the marine environment. An integrated approach for looking simultaneously at the spatial distribution of wind resources, constraints imposed by other marine activities or interests, and at electricity grid aspects is in an early stage of development. This increases uncertainty and the risk of delays or failure of wind energy projects at sea (European Commission, 2008a).

A more strategic and coordinated approach will be important for exploiting Europe’s potential wind resources and a range of planning instruments at EU or regional level may play a role in this respect. For both onshore and offshore wind energy the Commission has proposed that the New Directive on energy from renewable energy sources should contain an obligation to prepare National Action Plans. The implementation of the recently adopted Marine Strategy Framework Directive[25] provides an opportunity to member states to consider offshore wind farms in their overall assessment of the pressure and impacts on the marine environment. Finally the regional cooperation within the new European Network of Transmission System Operators (ENTSO) proposed under the ‘third package’ will be an important tool for optimizing the electricity grid for the implementation of large scale wind energy. Such interregional cooperation can benefit offshore wind energy initiatives at sites such as the North Sea (England, Netherlands, Denmark, Germany

[25] COM (2007) 575 Final

and Norway), the Baltic Sea (Sweden, Finland, Estonia, Latvia, Lithuania, Poland, etc.) and sites in the Mediterranean Sea (Greece, Turkey, Italy, etc), the Irish Sea (England and Ireland) and the Black Sea (Bulgaria, Turkey, and Romania)

Support Instruments

Support instruments are to date an exclusively national matter and are as such one of the most important differentiating factors in the development of wind energy in Europe. Member states with an economic support scheme (often feed-in tariffs) that provides financial security and with proven consistency over the years, tend to have the advantage in terms of development of renewable energy sources.

The main thresholds regarding support instruments relate to the sensitivity of investor- and banking confidence for new wind energy projects. It is a task of national governments to underpin confidence in the wind sector. EU's task in this can be to ensure that national action plans provide the investors confidence, discourage local rules that are detrimental to the financial conditions (such as a limit to the full load hours accepted by the grid), ensure that Government commitments are consistent over time and that national Governments are committed to follow an EU approved strategy that cannot be rescinded easily.

In this context important EU initiatives are the Seventh Framework Programme[26] (FP7), the Strategic Energy Technology Plan (SET-Plan)[27] and the Intelligent Energy Programme (IEE)[28] that stimulate research and development. Furthermore, where national economic support for wind energy development falls short, a number of EU countries can partly rely on the Cohesion Fund[29] for structural support which helps speeding up project implementation and inject confidence and dynamics into the European economy, among other things RES development. Other economical support can come from the European Bank for Reconstruction and Development and the European Investment Bank

7.9 Conclusions

As this study shows, the potential for wind energy are high. However, there are many aspects influencing the actual introduction of wind energy; among which legislation, planning rules and support instruments for wind energy. These aspects are studied in this chapter; based on four case studies.

Critical factors for failure or success for wind energy on a national level seem to be:
(1) In countries where renewables (among which wind energy) get priority in Government policy, the chances for wind energy seem to be higher. Prerequisites are a stable Government policy on the longer term, guaranteeing support for wind energy developments and thus lowering financial risks. Also (stable) economic support from the Government is important, because to date it is difficult for wind energy to compete with traditional power generation. Feed-in tariff systems in some Member States have been successful in the deployment of large amounts of wind power capacity.
(2) The legislative framework on the national level. The effort needed for a potential investor for receiving permits and allowances needed to be able to install a wind farm can act restraining. A "one desk policy" for coordinating necessary procedures seems the best way to improve efficiency and to reduce time needed for procedural issues;
(3) In countries having a high social involvement of the population, the chances for success can be improved by stakeholder involvement in an early stage of the planning process and/or by stimulating ownership among the stakeholders;

26 http://ec.europa.eu/research/fp7/index_en.cfm
27 COM (2007) 723, 22.11.2007
28 OJ 412, 30.12.2006, p.1.
29 MEMO/08/740

Especially off shore wind energy seems promising. Five regions seem to be most attractive in that respect: North Sea, Baltic Sea, Irish Sea and parts of the Mediterranean Sea and Black Sea. In this perspective, possible factors for failure or success have been identified. Planning rules for offshore wind energy seem to be copied in many countries from onshore planning rules. Criteria for considering different functionalities at sea are not very clear yet; and also differ between countries.

The European perspective on wind energy is promising given the fact that the EU comes with many initiatives to support its development on a European scale. The surplus of an international approach is that all Member States benefit from technical and economical experience and streamlines the increasingly transboundary orientated development of (especially offshore) wind energy. The development of a number of highly potential offshore wind energy sites would benefit from such cooperation.

To date however the European role has been modest, national legislation dominates development and is restraining in several occasions. Planning of primarily offshore wind energy on an international level outgrows its infancy and economic support is provided by a number of European Authorities.

The EU may contribute to solving a number of bottlenecks regarding legislation, planning and support instruments by offering a favorable institutional framework and provide economic support to financially sensitive and risky wind energy projects; also providing guidance to the member states for criteria to weigh-off functionalities in a consistent way.

7. Biodiversity constraints

8.1. Introduction

The replacement of fossil fuels by wind energy is associated with obvious benefits to the environment. Wind energy is essentially pollution-free, and any reduction of the emissions of carbon dioxide and other greenhouse gases helps counteracting climate change with its associated hazards to biodiversity. Since the onset of the recent development of wind energy, however, there have been concerns about adverse effects of wind farms to birds and other wildlife due to collision with rotors, exclusion from optimal feeding sites etc. The challenge is thus to meet the wind energy targets in a way that minimizes the negative impact on biodiversity.

There is a strong environmental legislative framework at the EU level to help address the issue of reconciling wind energy development with nature conservation. The Birds and Habitats Directives provide a framework for the conservation of species and habitats of EU conservation 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, and if this assessment concludes that there will be damage or significant disturbance to the nature values, the development can only proceed if there are no alternative solutions, if it is of overriding public interest and with the provision of compensatory measures.

Other international conventions on wildlife protection, such as the Bonn Convention, including the African Eurasian Waterbird Agreement (AEWA), Eurobats, ASCOBANS and ACCOBAMS, the Bern Convention, the Water Framework Directive (WFD), the Ramsar Convention, OSPAR and HELCOM also confer responsibilities on signatory parties.

A Marine Strategy Framework Directive (MSFD), which aims to achieve “good environmental status” of European marine waters by 2021, is currently being negotiated by the European Parliaments and EU Environment Ministers. If approved, the MSFD, together with the WFD, will provide an overall framework for developing and implementing marine management strategies that also take into account the development of offshore wind farms (European Environment Agency 2007).

8.2. Impact of wind farms on biodiversity

8.2.1. 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 of these were based only on finding corpses – a method that may seriously underestimate mortality.

Barrier effect. Wind farms are thought to be barriers when birds approaching them change their flight direction, both on migration or during other 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 through facilitation of access due to improved infrastructure. The scale and degree of disturbance, together with the availability and quality of other suitable habitats that can accommodate the displaced animals, determines the significance of the impact. Habituation may occur, especially for resident birds and mammals, but in several cases impacts are shown to persist or worsen with time (Stewart et al. 2004).

Habitat loss or degradation. The scale of direct habitat loss resulting from the construction of a wind farm and associated infrastructure depends on the size of the project but is generally small, although effects may be more widespread where developments interfere with hydrological patterns or disrupt geomorphological processes. Losses are likely to be significant only if the habitat is rare, such as sandbanks in shallow waters, or if the site is within an area of national or international importance for biodiversity. Direct habitat loss is, however, additive to effective habitat loss owing to displacement. An unknown factor is the extent to which improved infrastructure invites other economic activities, leading to further loss of habitat.

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:

- Wind farms may act as refuges if no fisheries or hunting are allowed within the wind farm area.
- Development of wind farms may relieve other pressures such as military activities, recreation activities or urbanization.
- 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.
- Changes in land management next to wind turbines including the interruption of monotonous agriculture may benefit a number of species, such as birds.

8.2.2. Significance of impacts and cumulative effects

It is essential to assess the significance, in population terms, of the possible impacts. Proximate, local effects, such as the death of one individual bat due to collision or the exclusion of 2,000 seaducks 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 7.1.

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 an 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).

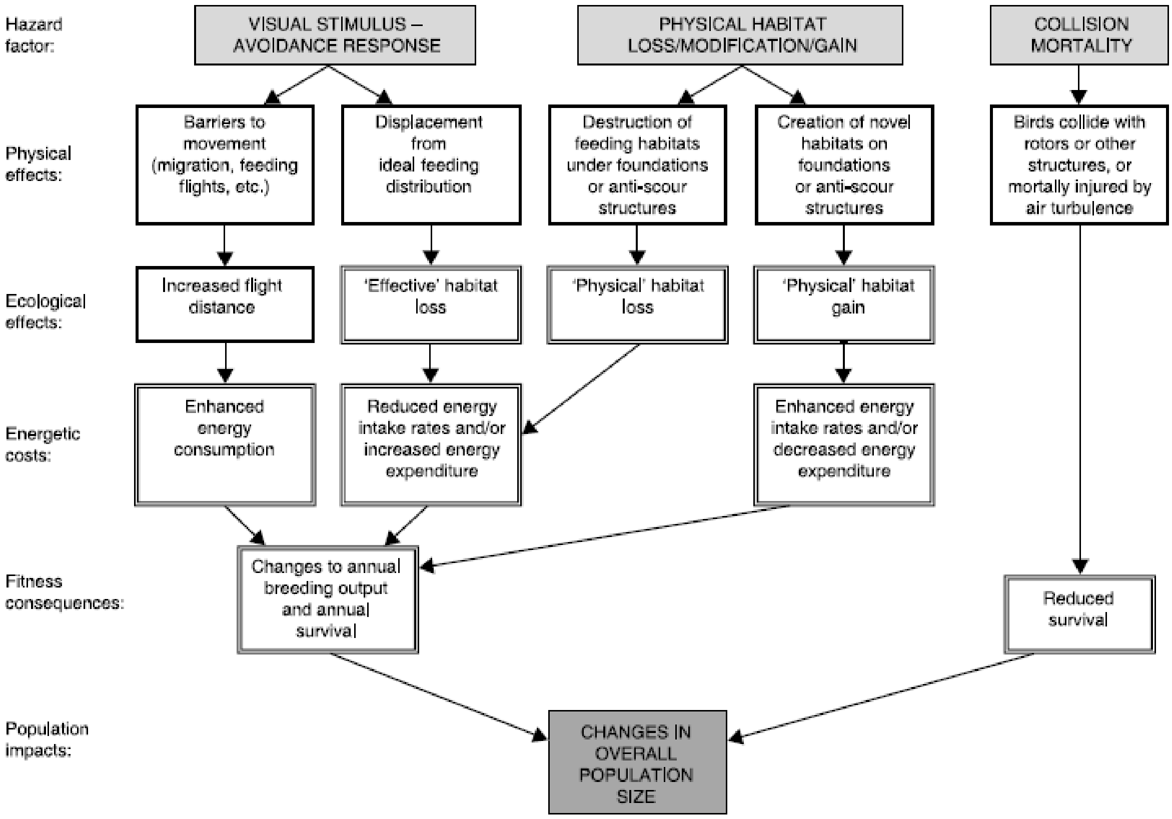

Figure 7-1: Flow chart describing the three major hazard factors presented to birds by the construction of offshore wind farms, showing their physical and ecological effects on birds, the energetic costs and fitness consequences of these effects, and their ultimate impacts on the population level. The boxes with a heavy solid frame indicate potentially measurable effects and the double framed boxes indicate processes that need to be modelled (from Desholm 2006).

8.3. Impact of wind farms on selected species groups

8.3.1. Impact on birds

Birds are the biodiversity element most obviously at risk to 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 & Pullan (2003) and Drewitt & 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, 1500 – 2300 of which golden eagles have been killed by collision here during the past two decades (Thelander & Smallwood 2007). Not surprisingly, 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 where 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 during 2000 – 2002 (Lekuona & 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 c. 2,000 pairs in Navarra and c. 20,000 pairs in Europe as a whole.

Fortunately, the general picture is less dramatic. The majority of studies of collisions caused by wind turbines have recorded relatively low levels of mortality, perhaps reflecting 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, so correction factors should 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/turbine/year were recorded. High-risk farms were either placed on mountain ridges, where chiefly raptors were killed, or near wetlands, where gulls were the main victims. Interestingly, the bird that are 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 species-, season- and site-specific. 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 & 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 the crucial information about the consequences of displacement for survival and breeding productivity is lacking.

On migration, raptors and other diurnal migrants are often concentrated 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, 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 (e.g. 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 & Stienen 2006).

Offshore

Information relating to 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. Major techniques currently underway include radar and thermal imagery. The number of casualties may then be modelled from (a) the number of birds passing the area of interest, (b) the proportion of birds entering the wind farm area, (c) the proportion of birds flying at rotor height, (d) the proportion of birds flying within the horizontal reach of rotor-blades, (e) avoidance behaviour (at each of the preceding levels), and (f) the by-chance 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 c. 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 minimize 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 other species 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 involving risks of 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. This is a well-known phenomenon from a wide range of lit structures (including lighthouses) at land (California Energy Commission 1995, Erickson et al. 2001), and 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 seaducks 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, 1999, Petersen et al. 2006, Petersen & 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 seabeds.

8.3.2. Impact on other species groups

Bats

Bat fatalities at wind farms have been known since the early 1960s, but the extent is not well documented although 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 & 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 SW 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 from 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 (Anon. 2004b). 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 the 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 (Anon. 2004a).

Monitoring of seals at the Nysted and Horns Rev wind farms showed that pile driving temporarily expelled the 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 the 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 and, contrary to these, some fish species are known to be sensitive to low frequency sound (Popper & Carlson 1998). The major effect 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 on a local level and introduce a large secondary production (Petersen & Malm 2006). Evaluation of this should therefore be an integrated part of offshore wind farm EIAs.

8.4. Identification and mapping of sensitive areas

Current evidence suggests that locations with high bird use, especially by species of conservation concern, are in general should 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. 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 is 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). 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 a mountain pass or a narrow sea-crossing, 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 & 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, 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 & 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 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 the land territory but the designation also included several coastal areas. No marine areas were included primarily because no knowledge existed of important bird areas off shore. In connection with plans to develop off shore wind farms in Danish waters in the 1990ies several surveys were carried out with the purpose to identify if off shore areas sensitive to biodiversity (with focus on seabirds) were overlooked in Danish waters. These studies in which airplanes were used lead to the discovery of several very important offshore wintering areas to sea duck and several marine SPAs (and SACs) were subsequently designated (see Figure 7.2). In Denmark SPAs and SACs in practical terms correspond to “zones where wind farm development is incompatible with biodiversity priorities” (see 7.5.1).

8.5. Principles for environmental assessment

In the majority of cases biodiversity impacts of wind farm development may be minimized, to the level where they are of no significant concern, by proper siting. Strategic planning on a national or regional level is a prerequisite for development of a coherent plan for wind energy deployment, which includes the siting and extent of future wind farms and is an appropriate way of addressing cumulative effects. At the level of individual farms, project screening and, if deemed necessary, more comprehensive impact assessments must be undertaken to determine the suitability of the proposed site.

8.5.1. Strategic Environmental Assessment

Strategic Environmental Assessments (SEAs) are strategic appraisals of major programmes or plans, assessing the impact on the environment that various options for achieving a pre-defined goal might have. National, regional and local governments shall undertake SEA of all wind energy plans and programmes that have the potential for significant environmental effects. The scale of a SEA should be determined by consideration of the likely scale of environmental impacts and the geographical scope of the plan or programme. If there are potential trans-boundary effects, international co-operation should 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 in-combination and cumulative effects.

SEA should include indicative sensitivity mapping of the area concerned, preferably identifying:

- Zones where wind farm development is incompatible with biodiversity conservation priorities (no-go areas).
- Zones where wind farm development and biodiversity concerns may conflict, but where more specific assessments may show that adverse effects are within acceptable levels or can be mitigated.
- Zones where conflicts between wind farm development and biodiversity concerns are unlikely.

Offshore, SEAs should specifically address the issues related to the limited extent of shallow water areas. These areas are highly attractive for the wind industry but also constitute the moulting and wintering grounds of the vast majority of European seaducks, which feed at water depths between 5 and 20 metres.

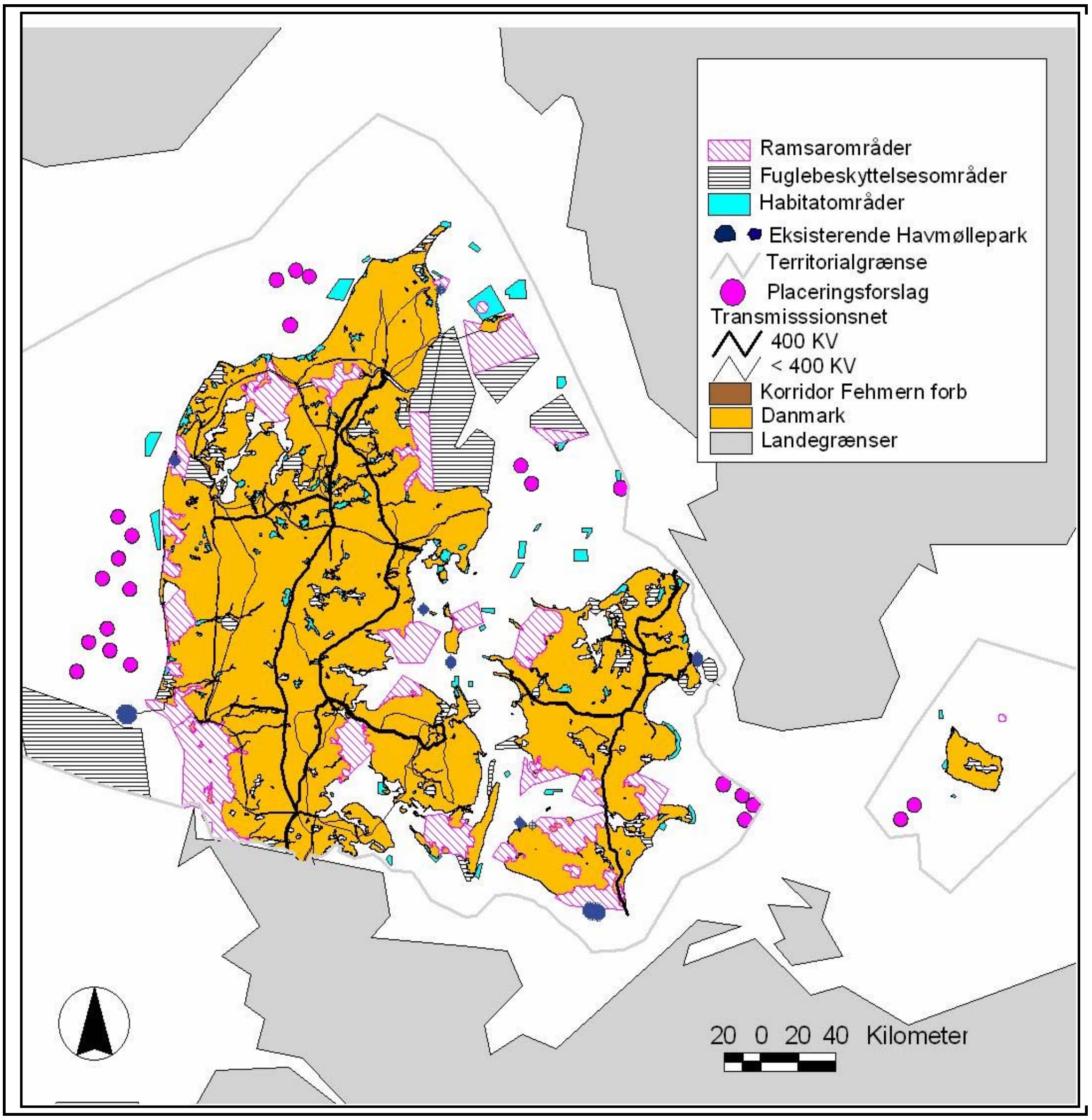

Figure 7-2. Marine protected areas and wind farm development in Danish waters; hatched areas are SPAs (areas with open hatching are also Ramsar areas), areas without hatching are SACs. Blue dots are excising off shore wind farm. Pink circles indicate proposed areas for future wind development (Danish Energy Authority 2007).

8.5.2. Environmental Impact Assessment

Environmental Impact Assessment (EIA) is an essential tool that identifies the impacts of plans, projects or proposals on the environment and potential measures to avoid these. Although there is considerable support for wind energy as an environmentally benign source of energy, stringent environmental assessment is just as important for wind energy as for other developments to ensure optimal siting and to avoid or at least minimize any adverse impacts.

Contrary to SEA, an EIA considers the immediate surroundings and the possible area of impact by looking at habitats, species and ecological processes occurring within the potentially affected area. All wind farm developments should initially be screened to determine whether or not significant environmental effects are likely, applying suitable selection criteria. Proper EIAs should then be undertaken for all proposed developments, including associated infrastructure, for which the screening process indicates a need. If a wind farm is proposed inside a Natura 2000 site, or is likely to have a significant effect on such a site, an Appropriate Assessment in accordance with the requirements of Article 6 of the Habitats Directive must be undertaken.

Every EIA must include a baseline study to determine the habitats and species potentially affected. The appropriate sampling design and duration of study will depend on the location and habitat, the species present, their sensitivity and conservation importance, and the size of the proposed wind farm. To ensure optimal use of the available resources it is important to identify and focus attention on the most vulnerable species. Studies should cover the full annual cycle and need to take into account diurnal, tidal-cycle, weather-related and seasonal variations in site use, as appropriate. Baseline data covering more than one year increase the reliability of the assessment by allowing for year-to-year variation in use. Study areas should comprise the development site, including a buffer zone, and at least one comparable reference area. This allows use of the Before-After Control-Impact (BACI) approach for subsequent monitoring of effects.

Appropriate sampling methods vary, depending on the habitat and focal species, and obviously differ considerably between onshore and offshore wind farms. Ornithological surveys should provide data on bird distribution and numbers, intensity of long- and short-distance movements, and altitude and orientation of flight during different weather conditions and at different times of day and year. Wherever relevant, daytime observations should be supplemented with nocturnal studies using radar, thermal imagery or image intensifier devices. The last two techniques are also relevant for bat studies, in combination with acoustic bat detectors. Bat surveys should enable mapping of feeding areas, roosts and main flight routes. Offshore, the distribution, numbers and movements of marine mammals may be mapped using aerial and ship-based surveys (which also provide information on seabirds), acoustic detectors and satellite tracking of tagged individuals.

Based on the baseline study, potentially adverse effects of the development on the species and habitats concerned shall be identified and their significance shall be assessed. Different proposal options shall be considered with the aim of preventing, or at least minimizing, any adverse effects. The EIA must take into account any cumulative effects that may arise from the wind farm in combination with other developments. If adverse effects are foreseen, the EIA shall identify appropriate mitigation or compensation measures to be implemented in case of project approval. Such measures may also include restrictions on construction works, e.g. with respect to timing and methods.

The EIA needs to be high standard in order to allow informed and objective decisions to be made. Insufficient data sampling or otherwise poor quality assessment should not lead to approval on the grounds of no demonstrable effect. In case of uncertainty, e.g. due to lack of information, the precautionary principle should be applied.

8.6. 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.

8.6.1. Mitigation measures

Mitigation measures may be separated in general (best-practice) measures and more site-specific measures. However, the two categories intergrade, and implementation of mitigation measures should always be based on a site-specific 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 may be placed as close together as technically feasible to minimize the overall footprint or 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 more precise recommendations with respect to colour and frequency must await future research. For offshore wind farms, underwater surfaces and scour protection material that minimize settlement of organisms should be used at sites where reef effects are unwanted.

Minimizing 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 minimized by careful timing and routing of maintenance trips.

Temporary shutdown. It has been suggested to turn off turbines at critical times of the year, such as during nights with high migration activity (e.g. 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 & 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 utilizing 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.

8.6.2. 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 (see Everaert & Stienen 2006 for an example of 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.

8.7. Summary

Being a pollution-free and CO_2 neutral source of energy, wind energy is essentially benign to natural ecosystems. Wind development may also 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, also 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 to possible biodiversity constraints is paid throughout the planning process.

Birds are the biodiversity element most obviously at risk to wind farm development and so far most studies have focused on birds. However, as the history of modern wind turbines is short so far only few long-lasting studies have been carried out and we are still very much in a learning process regarding the possible impact in population terms. Most studies indicate low frequency of bird strikes at onshore and off shore wind farms, but there are notable exceptions. Wind farms at 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 forest 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 re-occupy the wind farm area afterwards. The major impact on marine biodiversity probably stems from the introduction of hard substrate on otherwise soft sea-beds (reef effect) which enables new species to settle within the area.

With proper siting of wind farms most adverse impacts on biodiversity can be avoided. In particular for off shore wind farms, the siting process can been greatly facilitated if Strategic Environmental Assessments (SEAs) at regional and national level have been carried out. A particular important element in this context has been sensitivity mapping that identified areas of biodiversity concern.

8.8. Conclusion

Wind farm development gives obvious benefits to the environment and may also be beneficial biodiversity at local level. However, poorly sited wind farms can have a significant negative impact on certain species, in particular birds and bats.

Proper siting of wind farms is the key to avoiding or minimizing adverse biodiversity effects. Strategic Environmental Assessments (SEAs) that include sensitivity mapping at regional or national level shall identify no-go areas, areas where conflicts may occur and areas 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.

Whenever adverse effects of a proposal for wind development cannot be ruled out, an Environmental Impact Assessment (EIA) shall evaluate the significance of the impact, consider different project options and, if relevant, identify mitigation measures to be implemented in case of project approval.

9. The prospects of a North Sea electricity grid

9.1. Introduction

Various perspectives are developed for the interconnection of offshore wind farms by a trans national offshore grid including an estimate of the cost for marine power transmission infrastructure. These include Watson (2002), PBL (2005), Airtricity (2007, 2008), Czisch (2005), Norwegian TSO Statnett (2008) and DLR (2008). In annex 4 the results for the PBL (2005) are presented. The study shows clearly the structured effect that an electricity grid can have on the configuration of wind parks. This study builds on the acquired knowledge from these studies, especially the recent study by Greenpeace (Greenpeace, 2008).

It is clear from the earlier studies that the value of an offshore grid in the North Sea lies mainly in its role as a facilitator for power exchange and trade between regions and power systems. As such it can introduce additional flexibility to the power system. Moreover, an offshore grid allows the aggregation and dispatch of power from offshore wind farms from different regions, resulting in power generation profiles of low variability.

In the present study, an offshore grid topology is proposed (Figure 1) that is driven by two distinguished policy drivers: the need for connectivity between countries and power market regions and the demand for an economically efficient connection of offshore wind farms. While connectivity is considered the main driver today, the connection of offshore wind farms will gain importance in the future, when offshore converter stations for HVDC will be required for the connection of wind farms far from shore. The required converter stations will be on the open North Sea and with an additional investment they can be connected to each other or to another shore. This would allow the allocation of the spare capacity of the line to the power market, while it is not used by wind power. For arbitrage between market regions, the possibility to make use of an extended wind farm grid connection is a cheaper alternative to the development of separate cables. Since the prolongation of lines from offshore wind farm converter stations is economically beneficial as long as there is opportunity for arbitrage, an offshore grid will probably emerge in such a way

Figure 9-1: Example of a North Sea Electricity grid

Long-term scenarios (2020 to 2030) for offshore wind power in the North Sea envision a total of 40 to 100 GW of installed generation capacity. These wind farms will have to be connected to the onshore transmission grid. Wind farms close to shore will be connected directly to the main land grid, most likely via high voltage AC cables. At larger distances, more than 50 to 90 km away from the shore will probably use an HVDC connection and additional converter stations will be required. In the latter case the grid connection costs can be a substantial part of the investment costs (more then 50%). In the case of interconnection cables, connecting North Sea countries which each other, wind parks could be connected directly to this grid, resulting in substantial costs savings. In this chapter the potential for these costs savings is explored.

9.2. Assumptions

All offshore wind farms in operation today are connected to the onshore power system with high-voltage AC (HVAC) transmission cables. Due to the high capacitance of shielded power cables, the length of such AC cables for practical use is technically limited by the required charge current of the cable. Therefore the length of undersea AC cables is limited. This problem can be overcome by using high-voltage DC (HVDC) cables, as they require no reactive power. The HVDC technology can be used to transmit electricity over long distances or to interconnect different power systems whose grid frequencies are not synchronized. In Germany, HVDC technology will be used for connecting the offshore wind farms in the German Bight to the onshore transmission grid.

The cost of an HVDC VSC system mainly consists of the investment costs and installation costs of two components: the inverter station and the cable pair. Compared to HVAC technology, HVDC technology requires static inverters at both sending and receiving stations. They are expensive and have limited overload capacity. With short transmission distances the losses in the static inverters may be higher than in an AC transmission line. The cost of the inverters may not be offset by reductions in line construction cost and lower line losses. This leads to a break-even point for the choice between an AC and a DC cable. HVAC cable systems are favourable for transmission distance up to 50 - 90 km.

The costs parameter are taken from Greenpeace (2008), and are based on Lazarides (2005) and Lundberg (2003):

- The investment cost and installation costs of a converter station:
  The price of a converter station for HVDC VSC technology (including valves, transformers, filters etc) is about 0.11 M€/MW.
- Table 3 shows the specific cost (cost per km) of three types of cable pairs with a rated capacity of respectively 220, 350 and 500 MW at a rated voltage of 150 kV. These values are calculated using a formula proposed by Lundberg (also for 150 kV cables) C = 1.0887 P + 64.26 (1000 €/km),(2) where P is the rated power of the system in MW
- The installation costs of the cable pair: The cost for installing each cable is set to 100,000 €/km. The assumption is made that only one cable can be installed at a time thus for the cable pair the installation cost is set to 200,000 €/km

Based on the above given assumption the total investment cost of a 1 GW HVDC VSC system is calculated as:

Gc (million Euro) = 220 + 1,353*kmcable

Gc=total costs for a 1GW electricity grid

Table 9-1: Cost per cable pair with rated capacity

Cable rated power (MW)	220	350	500
Costs per cable pair (Meuro/km)	0.304	0.445	0.609

The costs are converted into costs per Kwh, assuming a technical lifetime of the cable of 30 year and a social interest rate of 4%.

9.2.1. exchange capacity from offshore interconnection

An offshore grid providing interconnector capacity between offshore wind farm clusters and onshore nodes in different countries is beneficial for the availability of offshore wind power. In a very simplified view, power from offshore wind farms can be aggregated and delivered to the country with the highest electricity price at any moment, via the offshore grid. In this view, the load duration curve for all aggregated wind farms in the North Sea (Figure 18c) reflects the ideal case of unconstrained transmission capacity. However in practice, wind power generation is part of the generation mix within a portfolio of generation and demand. In this respect, interconnectors serve for import and export as one means of portfolio management. More precisely, they can introduce flexibility into a portfolio. The capacity available for power exchange between countries can be used to complement periods of electricity surplus or shortage within the national power system. The value of interconnector capacity is high when the interconnected power systems have a complementary generation mix and demand profile. This is largely the case with Norway compared to Great Britain and parts of continental Europe. In Norway large reservoir hydro power plants are available, with an installed hydro power capacity of 28 GW, an annual inflow of 136 TWh and a reservoir capacity equivalent to 82 TWh of electricity [54].They can be ramped up and down very fast and complement the nuclear and coal power plants that are largely used in continental Europe and Great Britain. As a consequence of the time shift and of differences in industry and regional habits, the demand profiles of continental Europe, Great Britain and Scandinavia are also partly complementary.

9.3. Methodology

Based on the economic offshore potential, as described in chapter 3 an explicit spatial analyse has been performed with a resolution of 15x20km. The North Sea electricity grid example of figure 1 has hereby been taken as a reference. For each grid the distance to coast and the most nearby interconnection cable has been calculated. If the distance to the electricity grid was the smaller we calculated the potential costs savings based on the costs function of chapter 5 for offshore wind turbines. In the second step the costs savings are compared to the investment costs of the electricy grid. In the third step the generation costs for each location are calculated. Starting with the lowest investment costs first the most likely investment location is calculated up to a capacity of 100 GW. This allows to compare the amount of wind parks that would prefer direct coast connection to the wind parks that prefer grid connection as function of the installed capacity.

9.4. Results

Table 9-2 show the costs, the savings and the share of the electricity grid as function of installed capacity.

Gw	costs ct/kwh	supergrid	savings millions/year	costs millions/year	net costs
1	5,26	0,0	0,00	0	0
5	5,92	0,0	0,00	0	0
10	6,28	0,0	0,00	0	0
15	6,63	0,0	0,00	0	0
20	6,83	0,3	2,06	7	5
25	7,07	0,3	2,06	7	5
30	7,23	1,0	5,51	22	16
35	7,36	1,3	8,31	29	20
40	7,50	2,0	24,48	43	19
45	7,61	2,6	33,63	58	24
50	7,71	4,6	90,33	101	10
55	7,81	5,9	116,73	130	13
60	7,94	8,9	186,19	194	8
65	8,04	12,2	277,05	266	-11
70	8,14	14,2	318,46	310	-9
75	8,31	16,8	394,50	367	-27
80	8,45	18,8	462,96	411	-52
85	8,57	21,1	562,77	461	-102
90	8,68	24,1	675,09	526	-149
95	8,79	27,4	859,61	598	-262
100	8,90	30,7	1002,41	670	-333

Table 9-2: Costs and savings for a North Sea Electricity grid

After the cheaper direct connection location get depleted the share of grid connected locations increases. At a cumulative installed capacity of 65 GW the grid investment costs are fully compensated by the investment costs[30].

9.5. Conclusion

Above an accumulated installed capacity of 15 GW the benefits of an electricity grid start to emerge. At an accumulated capacity of 40GW an electricity grid could reach a share of 5% which would increase to 20% at 65 GW installed capacity. At 65 GW and above an electricity grid financed by governments (assuming a 4% social discount rate) would be beneficial compared to direct connection to the coast.

In addition an offshore grid in the North Sea facilitates trade and it increases security of supply by offering increased connectivity. It allows dispatching power from offshore wind farms to different countries depending on the highest demand. By enabling the supply of aggregated generation profiles from different regions to one market, the offshore grid contributes to reducing the variability of wind power generation in the range of hours. Moreover, an offshore grid in the North Sea allows the import of electricity from hydro power from Norway to the British and the UCTE system. This can replace thermal base load plants and increase the flexibility within a portfolio. In addition, increased liquidity and trading facilities on the European power markets will allow for a more efficient portfolio management. The value of an offshore grid in the North Sea lies in its contribution for increased security of supply, its function for the aggregation and dispatch of power from offshore wind farms, and in its role as a facilitator for power exchange and trade between regions and power systems.

Integrating interconnectors with connection lines for wind farms far from shore can yield efficiency gains for the development of both wind power projects and commercial interconnectors.

[30] In reality compensation will be reached earlier due to the additional use of the grid in trade, on average the grid capacity will be used for 40% by wind parks and there is therefore a substantial capacity available for trade.

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Annex I: Corine land cover classification

	Z(o) min	Z(o) max	ratio min	ratio max	Diff% min -max	Av ratio	Code Level 3	Label Level3
	0,5	1,6	1,6941	2,1347			111	Continuous urban fabric
	0,5		1,6941				112	Discontinuous urban fabric
CL 1					26%	1,91	121	Industrial or commercial units
	0,50	1,1	1,6941	1,9421			141	Green urban areas
							142	Sport and leisure facilities
	0,1000	0,8	1,4515	1,8233			122	Road and rail networks and associated land
CL 2	0,1000	0,8		1,8233	26%	1,64	123	Port areas
	0,1000	0,8000					124	Airports
	0,0024	0,1	1,2495	1,3997			131	Mineral extraction sites
CL 3	0,0024	0,1	1,2495	1,3997	12%	1,32	132	Dump sites
	0,0024	0,1	1,2495	1,3997			133	Construction sites
	0,03	0,17	1,3580	1,5103			211	Non-irrigated arable land
CL 4	0,03	0,17	1,3580	1,5103	11%	1,43	212	Permanently irrigated land
	0,03	0,17	1,3580	1,5103			213	Rice fields
	0,055	0,39	1,3997	1,6410			221	Vineyards
CL 5	0,055	0,39	1,3997	1,6410	17%	1,52	222	Fruit trees and berry plantations
	0,055	0,39	1,3997	1,6410			223	Olive groves
CL 6	0,055	0,2	1,3997	1,5316	9%	1,47	231	Pastures
							241	Annual crops associated with permanent crops
CL 7					19%	1,51	242	Complex cultivation patterns
							243	Land principally occupied by agriculture, with significant areas of natural vegetation
	0,04	0,390	1,3766	1,6410			244	Agro-forestry areas
	0,75	1	1,8028	1,9031			311	Broad-leaved forest
CL 8	0,75	1	1,8028	1,9031	6%	1,85	312	Coniferous forest
	0,75	1	1,8028	1,9031			313	Mixed forest
	0,0024	0,03	1,2495	1,3580			321	Natural grasslands
CL 9	0,04	0,06	1,3766	1,4065	13%	1,33	322	Moors and heathland
							323	Sclerophyllous vegetation
							324	Transitional woodland-shrub
CL 10	0,0003	0,06	1,1997	1,4065	17%	1,30	331	Beaches, dunes, sands
	0,0024	0,001	1,2495	1,2258			332	Bare rocks
CL 11	0,0024	0,03	1,2495	1,3580	9%	1,30	333	Sparsely vegetated areas
							334	Burnt areas
CL 12	0,001	0,0024	1,2258	1,2495	2%	1,24	335	Glaciers and perpetual snow
		0,1		1,4515			411	Inland marshes
		0,06		1,4065			412	Peat bogs
CL 13	0,0010		1,2258		18%	1,34	421	Salt marshes
							422	Salines
							423	Intertidal flats
	0,0002	0,001	1,1922	1,2258			511	Water courses
CL 14	0,0002		1,1922		3%	1,21	521	Coastal lagoons
	0,0002		1,1922				522	Estuaries
	0,0002	0,001	1,1922	1,2258			523	Sea and ocean
CL 15	0,0002	0,001	1,1922	1,2258	3%	1,21	512	Water bodies

roughness ECMWF	
Type of area	Z0 (m)
Water bodies	0,0002
Open terrain (air ports, open grasslands)	0,0024
Open agricultural land (grassland)	0,03
Agricultural land with some houses	0,055
Agricultural land with many houses, shrubs a	0,2
villages, small towns	0,4
large cities, with tall buildings	0,8
Very large cities	1,6
Forest area	1

Roughness Ecofys/KNMI		
ID	omschrijving	z0 (m)
0	geen data	0,03
1	gras	0,03
2	mais	0,17
3	aardappelen	0,07
4	bieten	0,07
5	granen	0,16
6	overige landbouwgewassen	0,04
7	buitenland	0,15
8	glastuinbouw	0,1
9	boomgaard	0,39
10	bollen	0,07
11	loofbos	0,75
12	naaldbos	0,75
16	zoet water	0,001
17	zout water	0,001
18	stedelijk bebouwd gebied	1,6
19	bebouwing in buitengebied	0,5
20	loofbos in bebouwd gebied	1,1
21	naaldbos in bebouwd gebied	1,1
22	Bos met dichte bebouwing	2
23	gras in bebouwd gebied	0,03
24	Kale grond in bebouwd buitengebied	0,001
25	hoofdwegen en spoorwegen	0,1
26	bebouwing in agrarisch gebied	0,5
27	start- en landingsbanen	0,0003
28	parkeerplaats	0,1
30	kwelders	0,0002
31	open zand in kustgebied	0,0003
32	open duinvegetatie	0,02
33	gesloten duinvegetatie	0,06
34	duinheide	0,04
35	open stuifzand	0,0003
36	heide	0,03
37	matig vergraste heide	0,04
38	sterk vergraste heide	0,06
39	hoogveen	0,06
40	Bos in hoogveengebied	0,75
41	overige moerasvegetatie	0,03
42	rietvegetatie	0,1
43	Bos in moerasgebied	0,75
44	veenweidegebied	0,07
45	overig open begroeid natuurgebied	0,03
46	Kale grond in natuurgebied	0,001

Annex II: Boundaries of the Economic Exclusive Zones (EEZ) in Europe

The Division for Ocean Affairs and the Law of the Sea (DOALOS), Office of Legal Affairs, United Nations Secretariat, has prepared comprehensive information on the status of State practice. The database contains the national legislation of coastal States and treaties dealing with the delimitation of maritime boundaries, as made available throughout the years to the United Nations. Whenever possible, the texts are accompanied by illustrative maps.
A selection has been made of the available information to provide relevant input in the form of coordinates, geodesic systems and illustrative maps.

More information can be found on the following websites:

http://www.un.org/Depts/los/LEGISLATIONANDTREATIES/index.htm
http://www.seaaroundus.org/eez/eez.aspx
http://www.gd-ais.com/capabilities/offerings/sr/gmbd.htm

Define boundaries with UN data and make these explicit in map. Undefined data: possible extrapolation or ‘logical connections’ based on expert judgement to create polygons that can be used in a GIS environment to calculate surface areas for wind energy potential calculations.

Annex 3: An Algorithm for estimation of sub-scale effects in ECMWF reanalysis

3.1. Introduction

In an analysis like the one attempted in this report to quantify the possibilities for wind energy to contribute to the renewable targets, one uses large-scale datasets for elevation, land use (from which the aerodynamic roughness is derived), and wind speed. The wind speed dataset used in this report has a resolution of 0.25 deg x 0.25 deg. However, the 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.
To exclude grid cells just based on one value is not realistic. There will always be some areas where local effects will increase the wind resource sufficiently to be able 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[31] program 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 50m resolution with a full blown wind resource model is not realistic. Even in 250m resolution on a reasonably modern PC, WAsP calculates about 20 minutes for a grid cell. With over 38.000 grid cells in the area in question, this was not possible in the limited time available.

3.2. Analysis

Therefore, we have tried to parameterise the variation in wind power within a grid cell through the variation in elevation. Using an Excel sheet with all grid point IDs and some sub-scale orography measures like minimum, maximum, range, mean, median and standard deviation (STD) of elevation, we chose 8 sites with reasonably different characteristics to tune the algorithm given below. We used the WAsP orographic flow model to calculate a few selected grid cells. The elevation came from the USGS (United States Geological Survey) SRTM (Shuttle Radar Topography Mission) version 2 dataset, with 90 m resolution in the horizontal. The roughness needed for WAsP to calculate was 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. We chose 8 different STD and Range values to do the analysis, and found areas in (mostly) Western Europe, since we wanted to compare the results with the European Wind Atlas, which was done for EU-15 in the 1980ies. However, to have a full comparability among the results, we later chose to do the analysis with the standard wind climate of WAsP. The 8 sites are very flat terrain in the Saone valley, France, and with a higher Range, but similar Mean, a site in central Portugal, some medium complex terrain sites at different altitudes in Belgium, near the border to Luxemburg, in Turkey, near the Wikipedia entry for “Garden of Eden”, in Molise in Italy, in Spain in-land of Valencia and a pre-alpine site in Austria, near Wiener Neustadt, and a very complex site in the Dolomites.

Table III. 3: The locations of the reference points. The FWHM is the Full Width Half Maximum of the visually estimated Gaussian distributions (see last section for the plots).

PointID	Lon	Lat	ISO	Label	MIN	MAX	RANGE	MEAN	STD	MEDIAN	FWHM
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	716,0	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	2419	1644	1511,6	374,4	1581	448
25623	15,75	47,50	AT	AT	575	1775	1200	1003,7	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	2635	2329	1327,2	458,4	1303	1065

[31] Details about the WAsP program can be found at the website: wasp.dk and its reference section

3.3. Methodology

First, a map is constructed. For the examples here, we use the medium complex site in Austria. The SRTM data is downloaded from an ftp server at NASA, cut down to size, converted to a WAsP map and UTM, and a single roughness line with 3 cm roughness on both sides is added. See below for the elevation map.

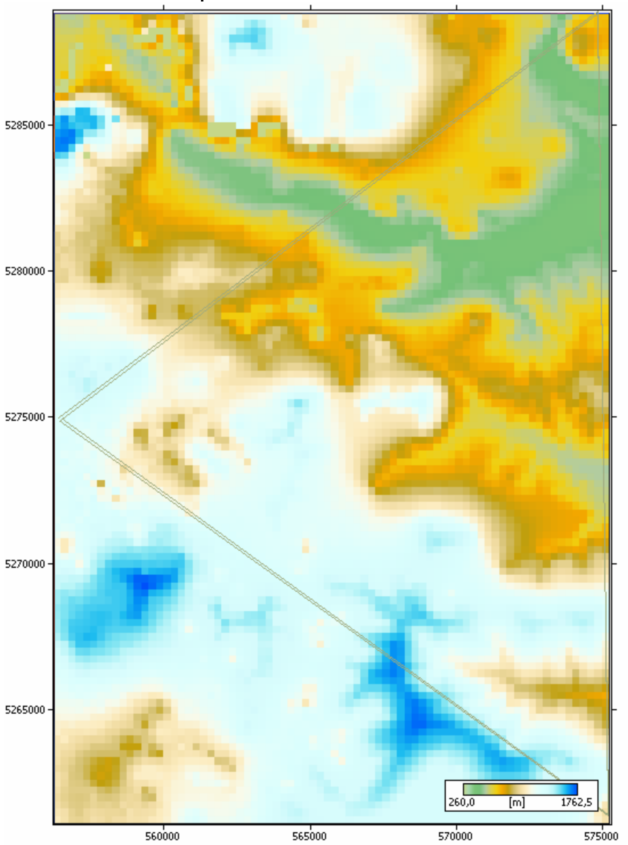


Figure III--0-1: Height distribution of Austria cell

Then, a resource grid with 250m resolution is calculated from that (left is wind speed, right is Annual Energy Production AEP).

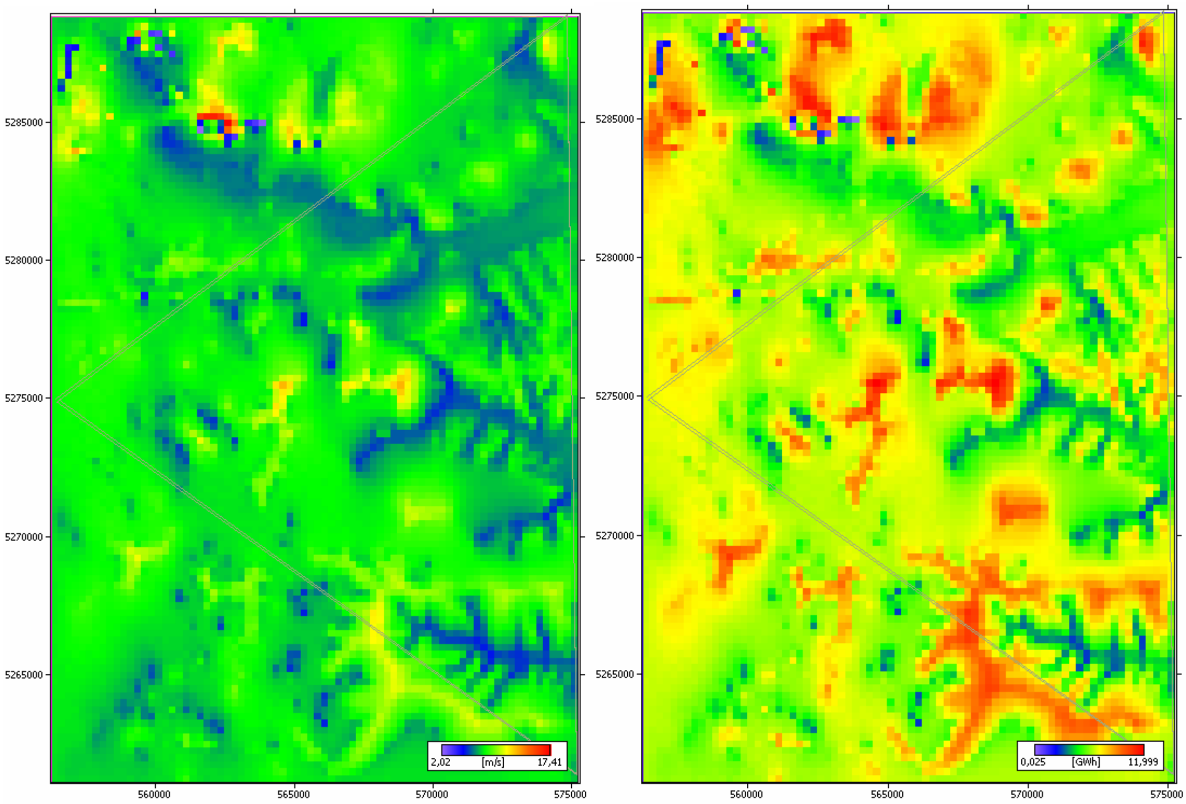


Figure III-0-2: Distribution of the wind velocity (left) and annual energy distribution (right)

One can see that the range of 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 from 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, and histograms are plotted. See Annex 4 for all the plots.

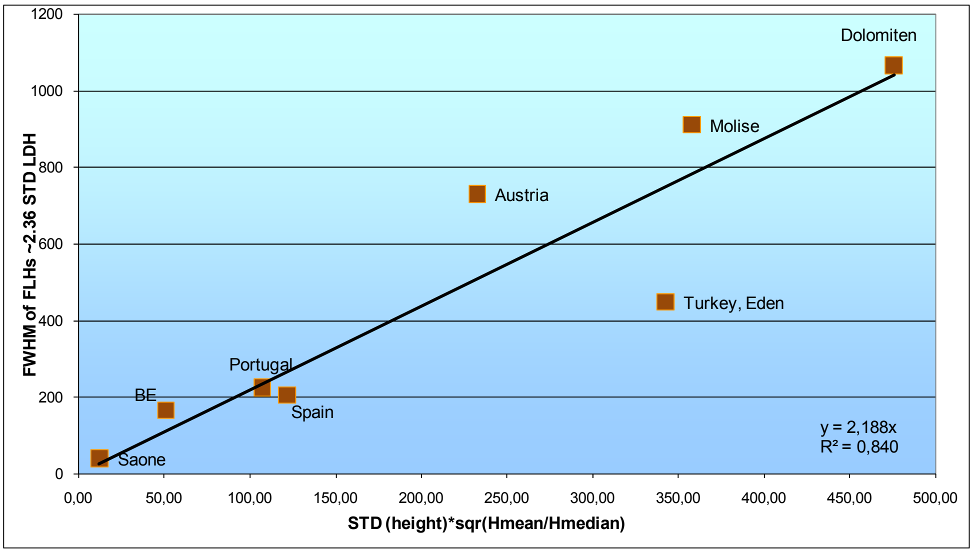


Figure III-0-3: Variation in the standard deviation of the full load hours as function of the variation in height

Finally, the Full Width Half Maximum is estimated from the plots, and converted into a FWHM of Full Load Hours. The result as seen over STD is given in Figure III-0-3.

3.4. Discussion

One can see a reasonable trend line in the plot. However, some points are clearly far off, especially Austria (at FWHM 730) and Turkey (at FWHM 420). If looking through the histograms of elevations, one can see that those are grid cells with quite non-gaussian/non-lognormal distributions of elevations, leading to a breakdown of the Standard Deviation idea, and therefore to inconclusive results. To account somewhat for the non-gaussianity of the 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.

It also has to be said that most grid cells are at the low end of STD, so therefore more emphasis is given to those. There, the trendline seems to capture the variation reasonably well. Of course, to have reliable results, one should do the analysis with more points.

3.5. Algorithm

The algorithm proposed is therefore as follows:

- Calculate the number of Full Load Hours (FLHs) in the usual fashion all over the map of Europe (i.e., use the result already available).
- To account for sub-scale variation, use this result as the centre for a Gaussian distribution of FLHs. Parameterise the width of the distribution from the elevation STD, as:

$$\sigma_{FLH} = {2{,}19}/{2{,}36} * STD * \left({Hmean}/{Hmedian} \right)^2 .$$

- 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.

In figure xx the 90th percentile (at least 10% of the sub grids has the minimal indicated load hour) of the corrected load hours as described above is presented.

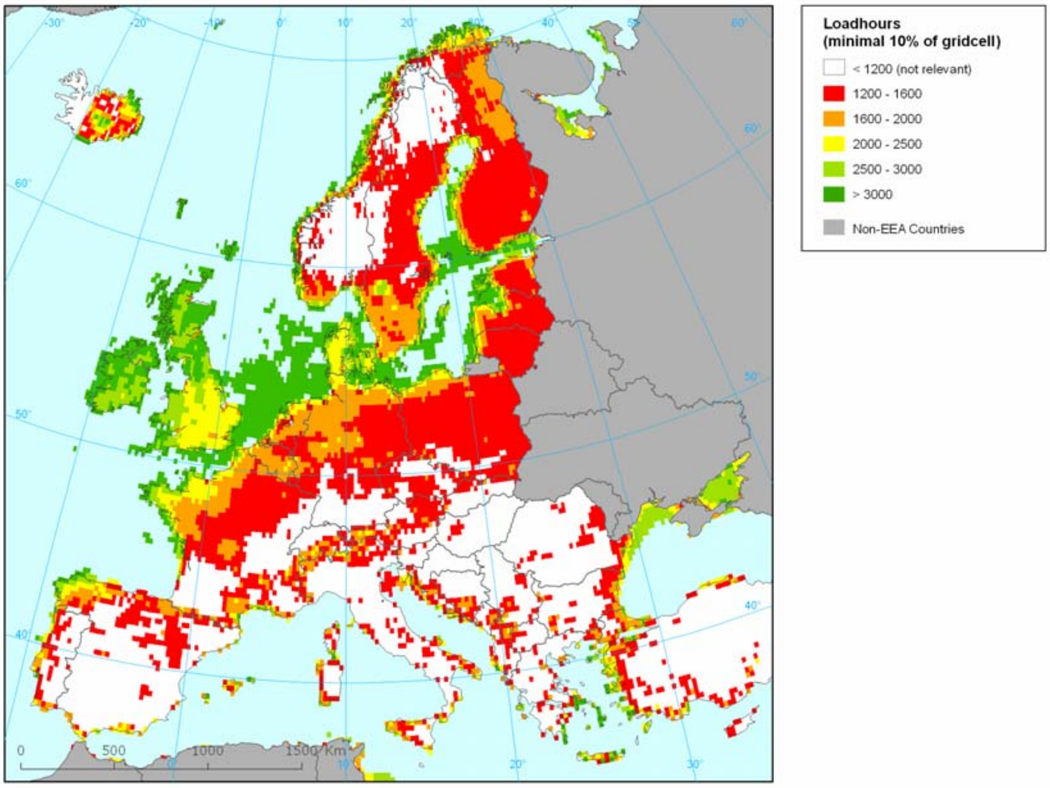


Figure III-0-4: Distribution of full load hours in Europe for the 90th percentile (at least 10% of the sub grids has the minimal indicated load hour)

3.6. Histograms of AEP, wind speeds and elevation for 8 sites in Europe.

AEP = Annual Energy Production [MWh], STD = Standard Deviation of altitude [m]

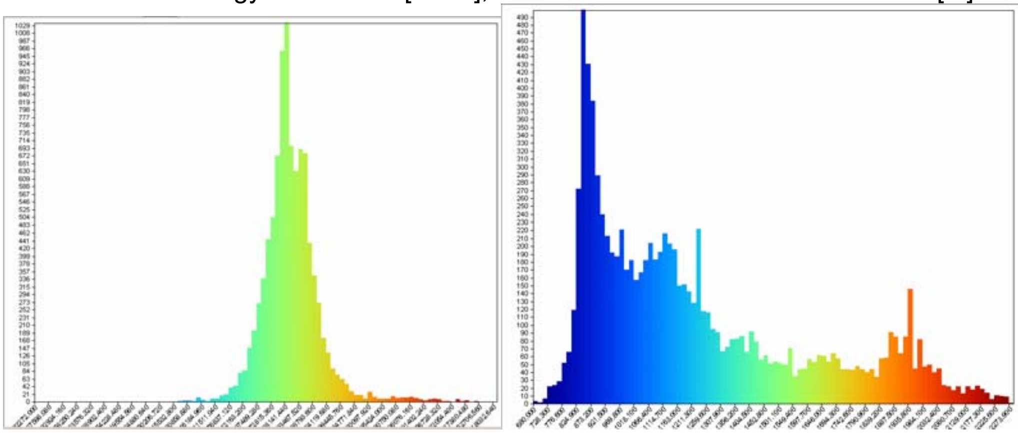


Figure III-0-5: Annual Energy production (Left, AEP) and distribution elevation (right); location Turkey

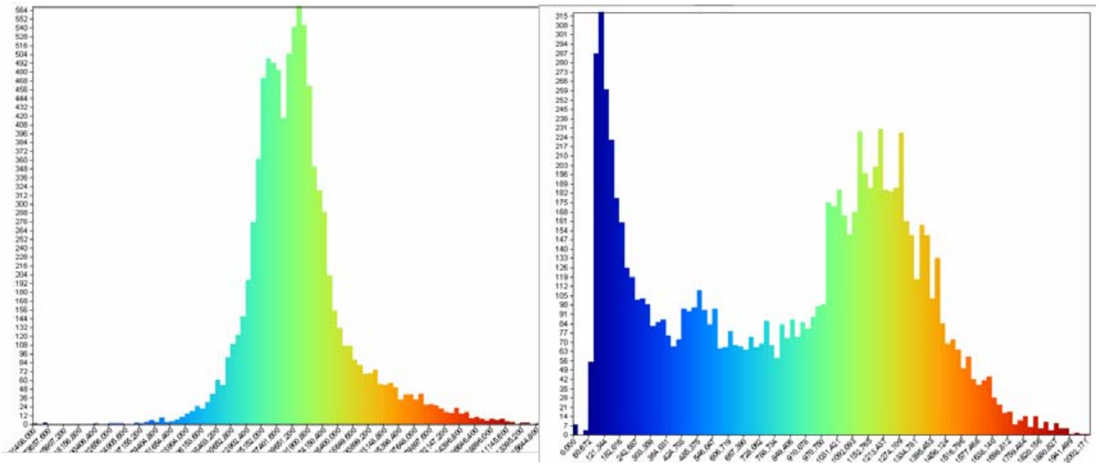


Figure III-0-6: Annual Energy production (Left, AEP) and distribution elevation (right); location IT, Molise,

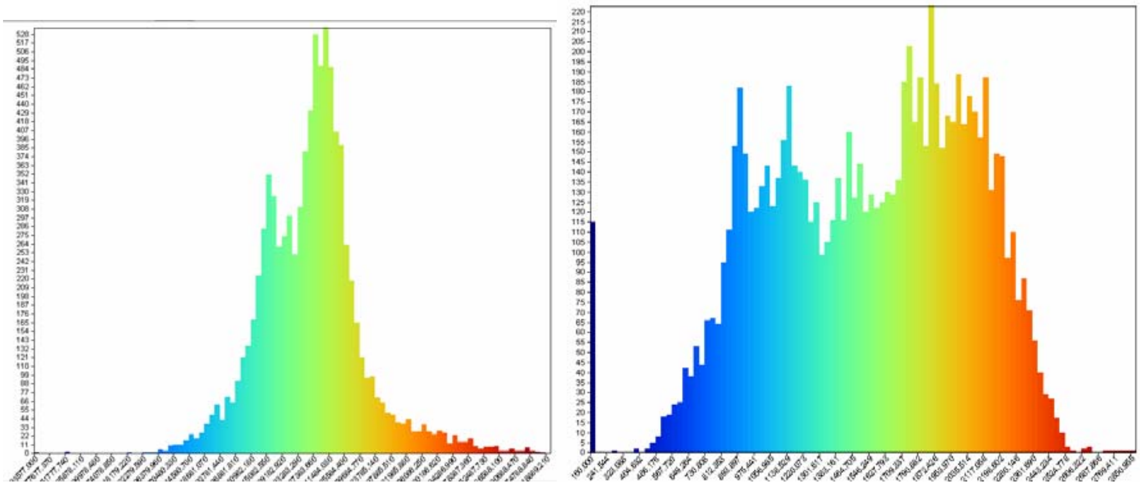


Figure III-0-7: Annual Energy production (Left, AEP) and distribution elevation (right); location Italia, Dolomites

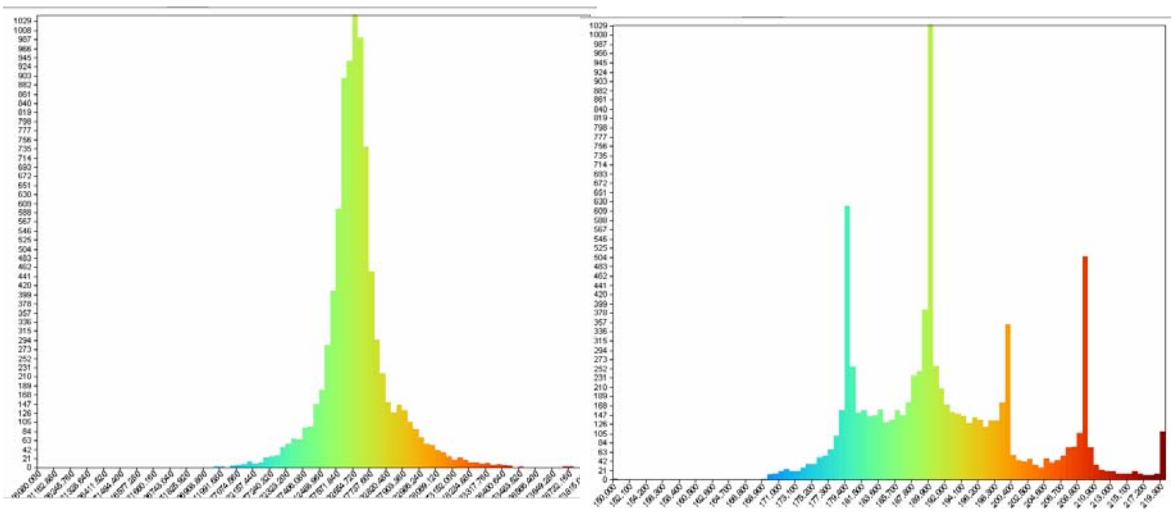


Figure III-0-8: Annual Energy production (Left, AEP) and distribution elevation (right); location France (Saone)

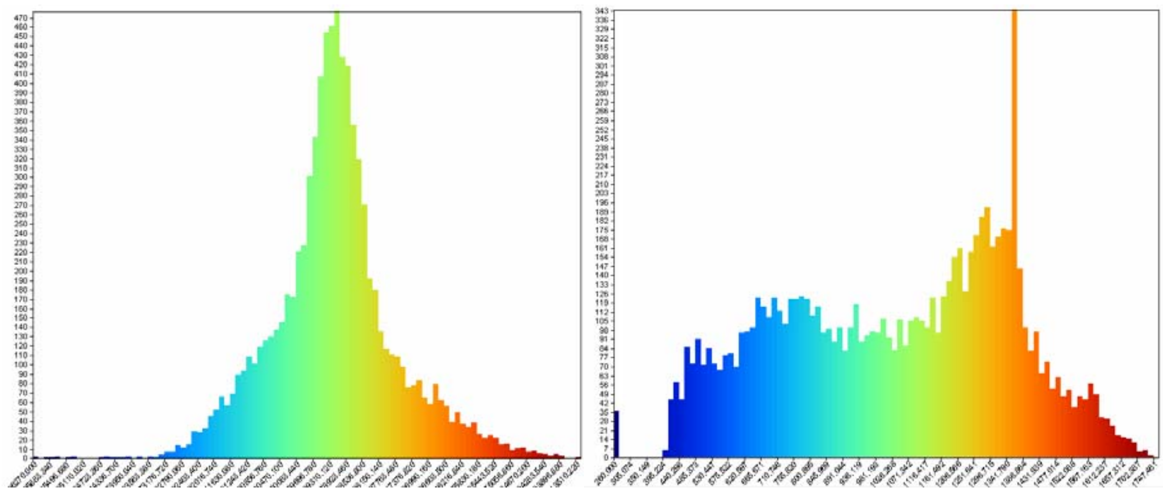


Figure III-0-9: Annual Energy production (Left, AEP) and distribution elevation (right); location Austria

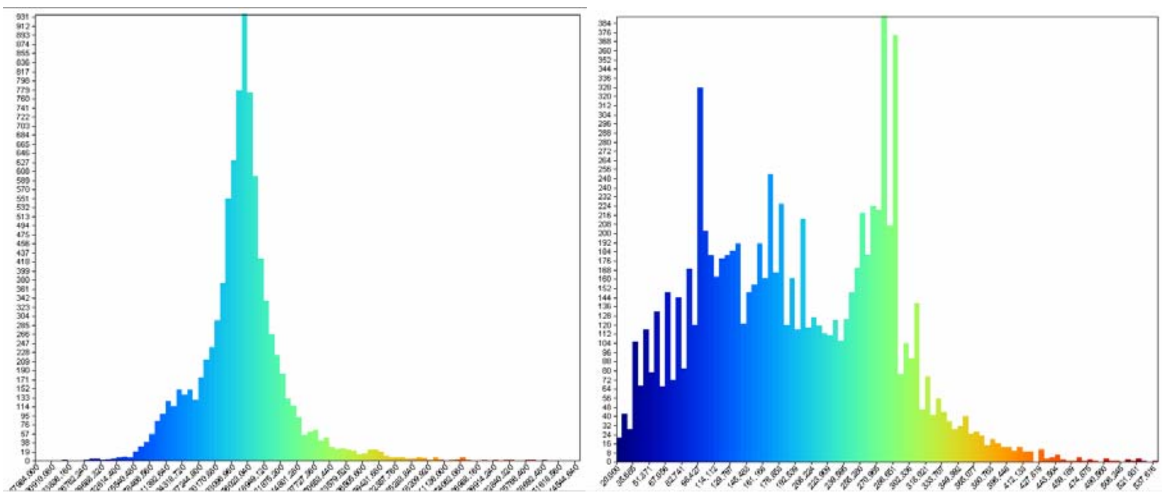


Figure III-0-10: Annual Energy production (Left, AEP) and distribution elevation (right); location Portugal

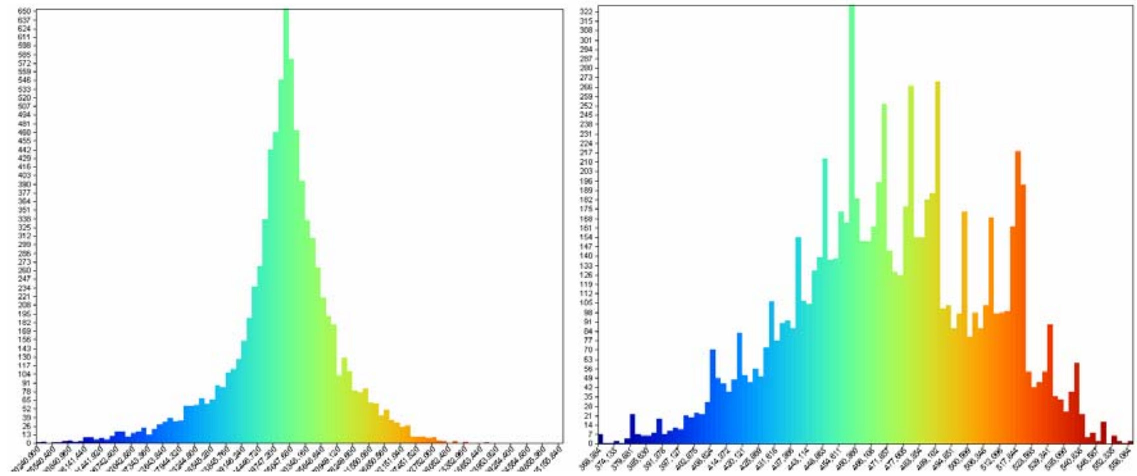


Figure III-0-11: Annual Energy production (Left, AEP) and distribution elevation (right); location BE

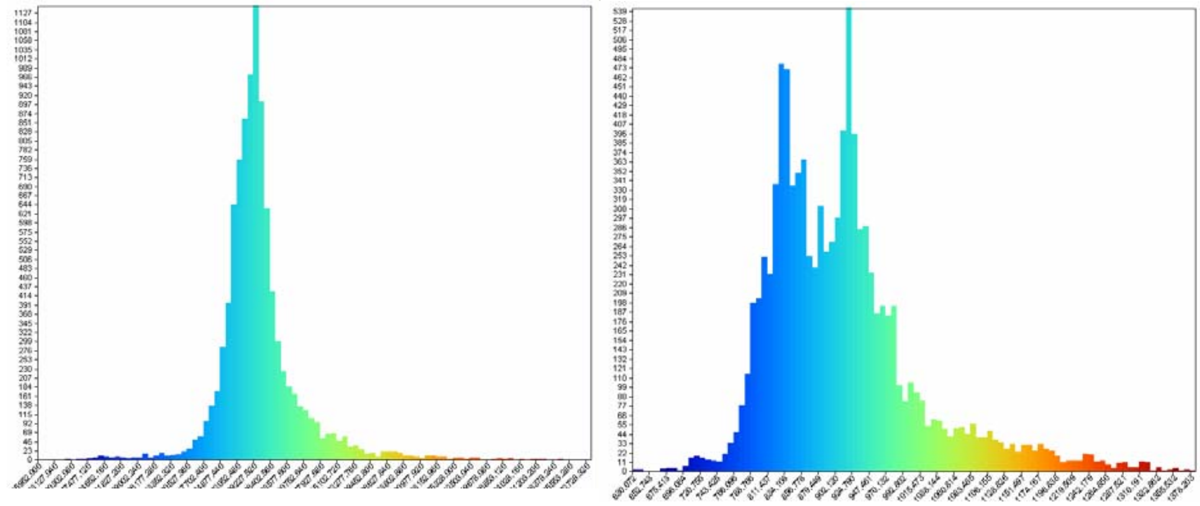
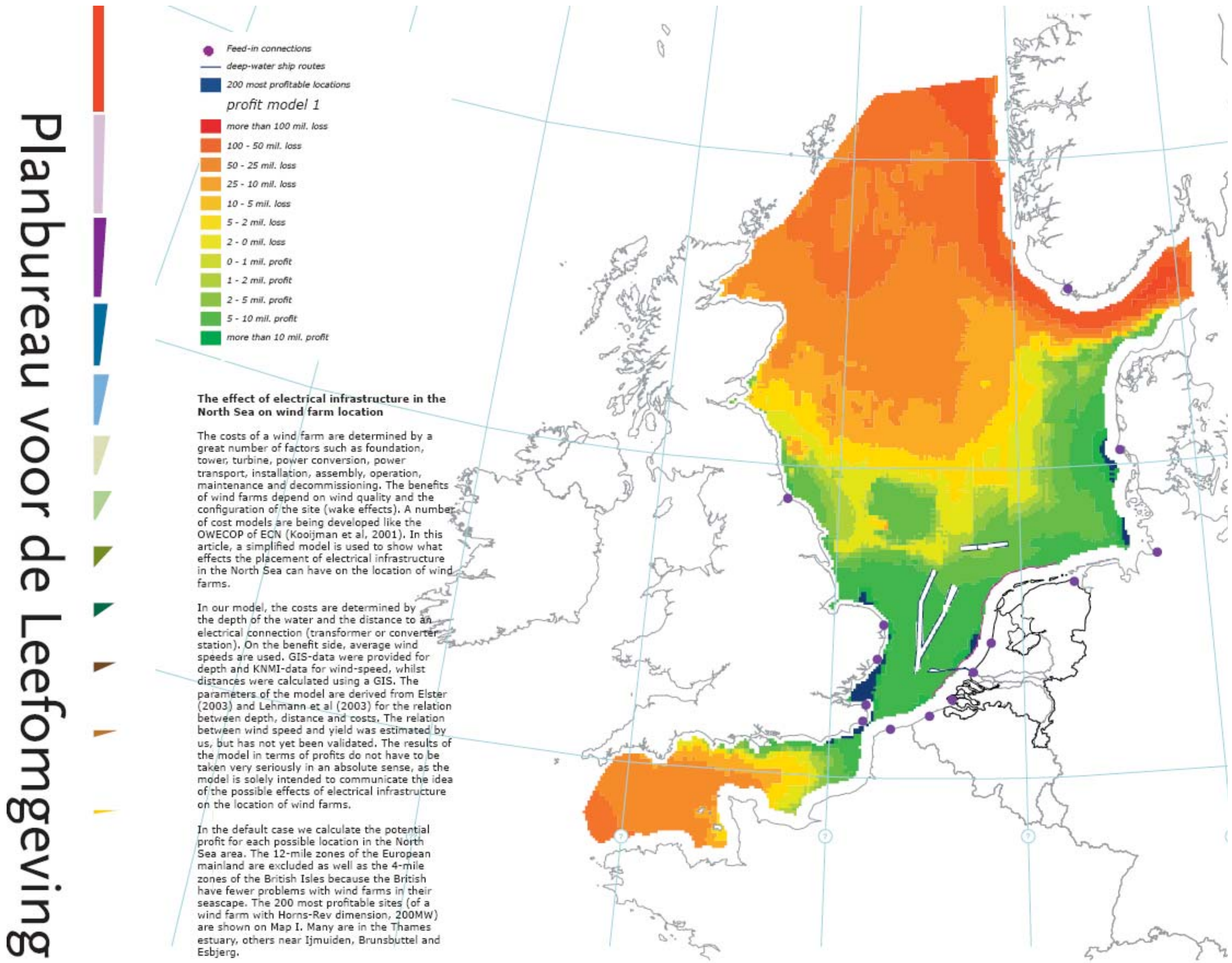


Figure III-0-12: Annual Energy production (Left, AEP) and distribution elevation (right); location Spain

Annex IV: The effect of an electricity grid in the North Sea on wind farm location, PBL 2005 study

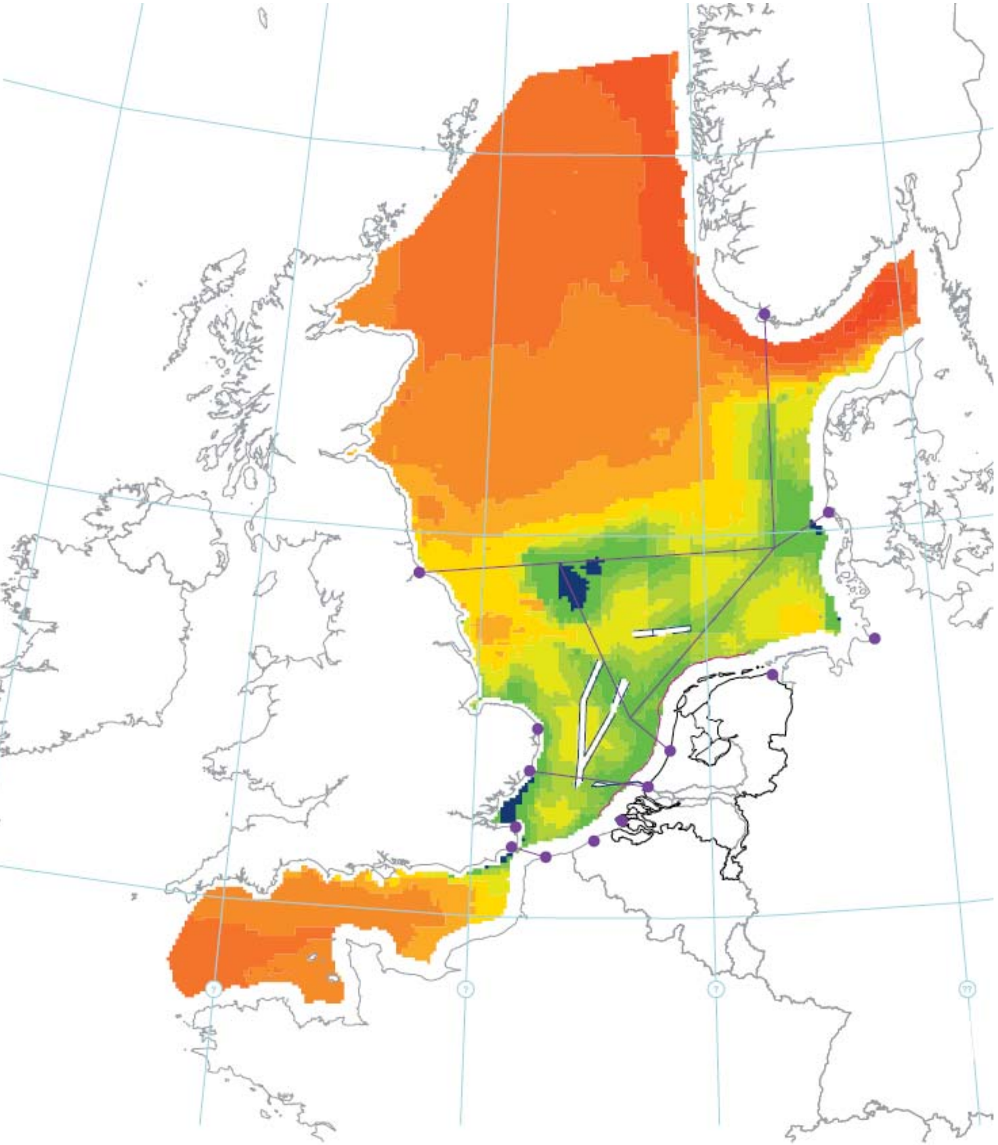


The effect of electrical infrastructure in the North Sea on wind farm location

The costs of a wind farm are determined by a great number of factors such as foundation, tower, turbine, power conversion, power transport, installation, assembly, operation, maintenance and decommissioning. The benefits of wind farms depend on wind quality and the configuration of the site (wake effects). A number of cost models are being developed like the OWECOP of ECN (Kooijman et al, 2001). In this article, a simplified model is used to show what effects the placement of electrical infrastructure in the North Sea can have on the location of wind farms.

In our model, the costs are determined by the depth of the water and the distance to an electrical connection (transformer or converter station). On the benefit side, average wind speeds are used. GIS-data were provided for depth and KNMI-data for wind-speed, whilst distances were calculated using a GIS. The parameters of the model are derived from Elster (2003) and Lehmann et al (2003) for the relation between depth, distance and costs. The relation between wind speed and yield was estimated by us, but has not yet been validated. The results of the model in terms of profits do not have to be taken very seriously in an absolute sense, as the model is solely intended to communicate the idea of the possible effects of electrical infrastructure on the location of wind farms.

In the default case we calculate the potential profit for each possible location in the North Sea area. The 12-mile zones of the European mainland are excluded as well as the 4-mile zones of the British Isles because the British have fewer problems with wind farms in their seascape. The 200 most profitable sites (of a wind farm with Horns-Rev dimension, 200MW) are shown on Map I. Many are in the Thames estuary, others near Ijmuiden, Brunsbuttel and Esbjerg.



In the second map, the electrical infrastructure is shown. In this exercise, we drew some HVDC power lines and calculated the costs using the distance to these power lines or land points in the cost curve. We deducted some costs for the electrical infrastructure of all wind farm locations to emphasize that the extra costs of infrastructure is carried by the wind farms. In this case, a great number of the 200 most profitable sites can be found in the middle of the North Sea, an area we call Doggersbank, along the electrical infrastructure. Some profitable locations are still to be found in the Thames estuary, Esbjerg and the German coast. The main focal point for offshore wind energy has however shifted to the Doggersbank area.

We can call this phenomenon the structuring effect of infrastructure.

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