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SPILLOVER EFFECTS FROM WIND POWER

Case study in the framework of the project Spillovers of climate policy

P. Lako

Acknowledgement/Preface
The present report is part of a research project called 'Carbon leakages and induced technological change: the negative and positive spillover impacts of stringent climate change policy' (or, more briefly, the so-called 'Spillovers of climate policy' project). This project is financed by the Dutch Ministry of Housing, Spatial Planning and the Environment as part of its National Research Programme on Climate Change (NRP-CC), particularly its sub-programme dealing with 'scientific assessments and policy analyses'. This programme is implemented by the National Institute of Public Health and the Environment (RIVM).

The project 'Spillovers of climate policy' has been coordinated by the unit Policy Studies of the Energy Research Centre of the Netherlands (ECN), where it has been registered under no. 77599. Together with the present report, companion reports are published as part of the project by the project coordinator Sijm (2004), Annevelink, et al. (2004), Kuik (2004), and Oikonomou, et al. (2004). The author would like to thank his colleagues of the project for their comments on earlier drafts of this report. Also, he wishes to express his gratitude for valuable remarks and suggestions for improvement from Martin Junginger (Utrecht University) and Ad Seebregts (ECN Policy Studies). Additional information on this report as well as on the project as a whole can be obtained from Jos Sijm (e-mail: sijm@ecn.nl, or telephone: +31 22456 8255).

Abstract
This case study presents an analysis of spillover effects in the development of wind power, based on a review of four recent studies on the development of wind power in EU countries. One of the studies reviewed considers knowledge spillover from Denmark to Germany and the UK. Another provides insight in spillover from Denmark and the US to Germany and Spain.

It is realistic to assume that spillover effects from wind turbine technology in Denmark to other Annex 1 countries of the Kyoto protocol have occurred in the period 1980-2000, although the magnitude of the effects is difficult to quantify. Spillover to non-Annex 1 countries has been far less important, as most developing countries are in an early stage of the development of their wind resources. A second type of spillover effect has to do with the adoption of policies favouring wind energy.

These spillover effects are related to onshore wind technology. The development of offshore wind power is in such an early stage that spillover effects may be hardly distinguished. EU countries and the EU could consider to support offshore wind power, not only for reasons of reducing greenhouse gas emissions and creating employment in indigenous wind turbine business, but also because of possible spillover effects to developing countries with regard to knowledge of offshore wind power.

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SUMMARY

This case study presents an analysis of spillover effects in the development of wind power, based on a review of four recent studies on the development of onshore and offshore wind in EU countries. The concept of spillover originates in the literature of R&D and technical change where it has been applied under a variety of other labels such as 'R&D spillovers', 'knowledge spillovers', 'technological spillovers', and 'innovation spillovers'.

Three EU countries - Denmark, Germany, and Spain - are regarded as the cradle of the modern wind turbine industry, next to the US and to a lesser extent other EU countries. In Denmark, development of wind energy became a cornerstone of the Danish energy policy after the oil crisis of 1974. Soon, Danish wind turbine manufacturers became market leaders. It is realistic to assume that spillover effects from wind turbine technology in Denmark to other countries have occurred in the period 1980-2000. Wind turbine manufacturers in other countries profited from the Danish wind energy technology: Nordex is a mixed Danish/German wind turbine manufacturer, and Gamesa Eólica (Spain) is a former subsidiary of Vestas (Denmark). Although spillover may have occurred, the magnitude of these effects is difficult to quantify.

Knowledge spillover to non-Annex 1 countries of the Kyoto protocol has been far less important than between Annex 1 countries, as most developing countries - except India - are in an early stage of the development of their wind resources. A second type of spillover effect has to do with the adoption of policies favouring wind energy. Also in this respect countries learned from the experience of the Danish government, by implementing R&D policies, feed-in tariffs, etc.

One of the literature sources refers to spillover effects in several ways:

- Knowledge spillover from Denmark to Germany is explicitly mentioned, in particular with regard to small wind turbines.
- Part of the price reduction for wind turbines in the UK is related to importing wind turbines, the prices of which have declined as a result of domestic sales. In particular spillover from Denmark to the UK is taken into account.

In the so-called EXTOOL project experience curves were established for wind power in Denmark, Germany, Spain, and Sweden. The study also provides insight in spillover effects, e.g. from Denmark to Germany and Spain. The successful deployment in the 1990s of proprietary wind turbine technologies by e.g. the German Enercon was based on both company funding and dedicated federal RD&D support.

In Spain, no wind turbines from indigenous wind turbine manufacturers were commercially available until 1992. Right from the start in 1983, the Spanish company Ecotècnia had to have the technology right in order to generate financing. Ecotècnia depended mostly on national budget subsidies for its early growth. Up to the mid-1990s, practically all wind power projects in Spain received some kind of 'RD&D support'. Knowledge spillover is observed from the wind turbine industry in the US and Denmark to manufacturers like Made and Ecotècnia.

Finally, spillover effects in the development of offshore wind power are shortly addressed. Long-term stable offshore prospects may support cost reductions, especially for the installation costs, but also for wind turbines. No single country has the potential to create an offshore wind market on its own. Thus, a joint European policy regarding the stimulation of offshore wind farms might be a great benefit both to ensure diffusion of offshore wind and cost reductions.

1. INTRODUCTION

1.1 Scope of the project

This case study focuses on spillover effects in the development of wind power. It is part of a research project called ‘Carbon leakages and induced technological change: the negative and positive spillover impacts of stringent climate change policy’ (or, more briefly, the so-called ‘Spillovers of climate policy’ project).

The concept of spillover originates in the literature of R&D and technical change - including the innovation and endogenous growth theories - where it has been applied under a variety of largely synonymous labels such as ‘R&D spillovers’, ‘knowledge spillovers’, ‘technological spillovers’, ‘innovation spillovers’ or equivalent terms such as ‘R&D or knowledge externalities’. These concepts all refer to the fact that knowledge has a high non-rival, public-good character and that, as a result, a private innovator may be unable to fully appropriate the social returns of investments in R&D and technological change (Sijm, 2004).

In the ‘Spillovers of climate policy’ project, a consortium of four research partners in the Netherlands, has conducted research on the following subjects:

1. A general assessment on the potential incidence of carbon leakage due to climate policy in Annex I countries of the Kyoto protocol, based primarily on analytical model studies.
2. A general assessment on the potential incidence of induced technological change owing to climate policy, including the diffusion of induced technological innovations to non-Annex I countries, based primarily on analytical model studies.
3. A case-study assessment on the potential incidence of climate policy spillovers in the energy-intensive industry, based primarily on empirical studies of this industry.
4. A case-study assessment on the potential incidence of climate policy-induced technological spillovers in the wind power turbine industry, based primarily on empirical studies of this industry (the present study).
5. A case-study assessment on the potential incidence of climate policy-induced technological spillovers in the biomass and bio-energy industry, based primarily on empirical studies of this industry.

These studies and case-studies have been summarised by the project leader Sijm of ECN Policy Studies in (Sijm et al., 2004).

1.2 Background and scope of study

For a number of reasons, the development of wind power is an interesting case of spillover effects:

- Wind power is a relatively young renewable energy source, besides hydropower and biomass. Its ‘track record’ is sufficiently long to analyse spillover effects.
- Three EU countries - Denmark, Germany, and Spain - are regarded as the cradle of the modern wind turbine industry, next to the US and to a lesser extent other EU countries. Only recently, the wind turbine industry became a global industry. There is dominant position for wind turbine manufacturers in the EU and the US.
- The EU countries try to develop wind power into a thriving industry. The EU-15 has the obligation to reduce its greenhouse gas emissions by 8% in 2008-2012 compared to 1990. Also, the EU-15 has formulated a target to increase the share of renewables from 6% of gross inland energy consumption in 1990 to 12% in 2010. Recent evidence (Environment Daily, 2004; Jansen et al., 2004) indicates that the share of renewables in electricity generation will be 18-19% instead of the targeted 22%, and that the share of renewables in

energy consumption will be 10 instead of 12% in 2010. Only if member states would initiate more vigorous policies with regard to renewable heating sources (solar heating, geothermal energy), the original targets could be met.

1.3 Current status of wind power

Table 1.1 gives an overview of the share of wind power in electricity generation in the EU countries Denmark, Germany, and Spain (Burges, 2004; Windpower Monthly, 2004a and b).

Table 1.1 *Share of wind power in electricity generation in exemplary EU countries*

Country	Wind capacity by end-year [MW]		Share of wind in electricity generation [%]	
	2002	2003	2003	2004 (estimate)
Denmark	2,880	3, 117	14	~20
Germany	11,968	14,609	4	~6
Spain	5,043	6,202	5	~6
Netherlands	727	938	1.2	1.5

Sources: Burges, 2004; Windpower Monthly, 2004a and b.

In 2003, the share of wind power in electricity generation was 14% in Denmark, 5% in Spain, and 4% in Germany. The projections for 2004 are 20% for Denmark, and 6% for Spain and Germany – presumed that 2004 is a normal year with regard to the average annual wind speed. In 2002, the global wind capacity grew by 7,200 MW, an increase of 29% over 2001. By end-year, the global wind capacity amounted to 32 GW (Figure 1.1, Internet source 1).

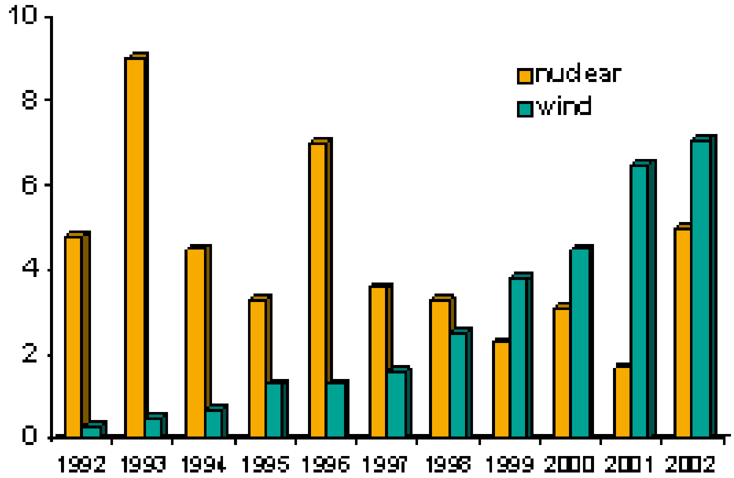

Figure 1.1 *Annual incremental installed capacity - Y-axis: [GW] - of nuclear/wind power*
Source: Internet source 1.

The global wind capacity of 32 GW by the end of 2002 is tantamount to an electricity output of approximately 65 TWh/a. Wind's share of the total global electricity supply was 0.4% in 2002. By the end of 2003, the installed wind capacity stood at 40.3 GW. About 20 years after the birth of the 'wind turbine industry', the wind industry is growing fast and has become more or less mature. The term 'mature' refers to the advanced level of the technology of current turbines compared to the early wind turbines of the 1980s. Germany, Spain, and Denmark are not only leading in terms of installed wind turbine capacity – only rivalled by the US – but these countries also host the main wind turbine manufacturers.

Despite several setbacks in the development of commercial wind turbines, wind energy made significant inroads in electricity generation in countries like Denmark, Germany and Spain, but also elsewhere. Sufficient experience has been gathered to warrant meaningful spillover effects for wind power. This is particularly true for onshore wind. However, spillover effects may also be expected to occur with regard to offshore wind.

1.4 Guidance to the reader

The following chapters review four studies dealing with certain aspects of spillover effects in the wind power sector in EU countries. In Chapter 2, the focus is on spillover effects from the Danish wind turbine industry, based on publications by Kamp (2002). These publications give a detailed analysis of the development of wind energy in Denmark and the Netherlands.

Chapter 3 focuses on two-factor learning applied to wind energy in Denmark, Germany, and the UK by Klaassen et al. (2003). Chapter 4 presents a review of the publications by Neij et al. (2003a and 2003b) on the use of experience curves for wind energy in Denmark, Germany, Spain, and Sweden. Chapter 5 covers technological developments and cost reduction in the wind sector, with emphasis on offshore wind, by Junginger et al. (2004).

Finally, Chapter 6 presents conclusions and policy implications with regard to spillover effects in the development of onshore and offshore wind power.

2. SPILLOVER EFFECTS OF THE DANISH WIND TURBINE INDUSTRY

2.1 Introduction

The Ph.D thesis (Kamp, 2002) and the article (Kamp et al., 2004) based on this thesis give an in-depth analysis of the development of wind power in Denmark and the Netherlands. This Chapter focuses on spillover effects of the Danish wind turbine industry, largely based on this thesis. In order to understand the spillover effects in the development of wind power, it is necessary to analyse the wind turbine industry during the last few decades.

According to (Kamp, 2002), technological learning is important, particularly in the case of technologies like wind turbines that consist of several interacting parts and have to function in changing environments. Variations on a dominant design are introduced in what is called the 'selection environment'. The most promising variations are selected. The selection environment is a broader concept than the market: it includes regulations, norms, beliefs and expectations of multiple actors, government policies, taxes and subsidies.

Research, Development, and Demonstration (RD&D) programs on a national and supranational scale (EU, IEA) have been important for the technological development of wind power. Also, financial measures for introduction and marketing of wind turbines proved to be indispensable. These driving forces may be observed in EU countries that are leading with regard to wind power – Denmark, Germany, and Spain – and in countries with a less thriving wind industry.

It is important to analyse the specific driving forces in order to qualify the spillover effects. §2.2 gives a brief introduction to different types of wind turbines. §2.2 presents an overview of the development of the wind turbine industry in Denmark. In §2.3, the position of the Danish wind turbine industry is shortly addressed. §2.4 presents some results from (Kamp, 2002) with regard to spillover effects of the Danish wind turbine industry.

2.2 Different types of wind turbines

The mechanical power output of a wind turbine depends on the wind speed and the pitch angle. There are basically two types of power control (Koch et al., 2003):

- Stall regulation
  The pitch angle in a stall-controlled turbine is fixed. The rotor is designed in such a way that it stalls at wind over-speed, thereby protecting the turbine from mechanical damage. Within the normal range of wind speeds, the power generation is determined by the actual wind speed.
- Pitch regulation
  In pitch-controlled turbines the pitch angle enables the continuous control of the power output despite the stochastically varying wind speed. Normally the pitch angle is adjusted for maximum output except under conditions of wind over-speed during which the output power is limited to the rated value by the pitch angle control.

Stall has proved to be appropriate for power control of medium scale turbines (≤ 1 MW). For larger turbines, other mechanisms are used: active stall – the turbine blades are pitched at low wind speeds until the stall position is reached – and full blade pitching with variable rotor speed.

2.3 Development of the wind turbine industry in Denmark

After the first oil crisis in 1973, the US and several European countries, among which Denmark, Germany, and the Netherlands, embarked on wind energy RD&D programs. From the 1980s, a nascent wind turbine industry in Denmark started to produce small wind turbines (<100 kW) that were coupled to the electric grid. Already in the 1950s, the Danes had become worried about growing dependence on imported fossil fuels for the first time, and the wind turbines of the 1980s were small-scale copies of the 200 kW Gedser turbine (in service from 1957 to 1967).

As the Danish government was poised to reduce the dependence on imported oil, development of wind power became a cornerstone of the Danish energy policy. The Danish government decided to support the development of large wind turbines with a capacity of hundreds of kW or MWs of an advanced type, and to foster market introduction of smaller conventional wind turbines by local industries.

In (Kamp, 2002), the policy of the Danish government to support development of large wind turbines is highlighted. This program on large wind turbines (1977-1990) included turbines with full blade pitching. The proved stall mechanism of the Danish Gedser turbine (operational from 1957 to 1967) was applied to the small Danish turbines of the early 1980s. Table 2.1 shows features of wind turbines developed in the program for large wind turbines.

Table 2.1 *Wind turbines developed in Danish RD&D program on large wind turbines*

Location	Commissioned	Capacity [kW]	Rotor diameter [m]	Power regulation	Cost [million DKK]
Nibe A	1979	630	40	Stall	70.5 (Nibe A, Nibe B, Koldby)
Nibe B	1980	630	40	Pitch	
Koldby	1982	265	N/A	Pitch	
Masnedø	1987	5 x 750	N/A	Pitch	50.0
Tjæreborg	1988	2,000	60	Pitch	65.0
Total	1977-1990	7,275			185.5

Source: Kamp, 2002.

These large wind turbines were built according to technical requirements from the Danish utilities. The technical objectives of the program – building and operating large, advanced wind turbines – were met. However, the turbines proved to be not marketable. Also in other countries – the US, Germany, and the Netherlands – developing MW-scale turbines ‘from scratch’ into marketable turbines proved to be too ambitious: governments sometimes spent substantial sums on ‘kick-starting’ an industry of MW wind turbines, but the results were rather disappointing. Also, the EU gave financial support to several demonstration wind turbines in the MW class.

The results of programs like the Danish program for large wind turbines (1977-1990) were not satisfactory. Large and advanced turbines, developed and demonstrated in the framework of this program proved to be ‘a bridge too far’. After a while, the Danes realised – and with them the wind community around the world – that it was easier to develop small wind turbines than to leapfrog by developing MW turbines ‘from scratch’. In 1990, the Danish government terminated the program for large wind turbines. This may be regarded as a sign that the Danish wind turbine industry had become more or less grown-up.

2.4 Position of the Danish wind turbine industry

Energy and industrial policy governed the development of wind energy in Denmark until the late 1980s. At that time, Danish utilities placed large orders and technological development had made wind turbines more and more competitive. Also, export of turbines was a prerequisite for a healthy Danish wind turbine industry. The export increased based on guarantees from the Danish state. The wind turbine industry introduced MW-scale turbines around 1995 (Table 2.2).

Table 2.2 *Prototype MW turbines commissioned by (Danish) wind turbine manufacturers*

Wind turbine manufacturer	Country of origin	Commissioned	Capacity [kW]	Rotor diameter [m]	Power regulation
NEG-Micon	Denmark	1995	1,500	60	Stall
Vestas	Denmark	1996	1,500	63	Active stall
Bonus	Denmark	1998	2,000	72	Active stall
NEG-Micon	Denmark	1999	2,000	72	Pitch
Nordex	Denmark/Germany	2000	2,500	80	Pitch

Source: Kamp, 2002.

The Danish manufacturers NEG-Micon, Vestas, and Bonus switched to pitch-control for their largest wind turbines. This shift in technology had its roots in technical-economic considerations: pitch control offers a significantly higher output at lower wind speeds than stall regulation. Also, pitch-controlled turbines have to be designed to lower loads than stall-controlled turbines of the same capacity. Danish manufacturers incorporated pitch control in the 2 MW turbines, just like Nordex (Denmark-Germany) and GE Wind Power (US) did.

Whereas the Danish government originally started with a two-pronged approach of an RD&D program for large wind turbines and a more market-oriented approach for small wind turbines, around 1990 the Danish government switched to an 'evolutionary' development of small and medium scale wind turbines. This does not mean that all the money spent on large wind turbines had gone to waste, but it was a logical conclusion from the results emerging from the two-pronged approach.

2.5 Spillover effects

The evolution of the wind turbine industry may be illustrated by data from (EurObserver, 2004) with regard to the wind turbine market in 2002 (Table 2.3).

Table 2.3 *Key data of wind turbine manufacturers in 2002*

Rank	Wind turbine manufacturer	Country of origin	Sold [MW]	Market share (2002) [%]	Turnover (2002) [million €]	Employees (2002)
1	Vestas[1]	Denmark	1,640	21.8	1,394	5,974
2	Enercon	Germany	1,333	17.7	1,200	6,800
3	NEG-Micon[1]	Denmark	1,030	13.7	842	2,180
4	Gamesa Eólica	Spain	924	12.3	583	1,398
5	GE Wind Power	US	638	8.5	N/A	1,700
6	Bonus	Denmark	509	6.8	279	800
7	Nordex	Denmark/Germany	504	6.7	445	791
8	Made	Spain	247	3.3	N/A	N/A
9	Repower	Germany	223	3.0	251	390
10	Ecotècnia	Spain	120	1.6	N/A	350
	Others		371	4.9	N/A	N/A
	Total		7,539	100.0	~ 6,000	~ 22,000

Table 2.3 shows that Denmark, Germany, Spain, and the US are leading with regard to wind turbine manufacturing. It is quite realistic to assume that spillover effects from wind turbine technology in Denmark to other countries have occurred in the period 1980-2000. Before 1980, the development of wind energy was primarily a national activity. After 2000, the scale of wind turbine manufacturing became so large that the importance of national boundaries dwindled.

[1] In 2003, the companies Vestas and NEG-Micon merged into the largest global wind turbine company, called Vestas.

In the timeframe considered – 1980-2000 – wind turbine manufacturers in other countries profited from the Danish wind energy technology: Nordex is a mixed Danish/German wind turbine manufacturer, and Gamesa Eólica (Spain) is a former subsidiary of Vestas (Denmark). Therefore, spillover effects from Denmark to e.g. Germany and Spain may have occurred, but the magnitude of these effects is difficult to quantify. Countries opened their markets to Danish wind turbines, as Denmark offered a superior wind turbine technology. This speeded up the technological development of an indigenous wind turbine industry in those countries.

Spillover effects have probably been significant between Annex 1 countries, but not from Annex 1 to developing countries. Spillover effects to non-Annex 1 countries were small, because most of these countries were still in an early stage of the development of their wind resources. India, however, is an example of a non-Annex 1 country with a successful wind turbine program and an indigenous wind turbine manufacturer, viz. Suzlon. As a matter of fact, Suzlon will build a prototype 2 MW wind turbine in southern India in the second half of 2004 (Windpower Monthly, 2004c).

The second type of spillover effect has to do with the adoption of policies favouring wind energy. Also in this respect, countries like Germany, Spain, and the Netherlands, learned from the experience of the Danish government, by implementing R&D policies, feed-in tariffs, etc. In some cases, e.g. feed-in tariffs, this spillover effect may have been important. However, there are also notable exceptions: in the UK tendering was favoured over feed-in tariffs.

3. TWO-FACTOR LEARNING FOR WIND POWER IN DENMARK, GERMANY, AND THE UK

3.1 Introduction

Two-factor learning is described by (Klaassen et al., 2003) for wind power in Denmark, Germany, and the UK. The analysis, performed by researchers of IIASA and the Royal Institute of Technology of Sweden, focuses on the contribution of public R&D and cumulative sales on the cost reduction of wind turbines. In the conventional learning literature, the focus is often only on the effect of capacity expansion (possibly stimulated by procurement policy) of the cost-reducing innovation. In contrast, Klaassen et al. extend the scope to the effect of public R&D[2].

In §3.2, the results of the analysis by (Klaassen et al., 2003) are briefly summarised. The results are also discussed within the context of wind energy development and policies in the countries of interest. §3.3 presents notions on spillover effects described by (Klaassen et al., 2003).

3.2 Two-factor learning

3.2.1 Main results

In order to analyse the relationship between the development of the investment costs over time on the one hand and cumulative capacity and the knowledge stock (based on public R&D) on the other, Klaassen et al. collected the following data:

- The (average) investment costs per kW. (Figure 3.1)
- Cumulative capacity. (Figure 3.2)
- Annual public R&D expenditures. (Figure 3.3)

Figure 3.1 shows the investment costs based on data collected in Denmark, Germany, and the UK. These costs also cover grid connections, foundations, and electrical connections.

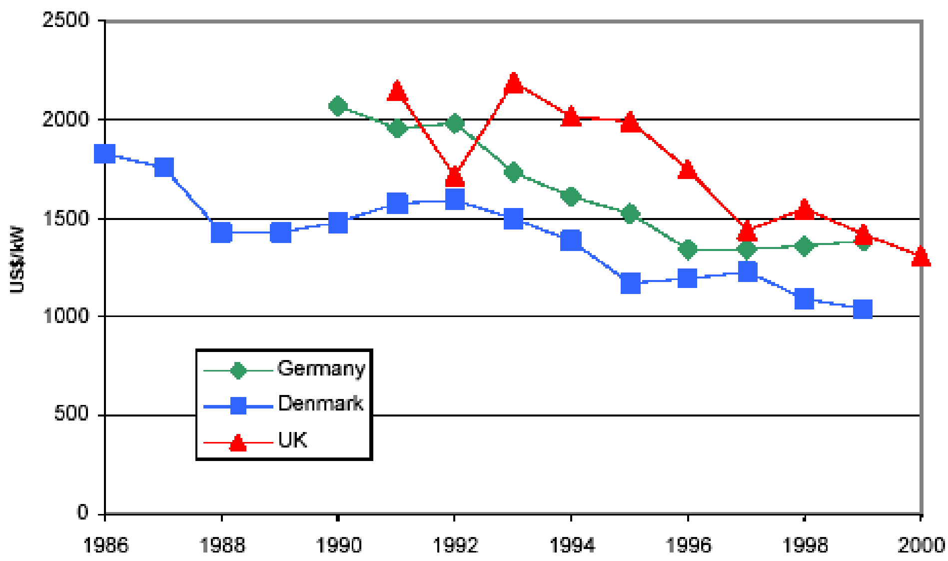

Figure 3.1 *Specific investment cost, including grid connection, etc., of wind turbines*

[2] Note that in (Sijm, 2004) ample examples are given of models and studies covering either this learning-by-doing or learning-by-searching, but only occasionally both types of learning at the same time.

In 1992, there was only one project in the UK, whereas data for the other years are generally averages of various projects. This is the explanation for the 'bumpy' curve in the period 1991-1993. Differences in the level of the costs across the countries are not only related to country-specific factors but also reflect differences in the average size of the wind turbines installed.

Figure 3.2 shows the cumulative wind capacity of Denmark, Germany, and the UK (Internet source 1; Windpower monthly, 2004a and b) for the timeframe 1990-2003 – the original graph in (Klaassen et al., 2003) referred to 1990-2000.

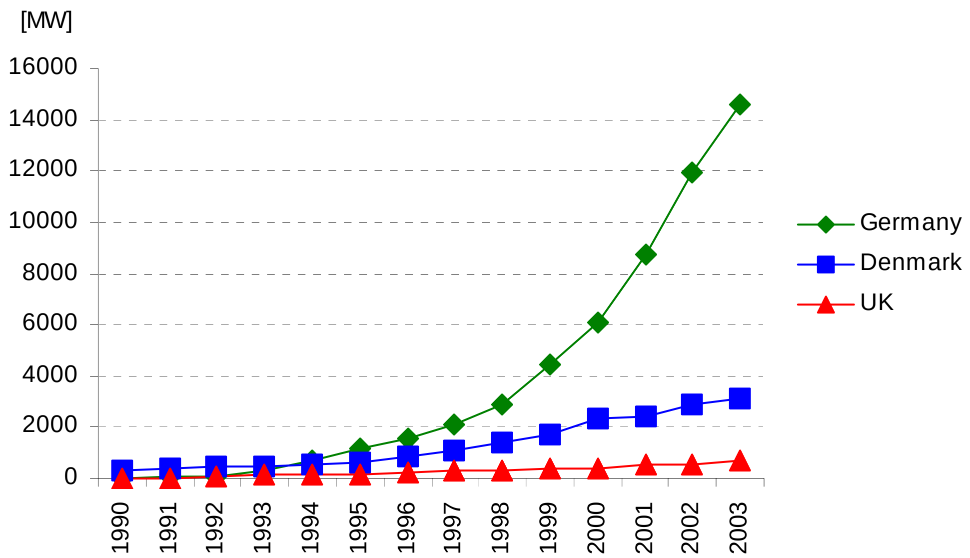

Figure 3.2 *Cumulative wind capacity in Denmark, Germany, and the UK*
Sources: Internet source 1; Windpower Monthly, 2004a and b.

Figure 3.3 shows the development of the annual public R&D expenditures on wind power based on IEA data (IEA, 2000a).

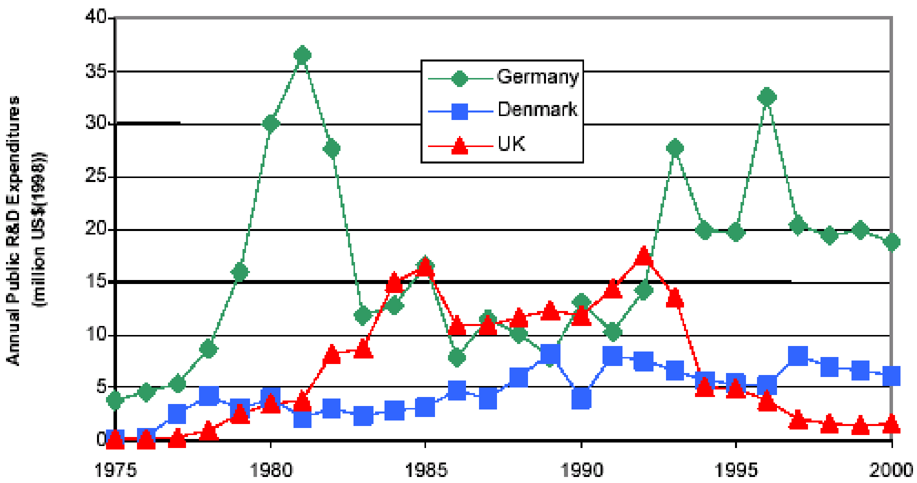

Figure 3.3 *Public energy R&D expenditures for wind power*
Sources: IEA, 2000; Klaassen et al., 2003.

In order to translate the annual public R&D expenditures from Figure 3.3 into the development of a knowledge stock, assumptions are needed on the time lag between R&D expenditures and their addition to the knowledge stock as well as the depreciation of the knowledge stock. Initial estimates by IIASA of the time lag for solar PV and wind turbines on a global base indicated that time lags of 2 to 3 years and depreciation rates of around 5% lead to acceptable statistical results. Klaassen et al. assume that the knowledge stock depreciates by 3%/a and that the time lag between public R&D expenditure and addition to the knowledge stock is 2 years. Figure 3.4 depicts the development of the R&D based knowledge stock for wind power.

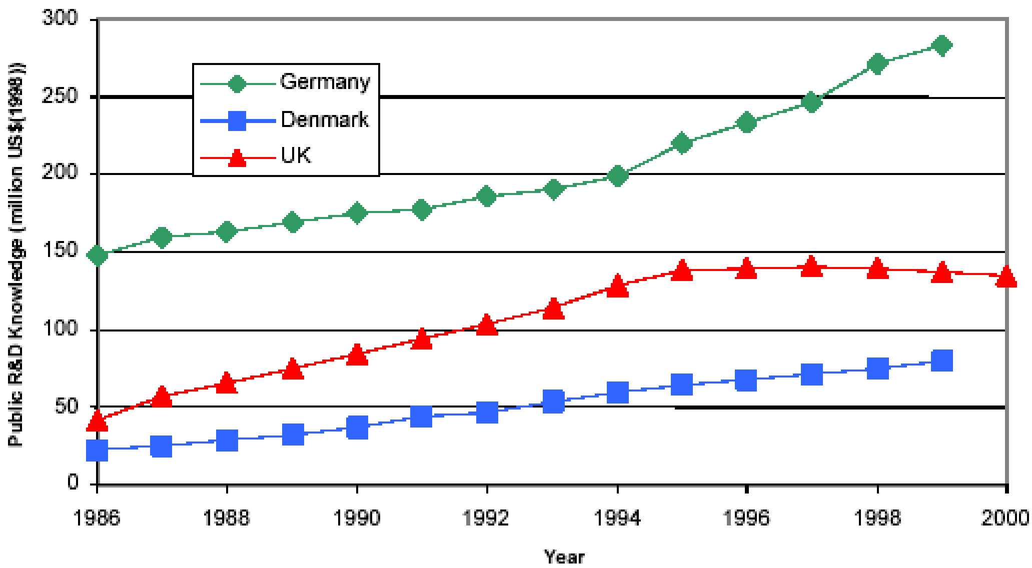

Figure 3.4 *Development of the R&D based knowledge stock for wind power*
Source: Klaassen et al., 2003.

In the UK, public R&D expenditures have been relatively large compared to the scale of its wind turbine market. It is noteworthy that the effect of reducing R&D expenditures in the UK since the beginning of the 1990s becomes noticeable and the depletion effect of old knowledge overweighs the creation of the new knowledge in the very recent years. This is not yet the case in Germany due to the time lags and the depreciation rate of public (R&D-based) knowledge.

Learning rates of 5.4% (PR = 0.946) for learning-by-doing and 12.6% (PR = 0.874) for the R&D based learning-by-searching for each doubling of cumulative installed capacity give the best fit with the development of wind power in Denmark, Germany, and the UK (1990-2000).

3.2.2 Discussion

The concept of knowledge stock with regard to RD&D on wind power is interesting, as public RD&D has been one of the cornerstones of e.g. the Danish energy policy (Chapter 2). This is also true for countries like Germany, Spain, and the Netherlands. A few comments to this study may be useful.

Klaassen et al. note that their study was restricted to the 1990s due to data limitations especially on investment costs. Also, it was restricted to an evaluation of public R&D expenditures and did not take into account private R&D expenditures as a separate factor. Another limitation of the study is the special situation in the UK. Relatively high public R&D expenditures may have been a necessary condition for the growth of wind power in the UK, in the absence of a significant indigenous wind turbine industry. The slow demand growth of wind power in the UK was one of the reasons why indigenous wind turbine manufacturers did not get a firm foothold in that country. So, the wind turbine market in the UK was quite different from that in Denmark and Germany. Inclusion of a country like the UK in the dataset may easily distort the equation in which the effects of cumulative capacity and knowledge stock are weighted.

Also, (Kamp, 2002) showed that the Danish government did much effort to create a more or less stable wind turbine market in Denmark and to foster the export market. The effect of financial incentives for wind power cannot easily be overestimated for Denmark and Germany. Financial incentives trigger more wind turbine sales, and indirectly more private R&D spending. This mechanism may have become rather important in Denmark and Germany in the second half of the 1990s. Generally, it is doubtful whether R&D is a constant factor in the development of a technology from the pilot stage to the commercial stage. In the UK the mechanism of triggering private R&D through financial incentives was much less important, as the wind turbine market didn't unfold as expected. Thus, it is conceivable that the ratio between learning-by-doing and R&D based learning-by-searching is different when private R&D is included.

Put it in another way, commercialisation of technologies is intimately linked with R&D (Lako, 2001). Or, as Wene formulated it in (IEA, 2000b): 'The cycle reinforces itself; it is a 'virtuous cycle'. There is a double boost from the sales on the market and from the improvement of knowledge through R&D'.

3.3 Spillover effects

Klaassen et al. refer to spillover effects in several ways:

- Knowledge spillover from Denmark to Germany is explicitly mentioned, in particular with regard to small wind turbines.
- Part of the price reduction for wind turbines in the UK is related to importing wind turbines, the prices of which have declined as a result of domestic sales. More than 95% of the wind turbines installed in the UK were imported and 80% were imported from Denmark in the timeframe considered. Therefore, in particular spillover from Denmark to the UK is taken into account.
- More analysis is deemed worthwhile by the authors with regard to the treatment of spillover effects between the three countries.

Klaassen et al. attribute much weight to spill-over effects from Denmark to Germany and the UK. This is in accordance with intuitive findings in § 2.4, partially based on (Kamp, 2002).

4. EXPERIENCE CURVES: A TOOL FOR ENERGY POLICY ASSESSMENT

4.1 Introduction

The study (Neij et al., 2003a) and the articles (Neij et al., 2003b; Neij, 2004; Neij et al., 2004) based on it give an analysis of experience curves for wind power in Denmark, Germany, Spain, and Sweden. These publications present results of the so-called EXTOOL project on behalf of the EC. §4.2 gives some results of the project and presents a discussion taking into account the development of wind power in the countries that are considered. §4.3 presents notions on spillover effects in the framework of the study.

4.2 Experience curves

(Neij et al., 2003a) gives an analysis of the development of experience curves (also called learning curves), of different sources of cost reduction, and of the effect of different energy policy programmes in relation to the experience curve, e.g. the effect on the ride down the experience curve, the effect on the experience curve itself, and the cost effectiveness of different programmes measured by the experience curve. The result of the project describes the advantages and disadvantages, the potential and limitations and the relevance of using experience curves as a tool for different energy policy programmes assessment.

In the project, the development of the experience curve methodology is based on case studies of wind power and analysis of cost reduction due to different wind policy programmes. The wind policy programmes in Europe in the 1990s have resulted in a major development and deployment of wind turbines. Therefore, a case study based on wind power enables the development of experience curves and the analysis of the policies involved.

An experience curve describes the cost reduction of a technology as a function of cumulative experience in terms of units produced, units sold, etc. However, experience per se does not lead to cost reductions, but rather provides opportunities for cost reductions. The cost reduction, and the experience gained, will depend on market demand and market enlargement.

Experience curves have originally been used to analyse the historical trend in cost reductions. More recently, experience curves have been extrapolated and used to analyse future cost reductions in strategic decision making (e.g. Seebregts et al., 2000; Schaeffer et al., 2004[3]). Experience curves are often based on price data and not on cost data. This is because analysts do not always have access to cost data. Substitution of cost data by price data is only a fair approximation, if price/cost margins remain constant over time. If they do not, differences in e.g. price margins have to be considered explicitly. Experience curves are also used for analysing future energy costs and the potential of commercialisation of new energy technologies. Such analyses provide policy makers with important information on the trend of cost reduction of new energy technologies. The extrapolation of experience curves has also been integrated into complex energy modelling for future energy scenarios.

Although the experience curve shows a simple quantitative relationship between price and cumulative production or use of a technology, the curve must be seen as the combination of

[3] Schaeffer et al. (2004) performed a recently completed study on solar PV with a similar scope as the so-called EXTOOL project.

several parameters that effect cost reduction. Neij et al. show how different energy policy measures effect cost reduction and how they effect the experience curve of wind power.

In general, experience curves can be considered as a complementary tool for the assessment of energy policy measures. However, in the prospective use of experience curves (trend extrapolation) there is a need for additional tools (Table 4.1).

Table 4 1 *Approaches to and methodologies used in prospective RTD[4] policy assessment*

Approach	Methodology
Technology Foresight	Monitoring and mapping historical data
Technology Forecasting, Monitoring, Early Warning - Technology radar - Emerging technologies - Critical (key) technologies list	Trend analysis - Simple extrapolation - S-curve analysis - Experience curve analysis Judgemental methodologies - Interviews - Expert panels, focus groups - Consensus conferences - Delphi surveys Multiple techniques (strategy oriented) - Scenarios - Road-mapping

Sources: Neij et al., 2003a and b.

The EXTOOL project presents technology, production and price data for wind turbines produced and installed in Denmark, Germany, Spain, and Sweden. New data were collected and existing data in databases from ISET (Germany) and Risø National Laboratory (Denmark) were verified, for a more complete database including data of approximately 17,000 wind turbines.

The data on wind turbines in the countries of interest are summarised as follows (Table 4.2):

- In 2000, Denmark counted a total of 6,427 wind turbines with an installed capacity of 2,341 MW. Of these, 3,226 (50%) were included in the database. Excluded were turbines produced by small manufacturers, sold only in small numbers, or lacking (reliable) data. Most technical data are unquestionable: since 1990 electricity production data were certified by independent authorities such as the Risø National Laboratory, Germanische Lloyds, and Det Norske Veritas. Although the price of wind turbines is more uncertain, the validity and reliability of the price data was checked.
- From 1983 to 2000, 9,228 wind turbines were installed in Germany. Of these, 5,246 are included in the database (57%). Price data were not as complete as in Denmark.
- Data on wind turbines in Spain in the period 1984-2000 cover 2,382 MW out of a total installed capacity of 2,836 MW in the same period of time (84%). No data were available on the price of wind-generated electricity in Spain.
- Data on wind turbines in Sweden in the period 1994-2000 cover 221 MW. In 2000, the total installed wind capacity in Sweden was 280 MW. No data were available on the price of wind-generated electricity in Sweden.

[4] RTD = Research, Transfer, and Dissemination.

Table 4.2 *Coverage of wind turbines in Denmark, Germany, Spain, and Sweden*

Country		Number of wind turbines 2000		Cumulative capacity 2000 [MW]	
		Total number	Database	Total cumulative	Database
Denmark	Produced	6,427	3,226	2,341	N/A
Germany	Produced	9,228	5,246	6,107	5,667
Spain	Installed	N/A	N/A	2,836	2,382
Sweden	Installed	N/A	N/A	280	221

Sources: Neij et al., 2003a and b; Neij, 2004.

Figure 4.1 shows the development of the average price of wind turbines from Denmark and Germany as a function of time.

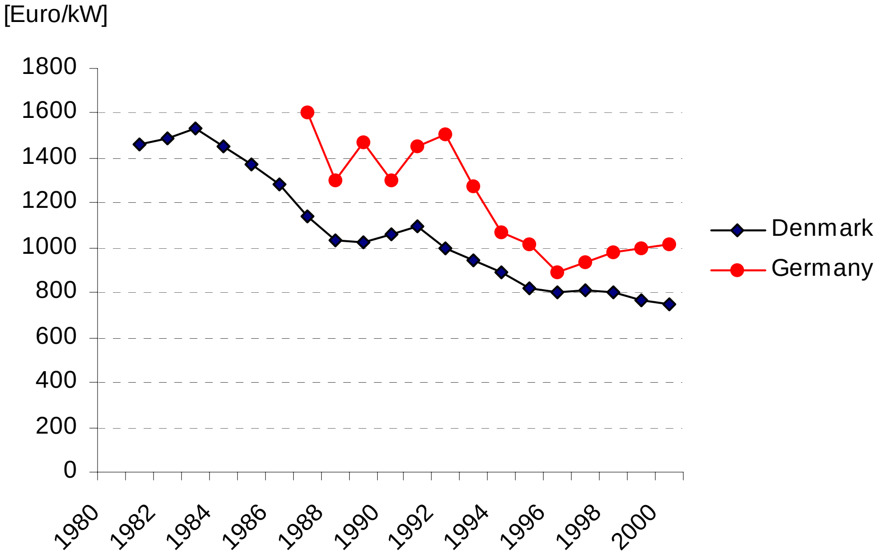

Figure 4.1 *Price of wind turbines (€$_{2000}$) from Denmark and Germany as a function of time*
Source: Neij et al., 2003a.

Figure 4.2 is based on the cumulative global sales of the Danish wind turbine industry in the period 1981-2000 and price data for a representative selection of Danish wind turbines.

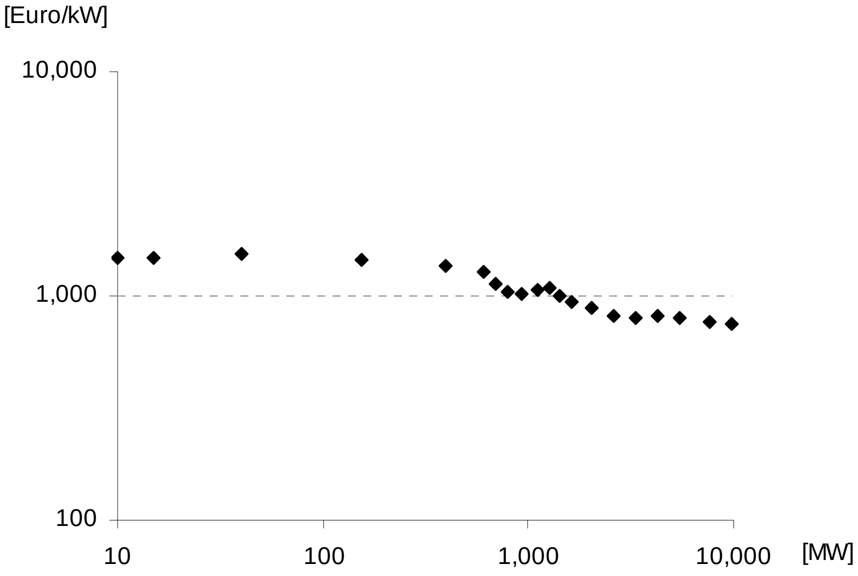

Figure 4.2 *Experience curve for wind turbines (price ex works, €$_{2000}$) from Denmark*
Source: Neij et al., 2003a.

Similarly, Figure 4.3 shows the experience curve based on cumulative global sales of the German wind turbine industry in the period 1987-2000.

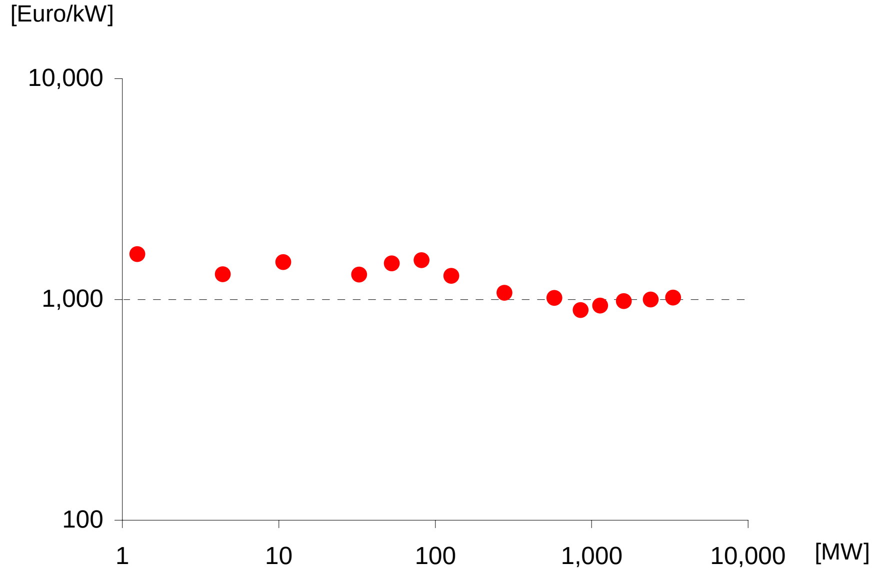

Figure 4.3 *Experience curve for wind turbines (price ex works, €$_{2000}$) from Germany*
Source: Neij et al., 2003a.

The Progress Ratio (PR) of wind turbines produced by the Danish wind turbine industry is 0.92, and the PR of German wind turbines is 0.94. The data for Denmark allow Neij et al. to extend the experience curve to the levelised production cost (unit: Euro/kWh); such an experience curve for Danish wind turbines shows a PR of 0.83. Experience curves for the specific investment cost (e.g. Figure 4.2 and 4.3) may be used for extrapolation. However, experience curves for the levelised production cost may not be extrapolated, as current wind turbines are so advanced that improvement of the capacity factor will not be significant, at least at constant hub height.

Figure 4.4 presents experience curves for the total installed cost of wind turbines as a function of the cumulative installed capacity in Denmark, Spain, and Sweden.

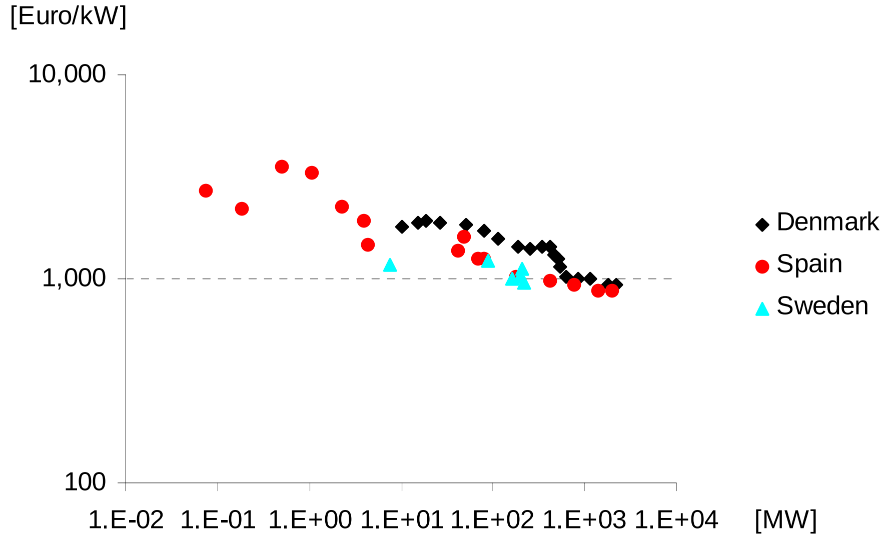

Figure 4.4 *Experience curve for total cost of installed wind turbines in EU countries (€$_{2000}$)*
Sources: Neij et al., 2003a and b.

Figure 4.4 shows that the cost reduction of the total installed cost (including civil cost, cabling, etc.) in Denmark and Spain is roughly comparable. The database for the total installed cost of wind turbines in Sweden is not so large, but the trend is similar to that in Denmark and Spain.

Finally, Table 4.3 summarises the public expenses for wind power in the four EU countries.

Table 4.3 *Cumulative expenses for wind power in four EU countries [million €]*

	Denmark	Germany	Spain	Sweden
Governmental RD&D				
Before 1990	47	177	32	100
1990-2000	53	50	27	28
EU RD&D	-	-	-	-
Private R&D	-	-	-	-
Investment subsidies	57	69	150	60
Production subsidies	332	131	-	27
'Feed-in law'	N/A	997	318	-
Total	>489	1,424	527	215

Sources: Neij et al., 2003b; Neij, 2004.

The authors conclude that the high public expenses for RD&D in Germany and Sweden, in comparison to Denmark, might not have been necessary for the development of wind power. However, in §2.3 it was noted that not all the money spent on the Danish RD&D program for large wind turbines had gone to waste. This is also true for programs in Germany and Sweden.

4.3 Spillover effects

(Neij et al., 2003a) provide insight in spillover effects from Denmark and the US to Germany and Spain. In the period 1985-2000, Germany witnessed a successful combination of:

- Favourable market policy for electricity generated by wind turbines.
- Favourable loans for wind turbine projects.
- Subsidies to investors.
- A monitoring program.

Neij et al. note that successful deployment in the 1990s of proprietary wind turbine technologies by e.g. Enercon was based on both company funding and dedicated federal RD&D support.

In Spain, no wind turbines from indigenous wind turbine manufacturers were commercially available until 1992. Right from the start in 1983, the Spanish company Ecotècnia had to have the technology right in order to generate financing. Ecotècnia depended mostly on national budget subsidies for its early growth. The Spanish government did not provide generous subsidies for indigenous wind turbine manufacturers, as in Denmark and Germany. Up to the mid-1990s, practically all wind power projects in Spain received some kind of 'RD&D support'. With regard to spillover effects, Neij et al. make the following observation:

> '*In general, Made and Ecotècnia have both adopted the practical strategy of combining technology transfer from the USA and Denmark with internal technology development. Thus the development of the Spanish industry has not solely been dependent on domestic RD&D efforts, but has made use of inputs from abroad*'.

From 1991, the Swedish government offered investment subsidies for wind turbines. Danish wind turbine manufacturers entered the Swedish market with their medium-sized wind turbines. In the framework of an RD&D program on large wind turbines, Swedish industries developed and demonstrated several MW-scale turbines. However, these wind turbines proved to be not marketable at that time. It must be acknowledged that the Swedish industry did not have a large home market as the Danish wind turbine industry did. Spillover effects from the Danish wind turbine industry to Swedish wind turbine manufacturers are not reported by Neij et al. However, this does not imply that such effects did not occur.

5. COST REDUCTION PROSPECTS FOR OFFSHORE WIND

5.1 Introduction

(Junginger et al., 2004) analyse technological developments and cost reduction trends in the onshore and offshore wind sector. Based on a bottom-up analysis they estimate future investment costs of offshore wind farms. §5.2 presents the framework of their study, and §5.3 the main results. In §5.4, spillover effects in the development of offshore wind are addressed., and in §5.5, policy implications from (Junginger et al., 2004) and other studies on this subject.

5.2 Framework of the study

According to (Junginger et al., 2004), offshore wind has several advantages over onshore wind:

- Due to the higher average wind speed offshore, offshore wind farms may yield up to 50% more than onshore wind farms of equal capacity (and hub height).
- Onshore wind farms may meet public resistance from visual impact, noise, and shadow casting; offshore wind farms, sufficiently distant from the shore, meet less resistance.
- Offshore wind has a very large potential compared to onshore wind. The potential of onshore wind is often curtailed by considerations of conservation of landscape.

Junginger et al. explore the range of reductions of the initial investment cost of offshore wind by a bottom-up analysis of technological improvements and cost reduction options. Important underlying drivers are identified for cost reductions. Apart from drivers directly related to the development of offshore wind, they explore exogenous developments in the offshore oil and gas sector and offshore experience with High-Voltage Direct Current (HVDC) transmission.

5.3 Main results

Table 5.1 present the following overview of the main components of the cost of offshore wind.

Table 5.1 *Overview of relevant factors behind cost reductions of offshore wind farms*

	Specific offshore wind developments	Exogenous developments
Wind turbine	Upscaling Improved design Standardization Economies of scale	Further development of onshore wind turbines Steel price
Grid connection	Standardised design of HVDC cables Applicability of XLPE[1] insulation to HVDC cables Advances in valve technology and power electronics	
Foundations	Standardisation Economies of scale Design regarding dynamic loads	Steel price
Installation	Learning-by-doing Development and structural deployment of purpose-built ships Standardisation of turbines and equipment	Oil price (oil rigs)

Note XLPE = Cross Linked Poly Ethylene.
Source: Junginger et al., 2004.

Parameters for modelling of specific investment cost of offshore wind are shown in Table 5.2.

Table 5.2 *Overview of parameters for the base case offshore wind farm*

Parameter	Unit	Value
Wind turbine capacity	[MW]	5
Hub height	[m]	90
Rotor diameter	[m]	125
Number of wind turbines		100
Wind farm capacity	[MW]	500
Water depth	[m]	20
Distance to shore	[km]	40
Foundations		Steel monopiles
Power transfer to the shore		
Type		HVDC
Capacity converter station	[MW]	500
Initial investment costs		
Wind turbines (47%)	[$€_{2001}$/kW]	752
Foundation (12%)	[$€_{2001}$/kW]	192
Internal grid (4%)	[$€_{2001}$/kW]	64
Grid connection (19%)	[$€_{2001}$/kW]	304
Installation (12%)	[$€_{2001}$/kW]	192
Miscellaneous (6%)	[$€_{2001}$/kW]	96
Total	[$€_{2001}$/kW]	1,600

Source: Junginger et al., 2004.

A PR of 0.81-0.85 is assumed for the wind turbines of offshore wind farms. This level is mainly based on cost reduction experienced with large wind farms in Spain and small wind farms in the UK. In Figure 5.1 Junginger et al. show the specific investment cost of wind farms in these two countries as a function of the global cumulative installed wind capacity in each year.

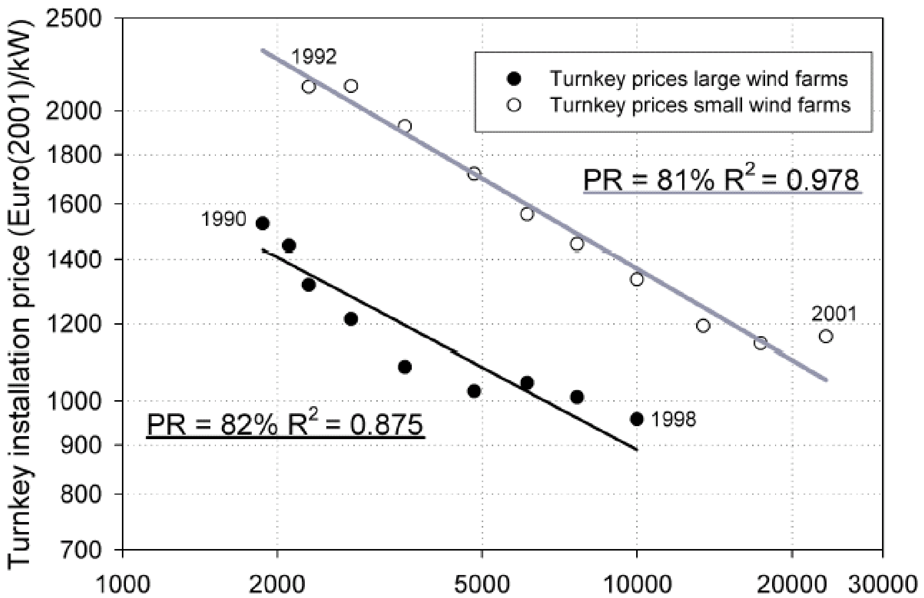

Figure 5.1 *Experience curves for wind farms as a function of global cumulative capacity (MW)*
Source: Junginger et al., 2004.

Junginger et al. make several assumptions with regard to cost reduction of main components, viz. wind turbines, grid connection, foundation, installation, and miscellaneous. They distinguish two deployment scenarios, viz. 'Sustained diffusion' and 'Stagnating growth' (Table 5.3).

Table 5.3 *Summary of quantitative cost reduction trends in two deployment scenarios*

	Scenario '*Sustained diffusion*'	Scenario '*Stagnating growth*'
Wind turbine	Annual growth rate of onshore and offshore wind declining from 27.5% in 2003 to 15% in 2020 PR = 0.81	Annual growth rate of onshore and offshore wind declining from 27.5% in 2003 to 10% in 2020 PR = 0.85
Grid connection	High growth rates of HVDC converter stations and submarine cables PRs of 0.62 and 0.71 respectively	Moderate growth rates of HVDC converter stations and submarine cables PRs of 0.62 and 0.71 respectively
Foundation	Cost of steel reduced by 2%/a	Cost of steel reduced by 1%/a
Installation	PR = 0.77	PR = 0.77
Miscellaneous	PR = 0.95	PR = 0.95

Source: Junginger et al., 2004.

In 'Sustained diffusion' the current high growth rate is assumed to decrease slowly by about 0.5%/a from 27.5%/a in 2003 to 15%/a in 2020. This is in accordance with the study Wind force 12 (EWEA, 2003a and b) from EWEA and Greenpeace. Scenario 'Sustained diffusion' would imply an offshore wind capacity of 50,000 MW in Europe, and 70,000 MW worldwide in 2020.

Scenario 'Stagnating growth' presumes a growth of the global installed wind capacity declining to 10%/a in 2020 instead of 15%/a in scenario 'Sustained diffusion', and a more conservative PR is used for the wind turbine as the main component of offshore wind farms. Also, the diffusion of High-Voltage Direct Current (HVDC) is assumed to be slower than in scenario 'Sustained diffusion'. Finally, it is assumed that the cost of steel will decline by 1%/a instead of 2%/a.

Figure 5.2 shows the resulting cost reduction for offshore wind farms in the two scenarios.

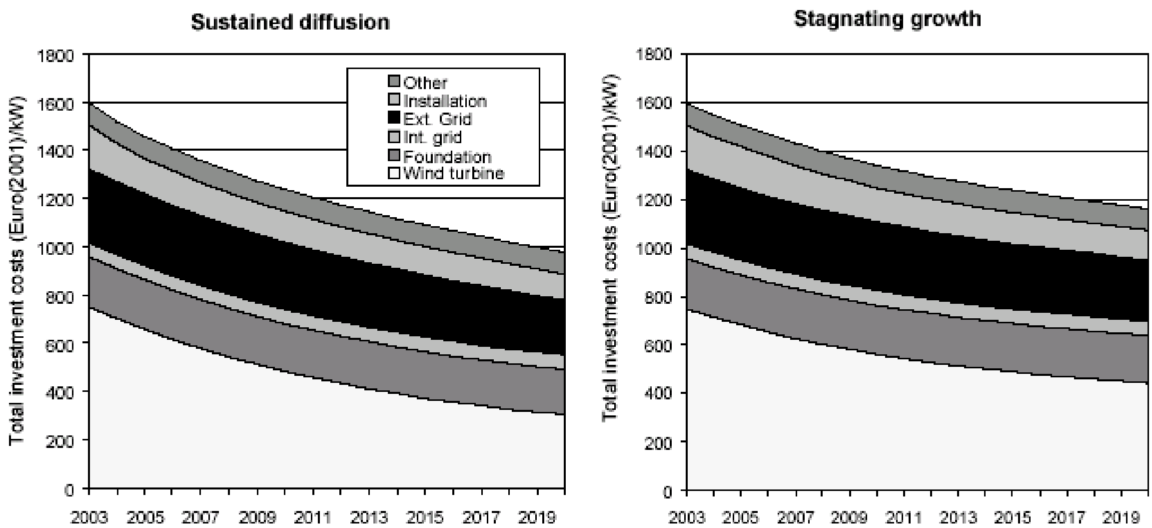

Figure 5.2 *Specific investment cost of offshore wind farms in two deployment scenarios*
Source: Junginger et al., 2004.

According to Junginger et al., the specific investment cost of offshore wind farms would come down from €1,600/kW in 2003 to €980/kW in 2020 in 'Sustained diffusion', and to €1,160/kW in 'Stagnating growth'. Such large cost reductions in a relatively short timeframe appear to be rather sensitive to assumptions on the PR of wind turbines. Neij et al. indicate a PR for Danish wind turbines (1981-2000) of 0.92 and for German wind turbines (1987-2000) of 0.94. If such PR's would be applied to the scenarios of Junginger et al., the cost level of €980 – 1,160/kW would probably be reached in 2030 rather than 2020, as may be concluded from (Lako, 2002).

5.4 Spillover effects

Junginger et al. do not explicitly address spillover effects in the development of offshore wind power to other world regions. However, they pay attention to the geopolitical dimension of offshore wind. Their analysis shows that long-term stable offshore prospects may support cost reductions, especially for the installation costs, but also for (offshore) wind turbines. No single (European) country has the potential to create an offshore wind market on its own. Therefore, a European policy regarding the stimulation of offshore wind farms is recommended, as this might be a great benefit both to ensure diffusion of offshore wind and cost reductions.

5.5 Policy implications

The development of offshore wind power is in such an early stage that spillover effects may be hardly distinguished. However, assessments of the potential of offshore wind in the EU indicate a potential along the European coasts of some 300-350 TWh/a (BTM Consult, 2003; de Noord, et al., 2004). Assuming an average capacity factor of 40% (Table 5.4), the offshore potential in Europe would amount to 85-100 GW. According to (BTM Consult, 2003), this potential could be realised around 2020. The market could peak with an annual demand of 1,000 turbines of 5 MW each. There would be room for two or three suppliers in the European offshore market. It may be expected, however, that offshore wind energy will also be developed outside the EU, e.g. in the US, India, etc. Also, the market for onshore and offshore wind cannot be regarded as totally independent. Therefore, in the near future spillover effects from offshore wind turbine technology will probably prove to be significant.

EU countries with offshore wind potential and the EU may be interested to support offshore wind power, not only for reasons of reducing greenhouse gas emissions and creating employment in indigenous wind turbine business, but also in view of the potential of offshore wind in other parts of the world. Therefore, EU countries and the EU could consider possible spillover effects from offshore wind turbine technology. For other world regions, it would be a sensible strategy to open up their markets for offshore wind technology becoming available from the EU and the US. Just like for onshore wind, it would be beneficial for these regions to profit from the high technological level of offshore wind turbines etc. developed in the EU and the US. Other world regions would then act as 'late adaptors', with the advantages of higher reliability, lower costs, etc. Although these regions would then rely on import of offshore wind technology for some time, there could also be scope for development of an indigenous offshore wind industry.

Table 5.4 *Characteristics of near-shore and offshore wind farms*

Project	Type of wind farm	Country	Location (sea)	Start of operation [year]	Average wind speed [m/s]	Distance to shore [km]	Water depth [m]	Capacity [MW]	Investment cost [10^6 €]	Investment cost [€/kW]	Capacity factor [%]
Vindeby	Near-shore	DK	Baltic Sea	1991	7.5	1.5-3	2.5-5	4.95	13.2	2,660	24.4
Lely	Near-shore	NL	Ijsselmeer	1994	7.7	0.8	4-5	2	5.3	2,600	21.7
Tunø Knob	Near-shore	DK	Baltic Sea	1995	7.4	3-6	3-5	5	11.6	2,325	28.5
Bockstigen	Near-shore	S	Baltic Sea	1998	N/A	4	6	2.75	4.2	1,530	24.7
Blyth offshore	Offshore	UK	North Sea	2000	7.2	1	6	4	6.44	1,610	35.0
Middelgrunden	Near-shore	DK	Baltic Sea	2000	7.2	2	4-8	40	48.96	1,225	25.4
Utgrunden	Near-shore	S	Kalmarsund	2000	8.5	8	8-10	10	18.3	1,830	43.3
Yttre Stengrund	Near-shore	S	Baltic Sea	2001	7.1	5	7.5-8.6	10	17.3	1,730	44.6
Horns Rev	Offshore	DK	North Sea	2002	9.7	14-20	6-14	160	268	1,675	41.0
Frederikshavn	Offshore	DK	North Sea	2002	N/A	N/A	N/A	10.6	N/A	N/A	N/A
Samsø	Near-shore	DK	Paludens Flak	2003	8.0	3.5	11-18	23	N/A	N/A	38.7
Nysted	Near-shore	DK	Baltic Sea	2003	9.0	6	6-9	165.6	N/A	N/A	36.0
North Hoyle	Offshore	UK	Irish Sea	2003	8-9	8	5-12	60	N/A	N/A	N/A
Arklow Bank	Offshore	IR	Irish Sea	2003	9.0	7-12	2-5	25.2	N/A	N/A	N/A
Breitling	Near-shore	D	North Sea	2003	N/A	<1	2	2.3	N/A	N/A	N/A
Klasården	Near-shore	S	Baltic Sea	2004	N/A	N/A	N/A	44	N/A	N/A	31.1
Utgrunden II	Near-shore	S	Baltic Sea	2004	N/A	N/A	N/A	72	N/A	N/A	38.0
Lillgrund	Near-shore	S	Baltic Sea	2004	N/A	N/A	N/A	76.8	N/A	N/A	N/A
Scroby Sands	Offshore	UK	North Sea	2004	8.0	2.5	2-10	60	N/A	N/A	N/A
Barrow	Offshore	UK	Irish Sea	2005	8.7	8	15-20	90	N/A	N/A	N/A
Noordzeewind	Offshore	NL	North Sea	2005	9.0	8	15-20	100	N/A	N/A	N/A
Q7-WP	Offshore	NL	North Sea	2005	9.0	23	20-25	120	N/A	N/A	N/A
Thornton Bank	Offshore	B	North Sea	2005-2007	8.8	27	10-20	216	500	2,315	N/A
Cape Wind	Offshore	US	Atlantic Coast	2005	8.9	8	4-15	420	N/A	N/A	N/A
Butendiek	Offshore	D	North Sea	2005	8.6	34	17-20	240	N/A	N/A	N/A
Wilhelmshaven	Near-shore	D	North Sea	2005	8.2	0.55	0	4.5	N/A	N/A	N/A

6. CONCLUSIONS AND POLICY IMPLICATIONS

The development of wind power is an interesting case of spillover effects because:

- Wind power is a relatively young renewable energy source, besides hydropower and biomass. Its ‘track record’ is sufficiently long to analyse spillover effects.
- Three EU-15 countries – Denmark, Germany, and Spain – are regarded as the cradle of the modern wind turbine industry, next to the US and other EU countries.
- The EU-15 countries try to develop wind energy into a thriving industry. The EU-15 has the obligation to reduce its greenhouse gas emissions by 8% in 2008-2012 compared to 1990. Also, the EU-15 has formulated a target to increase the share of renewables from 6% of gross inland energy consumption in 1990 to 12% in 2010.

1. (Kamp, 2002) and (Kamp et al., 2004) present an in-depth analysis of the development of wind power in Denmark and the Netherlands. Technological learning is important, particularly in the case of technologies like wind turbines that consist of several interacting parts and have to function in changing environments. Variations on a dominant design are introduced in what is called the ‘selection environment’. The most promising variations are selected. The selection environment is a broader concept than the market: it includes regulations, norms, beliefs and expectations of multiple actors, government policies, taxes and subsidies.

Most likely, spillover effects in wind power technology occurred from Denmark to other countries in the period 1980-2000. Countries opened their markets to Danish wind turbines, and this speeded up the technological development of wind turbine manufacturing: Nordex is a mixed Danish/German wind turbine manufacturer, and Gamesa Eólica (Spain) is a former subsidiary of Vestas (Denmark). The magnitude of spillover effects is difficult to quantify. Spillover to non-Annex 1 countries was less important, as most of these countries, except India, are still in an early stage of the development of their wind resources. Also spillover in terms of the adoption of policies favouring wind power has occurred (R&D policies, feed-in tariffs, etc.).

2. Two-factor learning is described by (Klaassen et al., 2003) for wind energy in Denmark, Germany, and the UK. The analysis focuses on the contribution of public R&D and cumulative sales on the cost reduction of wind turbines. In the conventional learning literature, focus is mostly given on the effect of capacity expansion (possibly stimulated by procurement policy) of the cost-reducing innovation. In contrast, Klaassen et al. extend the scope to the effect of public R&D[5]. Learning rates of 5.4% for learning-by-doing and 12.6% for the R&D based learning-by-searching for each doubling of cumulative installed capacity give the best fit with the development of wind power in Denmark, Germany, and the UK for the period 1990-2000.

Klaassen et al. refer to spillover effects in several ways:

- Knowledge spillover from Denmark to Germany is explicitly mentioned, in particular with regard to small wind turbines.
- Part of the price reduction for wind turbines in the UK is related to importing wind turbines, the prices of which have declined as a result of domestic sales. In particular spillover from Danish wind turbine manufacturing to the UK is taken into account.

3. (Neij et al., 2003a and 2003b) give an analysis of the development of experience curves, of sources of cost reduction, and of the effect of different energy policy programmes in relation to the experience curve. The result of the project describes the advantages and disadvantages, the

[5] Note that in (Sijm, 2004) ample examples are given of models and studies covering either this learning-by-doing or learning-by-searching, but only occasionally both types of learning at the same time.

potential and limitations and the relevance of using experience curves as a tool for different energy policy programmes assessment. The Progress Ratio (PR) of the investment cost of wind turbines produced by the Danish wind turbine industry is 0.92, and the PR of German wind turbines is 0.94.

Neij et al. also provide insight in spillover effects from Denmark and the US to Germany and Spain. In the period 1985-2000, Germany witnessed a successful combination of:
- Favourable market policy for electricity generated by wind turbines.
- Favourable loans for wind turbine projects.
- Subsidies to investors.
- A monitoring program.

Neij et al. note that successful deployment in the 1990s of proprietary wind turbine technologies by e.g. Enercon was based on both company funding and dedicated federal RD&D support.

In Spain, no wind turbines from indigenous wind turbine manufacturers were commercially available until 1992. Up to the mid-1990s, practically all wind power projects in Spain received some kind of 'RD&D support'. Neij et al. refer to spillover effects from the wind turbine industry in the US and Denmark to Spanish turbine manufacturers like Made and Ecotècnia.

From 1991 on, the Swedish government offered investment subsidies for wind turbines. Danish wind turbine manufacturers entered the Swedish market with their medium-sized wind turbines. Spillover effects from the Danish wind turbine industry to Swedish wind turbine manufacturers are not been reported by Neij et al. However, this does not imply that such effects did not occur.

4. According to (Junginger et al., 2004), offshore wind has several advantages over onshore wind:
- Due to the higher average wind speed offshore, offshore wind farms may yield up to 50% more than onshore wind farms of equal capacity (and hub height).
- Onshore wind farms may meet public resistance from visual impact, noise, and shadow casting; offshore wind farms, sufficiently distant from the shore, meet less resistance.
- Offshore wind has a very large potential compared to onshore wind. The potential of onshore wind is often curtailed by considerations of conservation of landscape.

Junginger et al. assume that the PR for wind turbines is 0.81-0.85, based on cost reduction of large wind farms in Spain and small wind farms in the UK. The specific investment cost of offshore wind farms would come down from €1,600/kW in 2003 to €980 – 1,160/kW in 2020. Such large cost reductions in a relatively short timeframe appear to be rather sensitive to assumptions on the PR of wind turbines. According to Neij et al. the PR for wind turbines from Denmark was 0.92 (1981-2000) and for turbines from Germany 0.94 (1987-2000). If such PR's would be applied, the aforementioned cost range would be attained in 2030 rather than in 2020.

They also pay attention to the geopolitical dimension of offshore wind. Long-term stable offshore prospects may support cost reductions, especially for the installation costs, but also for wind turbines. No single country has the potential to create an offshore wind market on its own. Therefore, a European policy regarding the stimulation of offshore wind farms is recommended, as this might be a great benefit both to ensure diffusion of offshore wind and cost reductions.

5. The development of offshore wind power is in such an early stage that spillover effects may be hardly distinguished. Nevertheless, EU countries with offshore wind potential and the EU may be interested to support offshore wind power, not only for reasons of reducing greenhouse gas emissions and creating employment in indigenous wind turbine business, but also in view of the potential of offshore wind in other parts of the world. Therefore, EU countries and the EU could consider possible spillover effects from offshore wind turbine technology. For other world

regions, it would be a sensible strategy to open up their markets for offshore wind technology becoming available from the EU and the US. Just like for onshore wind, it would be beneficial for these regions to profit from the high technological level of offshore wind turbines etc. developed in the EU and the US. Other world regions would then act as ‘late adaptors’, with the advantages of higher reliability, lower costs, etc. Although these regions would then rely on import of offshore wind technology for some time, there could also be scope for development of an indigenous offshore wind industry.

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