

# **Offshore Wind Farm Development**

Cost Reduction Potential

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Thesis for the fulfilment of the  
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*Lisa Isles*

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## **Abstract**

Offshore wind farms are believed to have significant potential as a renewable energy technology; although the current costs are far from competitive. Consequently the future development of offshore wind farms depends on cost reductions. The trend for a large number of renewable energy technologies has been that as experience increases the costs associated with the technology will decrease; experience is generally measured in terms of cumulative capacity. In this study the development of total installation costs for offshore wind farms has been analysed through the use of experience curve methodology with emphasis on the collection and verification of good data. The trends observed have been opposite to what was expected; total installation costs have been observed to be increasing with increasing experience. The main reason for the trends observed has been attributed to the use of price data as opposed to cost data. The differences between price and cost data have been attributed to market structure. In the case of offshore wind farm development the apparent disconnect between price and cost data is predominantly due to a lack of competition amongst turbine manufacturers; this lack of competition is mostly as a result of the high risk of investment in offshore wind farms combined with accelerated development of onshore wind farms. The booming onshore industry makes investment in high risk offshore projects even more unattractive. The costs of producing and installing offshore wind turbines is still anticipated to be following a trend where costs are decreasing relative to increasing experience. This trend of decreasing costs will only be evident in the total installation cost (essentially price) curve once the market stabilises; when prices will track at a relatively constant increment above costs. This study of the development of offshore wind farms has highlighted the need to use additional and complimentary methods of analysis in combination with experience curve analysis.



## **Executive Summary**

The installed capacity of offshore wind farms currently sits at approximately 0.9 GW. Future development plans for offshore wind farms are ambitious, in fact by 2009 the global offshore wind farm capacity is expected to be approximately 7.7 GW (Westwood, 2005a); more than 7 times the installed capacity as at 2006. Offshore wind farms have a number of advantages over onshore wind farms; offshore wind farms are more practical in highly populated areas where land is often too valuable to locate a wind farm. Additionally offshore the average wind speeds are higher and energy yields can be up to 50% higher in comparison to equal capacity onshore installations. Offshore wind farms can also be located at a sufficient distance from shore so that noise and visual pollution are much less of an issue.

The potential for offshore wind energy, in terms of production capacity, has been estimated to be far in excess of onshore wind energy although at present offshore wind energy is not financially competitive with other currently utilised energy technologies including onshore wind. As a result the future success of offshore wind energy is dependent upon cost reductions.

The overall objective of this research project is to explore the cost reduction potential for offshore wind farms. This will be based on addressing a number of research questions:

- 1) What trends can be observed in the historical cost development of offshore wind farms? How do these trends compare with expectation?;
- 2) Can experience curves be used to forecast the future cost reduction potential for offshore wind energy? Are there limitations to the application of experience curves in the case of offshore wind?; and
- 3) What are the underlying reasons for the historical trends and current investment costs for offshore wind developments?

This project considers the development of offshore wind from a global perspective and is primarily concerned with the development of total investment costs, although operating and maintenance costs will be considered.

In this study new experience curves have been developed to track the development of investment costs for offshore wind farms. Prior studies of both onshore and offshore wind farms using experience curve analysis have been used as a basis for comparison. A major strength of this study has been the high quality of data that has been independently collected and verified.

Studies of the development of onshore wind turbines and farms through the use of experience curves have been completed by a number of authors including;

- National studies: Neij (1997), Durstewitz and Hoppe-Kilpper (1999), Neij, Andersen, Durstewitz, Helby, Hoppe-Kilpper and Morthorst (2003); and
- Global studies: Junginger (2005a).

Junginger (2005b) also completed a study looking at the cost reduction opportunities for offshore wind farms using experience curve analysis. All of these studies showed that for increasing experience both turbine price and wind farm total installation costs decreased. As a result it was expected that total installation costs for offshore wind farms should decrease with increasing experience, measured in terms of installed cumulative capacity. The study by Neij et

al. (2003) also showed significant operating and maintenance cost reduction potential. In order to test this theory new experience curves were constructed.

Following established methodology an experience curve for the development of total installation costs for offshore wind farms was constructed; this experience curve is presented in Figure 5-3.

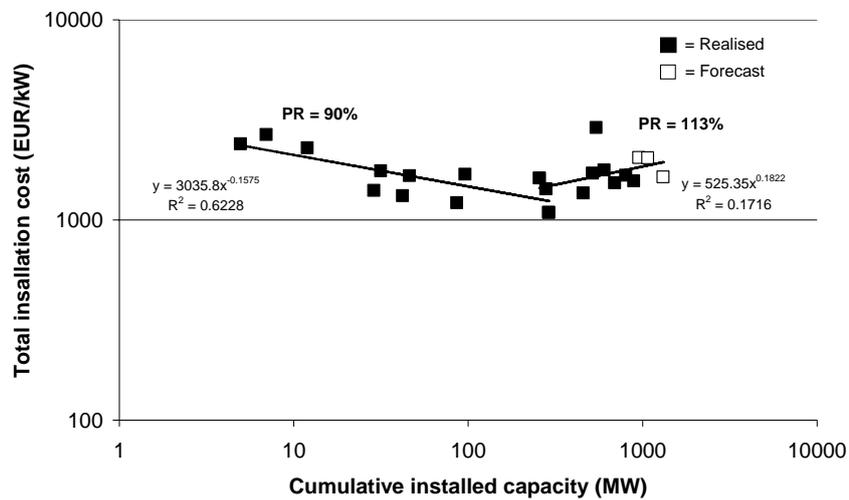


Figure 5-3: Experience curve for offshore wind farms located globally showing two phases of development, data adjusted for inflation and exchange rate

The results of this study showed that regarding the total installation costs for offshore wind farms, although initially decreasing with increasing experience, the current and longer term trend is that the total installation costs for offshore wind farms have been increasing with increasing experience. These trends can be clearly observed in Figure 5-; the increasing trend observed is in contrast to expectation.

The unexpected trend of increasing total installation cost for offshore wind farms was the starting point for the analysis of results. The data set utilised was determined to be both reliable and comparable. The next step was to consider the type of data used. True experience curve analysis relies on cost figures although it is often the case that cost figures are not available and price figures are used instead. Price data are said only to provide an accurate representation when the price/cost margin is consistent. The total installation cost data used for this project is essentially price data. Based on this, it has been determined that the price/cost margin inherent in this analysis is inconsistent. This conclusion highlighted the need for additional analysis of the factors affecting the total installation cost to complement the results of the experience curve analysis.

This disconnect between price and cost data has been identified as being a result of market structure. The factors influencing the market structure that predominantly relate to a lack of competition have been determined to be: the booming onshore industry, the high risk associated with involvement in offshore projects, limited competition amongst turbine manufacturers, uncertainty regarding government policy and approvals, difficulty of access to funding, limited potential for experience related cost reduction and a shortage of both installation vessels and skilled contractors.

Although not evident in the price data it is still expected that the cost of producing and installing turbines, foundations and electrical infrastructure is decreasing with increasing experience. It is anticipated that cost reductions from both a capital and operating perspective are occurring. The major influencing factors for the reduction of capital costs can be summarised as: a) turbines – standardisation and economies of scale as well as technological development, b) grid connection – use of HVDC technology, c) foundations – standardisation and economies of scale as well as optimisation of design and d) installation costs – through the utilisation of purpose built vessels and experience. In addition to the expected decreases in capital costs, decreases in operating costs may also be significant. The biggest potential for reducing operating costs has been determined to be through increases in the availability and efficiency of offshore wind turbines. It is only once the market stabilises and price/cost margin becomes reasonably consistent, that the decreases in costs detailed will be observed in the total installation costs for offshore wind developments.

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# 1. Introduction

## 1.1 Background and problem description

As we move on in time the existence of accelerated climate change is becoming less of a question and more of a reality. The link between elevated levels of CO<sub>2</sub> in the atmosphere and global warming is an accepted theory. Based on this evidence the global effort to reduce the levels of CO<sub>2</sub> in the atmosphere is gaining momentum, with more and more countries taking steps to implement strategies aimed at the reduction of CO<sub>2</sub> emissions. A significant proportion of CO<sub>2</sub> emissions originate in the production and generation of energy. With a globally sustainable energy system as the overarching vision much greater utilisation of renewable energy sources is an absolute necessity.

The combustion of fossil fuels to produce energy accessible to humans accounts for the majority of anthropogenic CO<sub>2</sub> emissions. This means that strategies aimed at reducing CO<sub>2</sub> emissions will undoubtedly have a strong focus on reducing the consumption of fossil fuels and hence much greater utilisation of renewable energy sources will be required. At the same time energy generated from renewable sources often comes at a premium price. This means that complete substitution of fossil fuels with renewable energy sources to produce electricity would translate into drastic increases in the cost of electricity; in the case where external costs associated with the likes of CO<sub>2</sub> emissions are not part of the equation. In today's economic climate only subtle changes in the cost of electricity are considered tolerable to maintain the stability of a nation's economy. As a result a renewable energy technology will only be developed if it is believed that at some point in the foreseeable future the technology has the potential to be independently competitive with existing energy sources and their associated technologies.

Wind energy is one potential renewable energy source that is of interest in terms of the mitigation of accelerated climate change. In addition to this offshore wind energy has been presented as an energy source that could play a central role in the future global energy system. At present offshore wind energy is not independently competitive with currently utilised energy technologies from a financial perspective. As an approximation of the comparative cost of electricity from different sources, excluding external costs, the cost of producing electricity from coal, gas, onshore wind and offshore wind resources, in €(EUR)/kWh<sup>1</sup>, is 3.6-4.7, 3.2-4.6, 5.4 and 8.1 respectively (Royal Academy of Engineering (RAE), 2004b). Based on these costs for producing electricity it is important to develop an understanding of the future cost reduction potential associated with the production of electricity through the use of offshore wind turbine technology.

There are a variety of both quantitative and qualitative methods that are employed to study the development of technologies. Experience curve analysis is a method that is often used to assess the expected cost development of new technologies. Through the use of experience curve analysis it has been observed that the long term development of a new technology often follows a pattern. The pattern generally observed is one of exponential decline; the opposite of exponential growth. Put simply, at the onset of the deployment of a new technology the rate at which cost reductions occur is rapid. Then as cumulative capacity increases the rate at which cost reductions occur decreases until the cost associated with the

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<sup>1</sup> Using an exchange rate of GBP 1 = EUR 1.47

technology reaches a stable level where only minimal changes are observed. Experience curves have been developed for a range of energy technologies, for further details please refer to McDonald & Schrattenholzer (2001).

In this report experience curves will be used to map the historical development of the total installation costs for offshore wind farms. The use of experience curves to assess cost development is often criticized due to the high level of aggregated costs. As a result the experience curve analysis will be complemented by additional methods of analysis whereby a variety of aspects affecting both the historical and current costs associated with offshore wind farms will be identified and discussed primarily from a qualitative perspective.

## 1.2 Objective

Energy produced by offshore wind farms is currently not cost competitive with other mainstream energy technologies, as a result the long term viability of offshore wind farm technology is dependent on future cost reductions. The overall objective of this research project is to explore the cost reduction potential for offshore wind farms. This will be done by analysing the historical development of the total installation costs for offshore wind farms through the use of experience curves. The construction of experience curves will allow the identification of total installation cost development trends. These trends should provide insight into the future development of the total installation costs for offshore wind farms. Also the other factors influencing the total installation costs for offshore wind farms will be considered.

In order to satisfy these objectives a number of research questions have been formulated:

- What trends can be observed in the historical development of total installation costs for offshore wind farms? How do these trends compare with expectation?
- Can experience curves be used to forecast the future total installation cost reduction potential for offshore wind farms? Are there limitations to the application of experience curves in the case of offshore wind?
- What are the underlying reasons for the historical trends and current total installation costs for offshore wind developments?

## 1.3 Scope and Limitations

This research project is intended to look at the development of total installation costs for offshore wind farms from a global perspective. There has been one documented offshore wind farm installed outside of Europe; a 1.2 MW, two turbine, development in Japan. Due to the relative small scale of this development combined with a lack of available information this wind farm has not been considered for the purposes of this study. This means that although the geographical scope of the project is global all data utilised are based on offshore wind farms located in European waters.

This research is primarily concerned with analysing the development of total installation costs. Total installation costs refer to the capital invested in a project starting at the scoping and design phase and finishing at the commissioning of the wind farm. The focus on total installation costs is justified by the fact that these costs often account for more than 75% of

the lifetime costs associated with an offshore wind farm (Department of Trade and Industry UK (DTI), 2006). Operating and maintenance costs have not been looked at in detail although their magnitude and opportunity for cost reduction will be briefly discussed.

Although initially quantitative in terms of tracking the development of total installation costs for offshore wind farms, the majority of the analysis made is from a qualitative perspective. Due to the privatised and highly competitive nature of the offshore wind energy sector detailed financial data relating to offshore wind farm projects is considered commercially sensitive and as a result is extremely difficult to access. As a result high level total installation costs as opposed to component costs have been utilised for the experience analysis performed for the study. The standard method for the construction of an offshore wind farm is that the production and installation of the major components is contracted. The major components are considered as the turbines, foundations and electrical connections. As a result total installation costs can be most closely related to the prices of the production and installation of the major components of an offshore wind farm.

## **1.4 Methodology**

Experience curves will be used to assess the development of total installations costs for offshore wind farms. Existing studies of experience curves for wind energy will be reviewed in order to establish a theoretical background to the study and become familiar with the total installation costs development trends that are expected to be observed. New experience curves for offshore wind turbines will be developed. The experience curve analysis will be based on independently collected and verified data. Additional and complimentary methods of analysis will be combined with the experience curve analysis; this will include consideration of the factors influencing the historical and future development of total installation costs for offshore wind farms.

The study has been performed in a number of sequential stages that can be summarised as follows:

- Intensive data collection and verification;
- Data treatment and processing;
- Data utilisation and manipulation;
- Interpretation and presentation of results; and
- Discussion of results.

In the first instance all known offshore wind farms were identified. This listing was based predominantly on available literature, the majority of which was from reliable online sources as well as some print sources; much of the information from online sources is also available in print form. Online sources included Wind Service Holland (2006), where a continuously updated listing of offshore wind developments is available, as well as other industry association sites dedicated to wind energy; the British Wind Energy Agency (BWEA) (2006), the Danish Wind Energy Association (2006) and the Global Wind Energy Council (GWEC) (2006).

Once the listing of offshore wind farms was completed a range of data was collected for each of the wind farms identified. The countries included in the study are Denmark, Sweden, the Netherlands, the United Kingdom, the Republic of Ireland, Germany, Belgium and Spain. Projects scheduled for commissioning up to 2007 have also been included. For each project a range of data were collected including the following information:

- Year of (planned) commissioning;
- Number of turbines;
- Turbine capacity (MW);
- Total wind farm capacity (MW);
- Average water depth (m);
- Average distance from shore (km); and
- Total project investment cost (in published currency).

During the data gathering phase contact was made with over 15 companies and organisations including the majority of offshore wind farm developers, the major turbine manufacturing companies and national energy agencies in a number of countries. Contact was made primarily by telephone and to a lesser extent by e-mail. The contact made with the relevant companies met with varying levels of success. Cooperation from a number of major offshore wind farm developers has led to a high level of data verification, adding to the strength of this research project. Data were also sourced from wind farm specific websites, generally hosted by the wind farm developer, as well as annual reports.

Data were collected for a total of 25 farms that were either commissioned or due to be commissioned by end-2007. For three of the farms, representing 7% of the installed capacity, total installation cost data were not available. For the 22 farms for which price data were available 66% of the wind farm total installation costs, in terms of installed capacity, were verified with the developing company through interviews and electronic correspondence. The remaining 34% of total installation costs were obtained from highly reliable sources; predominantly from a report published by the International Energy Agency (2005b), and to a lesser extent a report published by Deutsche WindGuard GmbH, Deutsche Energie-Agentur GmbH (dena) & the University of Groningen (2005).

Following the collection and verification of data, as far as possible, data treatment and processing was necessary. Due to the fact that data were gathered for a large number of reference years and currencies it was necessary to normalise the data for each wind farm to enable the comparison of results and the identification of trends. The reference year and currency were chosen to be 2005 and Euro (EUR) respectively. The choice of currency was due to the EUR being the most prevalent currency amongst the European countries. 2005 was chosen as the most recent year where reliable inflation adjustment factors were available from the International Energy Agency (IEA).

Once the data was normalised it was then possible to utilise the data to construct a range of plots that could be used to establish historic trends in the total installation cost development for offshore wind farms. The adjusted data were utilised to construct experience curves as well as more simplistic curves showing the development of total installation cost with time. Experience curve analysis was the key analytical tool utilised for this project. Once trends in

the data could be identified this led to the stage where the results were interpreted and presented.

Literature review was also used for the interpretation, analysis and discussion of results. Junginger (2005b) dedicates a section of his PhD Thesis: 'Learning in Renewable Energy Technology Development' to the topic of cost reductions prospects for offshore wind farms. Based on this and additional research, Junginger et al. (2005), have also published a summary paper considering the cost reduction prospects for offshore wind farms. Otherwise prior research dedicated to investigating the cost reduction potential for offshore wind farms is somewhat limited. Both the publications mentioned have been reviewed in detail for the purposes of this thesis project. Due to the small number of publications that exist, comparable research for the onshore wind energy sector has also been utilised as a basis for comparison.

To complement prior research available in print and online forms interviews were also heavily relied upon for the analysis and discussion of results. Both personal and telephone interviews were conducted with a number of highly respected industry professionals from a number of high profile companies including: Elsam, Nuon, E2 and Siemens Wind Power. A large amount of extremely valuable information and insight was sourced from the interview process.

## **1.5 Structure of the thesis**

Chapter 1 introduces the study by providing details of the background and problem description. The objective of the study is also defined along with the scope and limitations of the research. The methodology followed to carry out this project is also detailed.

Following on from this Chapter 2 provides details of the historical and expected development regarding offshore wind farms.

The aim of Chapter 3 is to introduce the experience curve methodology. The next step is to determine the results that are expected from the experience curve analysis for the development of total installation costs for offshore wind farms. This is done by considering a number of studies of particular relevance. The studies considered use experience curve analysis to study the development of onshore wind installations from both national and global perspective and offshore wind farm development from a global perspective. Through the summary of these prior studies a theoretical basis for the expected results is established.

Experience curves for the development of total installation costs for offshore wind farms are constructed in Chapter 4. This chapter explains the construction of the experience curve in terms of data collection and verification, data treatment and processing through to the development of the experience curve. Finally the results of the experience curve analysis are detailed and compared with the expected results as determined in Chapter 3.

The main findings of this study are detailed in Chapter 5 where the results of the study are considered and discussed. The discussion begins by comparing the actual results to those that were expected, then moves on to discuss aspects relating to experience curve analysis and the use of price data. Following this the differences between the actual and expected results are analysed in terms of the factors influencing the total installation cost development for offshore wind farms. Finally, this chapter considers the factors influencing the expected development of the production and installation costs relating to offshore wind farms.

Chapter 6 and Chapter 7 conclude the report by providing concluding remarks and recommendations for future work.

## 2. Offshore wind energy development

In 1990 the first offshore wind turbine was commissioned at Nogersund, Sweden. Subsequently in 1991 the first offshore wind farm, Vindeby, was commissioned in Danish waters. Since that time offshore wind energy has experienced a phase of rapid growth, particularly from 2000 onwards, as depicted in Figure 2-1. As can also be seen in Figure 2-1 the installation of offshore wind farms has been predominantly in Europe. This is with the exception of a wind farm installed in Japan in 2004; the capacity of this wind farm is only 1.2 MW and has not been included in Figure 2-1.

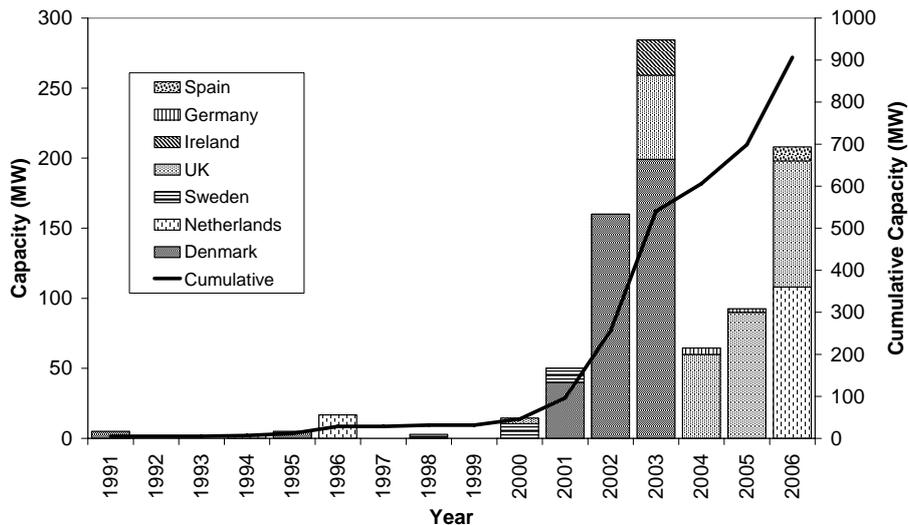


Figure 2-1: Global Offshore Wind Capacity (Wind Service Holland, 2006; updated with data from: NordseeWind, 2006)

Westwood (2005a) gives an indication on the likely potential growth of the industry. The expected development of the offshore wind power sector from 2005 – 2009 was forecast to be 7.7 GW of installed capacity; a ten fold increase based on the cumulative capacity installed as at 2005. Total planned expenditure for the period was approximately 10.4 billion EUR<sup>2</sup>. The currently planned projects, as at 2005, are summarised by Westwood (2005a), as follows:

- 2005: UK – 180 MW, Netherlands – 120 MW and Germany – 4 MW (demonstration unit);
- 2006: 747 MW from predominantly the UK as well as Germany and Belgium;
- 2007: 1.8 GW including 125 MW in Sweden, the first US project Cape Wind is expected online with capacity in the UK, Germany and Belgium being forecast to increase;
- 2008 – 2009: Leaders will continue to install additional capacity with significant projects in Denmark due to come online and Finland and Spain enter the sector with new developments;

<sup>2</sup> Using an exchange rate of USD 1 = EUR 0.78

- 2005 – 2009: The forecast installed capacity for this period by region is: UK 33%, Germany 23%, Denmark 5% (compared to its current share of 69% of all offshore capacity), Europe (rest of) 20%, North America 17% and Asia 2%.

Further to this, a report by Jones and Westwood (2005) stated that in terms of global investment in renewable energy, offshore wind energy is the fastest growing sector. In general wind energy is one of the fastest growing energy sectors in the world; since 1990 its average annual growth rate has been more than 26% (GWEC, 2005). In 2005 the total installed wind power capacity worldwide was estimated to be 59 084 MW, an increase of 24% compared to 2004 levels. The top six countries with the highest installed wind power capacities as at 2005 are detailed in Table 2-1.

Table 2-1: *Wind power capacities of the countries with the highest installed wind power capacities (GWEC, 2005)*

Country	Germany	Spain	USA	India	Denmark	Italy
Capacity (MW)	18 428	10 027	9 149	4 430	3 122	1 717

The benefits of wind energy are many and varied, similar to other renewable energy sources, and can be summarised as follows. Wind as a resource can often be sourced locally at no cost, and has the potential to increase energy security through the diversification of energy supply. Due to the fact that wind power does not generate CO<sub>2</sub> emissions (other than during the fabrication and installation phase) it has the potential to mitigate accelerated climate change. It also has the ability to improve electricity access in remote and rural areas, in some cases combating poverty. Wind power can also deliver power on a large scale while at the same time being modular in design.

Offshore wind energy has significant potential for generating large quantities of electricity. The potential for onshore wind energy has been estimated as being between 20 000 and 50 000 TWh/yr; with offshore wind power the potential is expected to be far in excess of these figures (Turkenburg et. al., 2000). As detailed in Table 2-1, at the end of 2005 the global energy generating capacity for wind energy stood at over 59 GW (GWEC, 2005); capable of generating 120 TWh annually at typical load factors (BP, 2006). Consequently wind as an energy resource remains largely unexploited and it is predicted that by 2020 wind energy could supply 12% of electricity world wide (GWEC, 2005).

Although the onshore wind energy industry is still in a period of rapid growth there are a number of reasons that make the installation of offshore wind farms attractive, particularly in Europe:

- In Europe population density is very high; this leads to a situation where land is often considered to be too valuable to locate a wind farm on. As a result sites for onshore wind farms are scarce; as population grows and more onshore wind farms are constructed this situation will only be exacerbated. Comparatively most European countries have large areas available for the development of offshore wind farms. An example of this is that for the Netherlands it is estimated that potential exists for the installation of up to 60 GW of offshore wind power compared with only 3 GW onshore (Junginger, 2005b).

- Average wind speeds for onshore locations are affected by the surrounding terrain e.g. topography, vegetation and buildings. As a result there are a limited number of sites where a wind farm can be located and have favourable economics on land. Due to the lack of obstacles at sea the average wind speeds are higher and the wind patterns are more uniform than on land, this can result in increases in the efficiency of turbine where the electricity output from a single turbine can be as much as 50% more than an onshore wind turbine of equivalent capacity (Junginger, 2005b). As can be seen in Figure 2-2, in Europe the greatest potential for offshore wind farms exists in northern Europe where the development of offshore wind farms sector has been focussed.

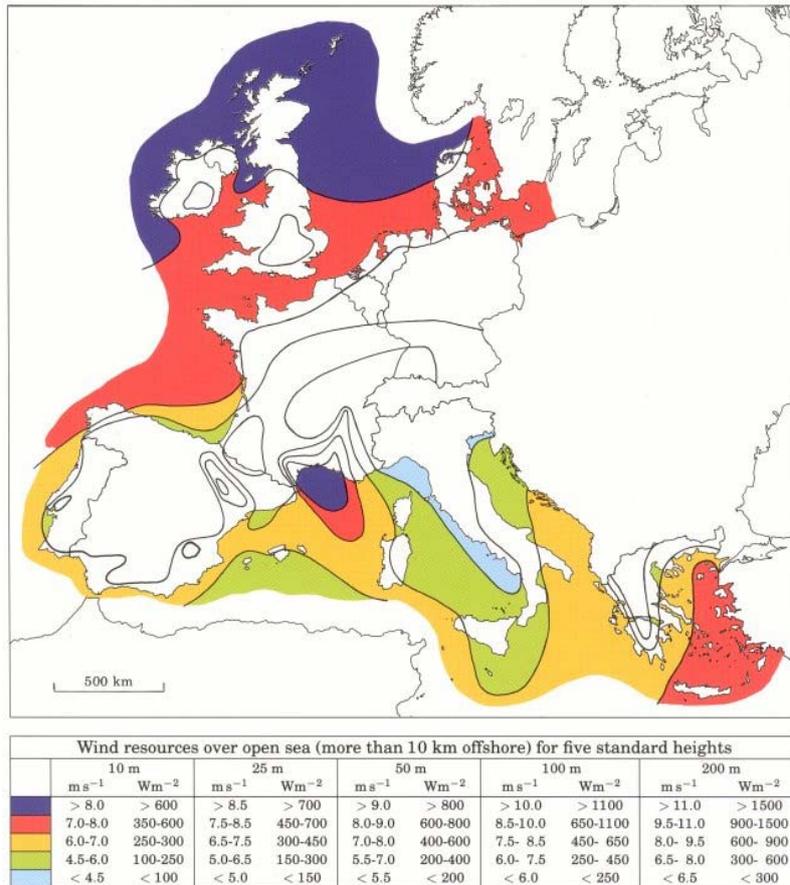


Figure 2-2: Wind resources over the open sea in Europe (Wind Atlas, 2004)

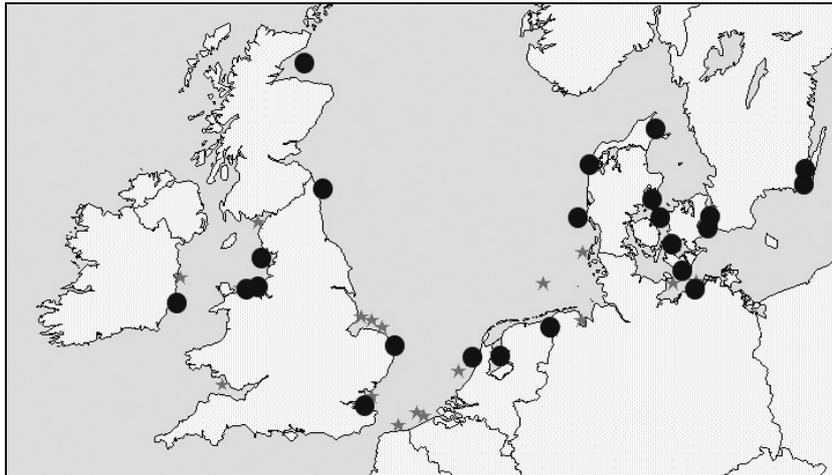


Figure 2-3: Map of existing and planned wind farms in Europe (black circles = actual wind farms, grey stars = planned wind farms) (Offshore Windenergy Europe, 2006)

The location of wind farms that have been commissioned, are in construction phase or are planned to be developed are indicated in Figure 2-3. In addition to this a wind farm with an installed capacity of 10 MW has also been installed to the north of Spain where further projects are also planned.

- Offshore wind turbines can also be located at a sufficient distance from shore so that noise and visual pollution are much less of an issue than for onshore installation. This makes it possible for the capacity of offshore wind turbines and consequently farms to be of comparatively larger scale than those located onshore. The development of a great number of onshore developments has been met with strong opposition from surrounding residents due to the anticipated visual and noise pollution associated with the projects; this has been a major reason for the cancellation of projects and can be the cause of considerable expense for the wind farm developer.

Currently the most significant downside for offshore wind power is that the investment and operating costs are considerably higher than for onshore developments. To give an indication the total investment costs for an onshore wind farm and an offshore wind farm are 800-1100 EUR/kW (Junginger, 2005b) and 1600-2600 EUR/kW (Westwood, 2006) respectively. This difference in cost is mainly due to the fact that offshore wind turbines are more complicated to build and anchor than onshore. Maintenance costs can also be more significant due to both accessibility and the harsher conditions of the open ocean including corrosion.

It is important to highlight that the higher costs for offshore wind farms can be somewhat offset by the higher efficiency of offshore wind turbines compared to onshore wind turbines. An offshore wind turbine has the potential to produce up to 50% more electricity compared to a wind turbine of equivalent capacity located onshore (Junginger, 2005b). As a result the lifetime costs for an offshore wind farm could potentially be up to 50% more than an onshore wind farm of equivalent capacity while still producing electricity at the same unit cost.

The offshore wind energy sector could still be considered in its infancy in terms of total installed capacity, number of individual projects and number of competitors. As shown in Figure 2-1 the installed capacity of offshore wind farms in 2005 was approximately as 0.7 GW; just over 1% of the total global capacity for wind power generation of approximately 59 GW (GWEC, 2005).

Due to the method of capturing energy from wind using turbines, the resulting useable energy is typically in the form of electricity. As a result the cost for wind energy competes primarily with other sources of primary energy used for the production of electricity. Currently the cost of offshore wind power generation is comparatively higher than onshore, which is in turn comparatively higher than fossil fuel generated power. The continued development of offshore wind farms is therefore dependent on the cost reductions; this issue will continue to be discussed in the following sections.

### 3. Cost reduction of wind power as described by experience curves

#### 3.1 General introduction to experience curves

One method of predicting the cost reduction potential associated with a new technology is through the use of experience curve analysis. This method of analysis has been widely applied over the last several decades and builds on the learning curve approach. Learning curves, originally applied to manufacturing operations, have been used to illustrate the unit cost reductions that occur as experience grows; a concept referred to as ‘learning-by-doing’. Learning curves are used to assess the cost reduction potential relating to the production of a standardised product produced by an individual company. In addition to this, experience curves can also be applied in a similar fashion to non-standardised products at a global and national as well as individual company scale. Both the capital investment and operating phases of technologies can be captured both separately and in a variety of combinations using experience curve methodology. Learning curves and experience curves can be used to both map historical data and forecast the future potential of a given technology. A basic overview of experience curves and their typical application is presented in this section.

The very name ‘experience curve’ implies that experience is the underlying driver for cost reductions for a new technology. Experience will not automatically manifest itself in the form of cost reduction but rather provides the means of identifying cost reduction opportunities. It follows that as experience grows so do the opportunities for cost reductions. The role of experience opens a pathway between the output and input of a learning system, a feedback loop, as depicted in Figure 3-1. The experience curve provides a means of modelling the efficiency of this interaction.

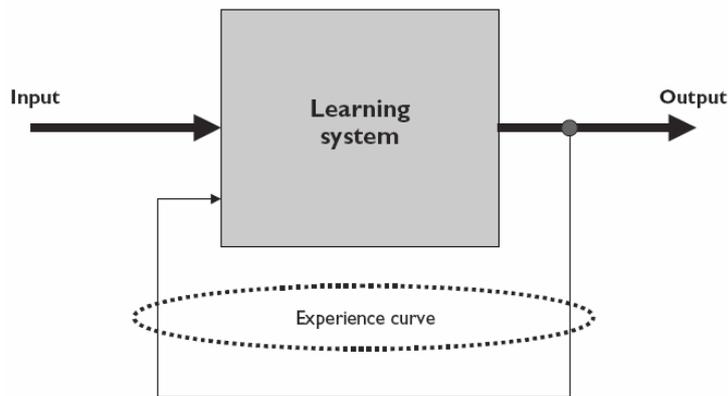


Figure 3-1: Basic model for a learning system (IEA, 2000, p.27)

Experience curves have often been employed to map the historical cost developments of renewable energy technologies including wind and solar power. These historical trends are then extrapolated to provide an indication of the potential further cost reductions that may occur for a given renewable energy technology. This information can then be used to provide an indication of the most appropriate renewable energy technologies to develop and what form future energy supply scenarios may take.

Experience curves have been widely used to estimate the cost reduction potential for a variety of renewable energy technologies; examples of this include combined cycle gas turbines (Claeson Colpier & Cornland, 2002) and ethanol production (Goldemberg, 1996). Extensive work has also been conducted analysing the development of wind energy technology experience curves have been developed for a number of countries including Denmark (Neij, 1999), Germany (Durstewitz & Hoppe-Kilpper, 1999), the USA (Mackay & Probert, 1998) and other countries (Ibenholt, 2002; Klaassen et al., 2005). The accurate representation of the development of a technology is highly dependent on the quality of the data that is used. This will be further explored in Section 5 based on the case of offshore wind farms.

In order to accurately represent the progression of a technology experience curves must be based on cost data as opposed to price data. Although price data can be utilised it will only provide an accurate picture if the price/cost margin is constant over time. In a competitive market cost data are often classified as commercially sensitive and as a result is extremely difficult to access. Consequently experience curves are often constructed based on price data due to the accessibility of information. In the case of an offshore wind farm developer utilising multiple manufacturers and contractors the potential for the price cost/margin to fluctuate are compounded. In a market where the price of the end-good is particularly buoyant a situation will arise where companies at all levels of the supply chain will artificially inflate their prices, this phenomena is observed in the oil and gas industry where as the price of oil increases so to do the prices of goods and services provided to the industry, increases in the price of steel causes a similar affect; it is also often true that once prices go up they rarely come back down even as the commodity price, e.g. oil or steel, decreases. For example turbine manufacturers with the same goal of maximising profits will adjust the price/cost margin to ensure the cost savings made due to increased experience will only be partially passed on to the wind farm developer.

It is a fact that for many products and services the unit cost decreases with increasing experience. An accepted method for the modelling of this behaviour is through the use of experience curve analysis; a curve used to show the empirical relationship between costs and accumulated production or capacity. A characteristic of experience curves is that in general unit costs decrease by a constant percentage, for each doubling of cumulative production. The constant percentage decrease for each doubling of cumulative production is quantified using a progress ratio (PR); this term will be explained in further detail. The use of experience curves for the analysis of energy technologies is becoming more frequent.

The costs for a given technology that can be represented using experience curves include: capital investments and operating costs (labour and administrative costs) as well as research and development expenditure. Cost reductions for an energy technology are generally achieved through both production changes (process innovation, learning effects and economies of scale) and product changes (product innovation, redesign and standardisation) (Neij, 1999).

The basic equations relating to experience curve analysis, as presented by (Neij, 1999), can be expressed as:

$$C_{Cum} = C_0 Cum^b \quad (1)$$

$$\log C_{Cum} = \log C_0 + b \log Cum \quad (2)$$

$$PR = 2^b \quad (3)$$

$$LR = 1 - PR = 1 - 2^b \quad (4)$$

where:  $C_{Cum}$  = unit cost  $C_0$  = cost of first unit produced  
 $Cum$  = cumulative (unit) production  $b$  = experience index  
 $PR$  = progress ratio  $LR$  = learning ratio

A unit can be defined in a number of ways, in manufacturing a unit can simply be defined in terms of a physical unit e.g. a motorbike or a mobile phone. When discussing energy technologies it is more common for a unit to be defined in terms of energy capacity e.g. kW or MW; this is how a unit will be defined for the purposes of this study. The progress ratio (PR) represents the rate at which costs decline in relation to each doubling of cumulative capacity or experience. In comparison the learning rate (LR) expresses the rate of cost decrease with each doubling of experience; if PR=90% (0.9) then LR=10% (0.1), this translates to a 10% cost decrease for each doubling of experience. As a result as PR increases the rate of cost reduction decreases where as LR increases (and PR decreases) the rate of cost reduction increases. Due to this relationship it is often more straightforward to consider the LR rather than the PR; although PR is a term more commonly used in literature.

Typically experience curves are depicted in one of two ways, linearly or double-logarithmically as shown in Figure 3-2 and Figure 3-3 respectively. Some basic reasons behind the choice of representation can be: *linearly* – emphasises the rapid advancements that can be achieved in the early stages of the development of an energy technology, focussing to a lesser extent on the long-term prospects; and *double-logarithmically* – enables comparisons between different technologies and more simple calculation of learning rates and progress ratios (both calculated based on the gradient of the line) and their level of fit, this representation also emphasises the more long-range characteristic of progress that can otherwise be overshadowed. The double-logarithmic representation of the experience curve has been the most commonly utilised form.

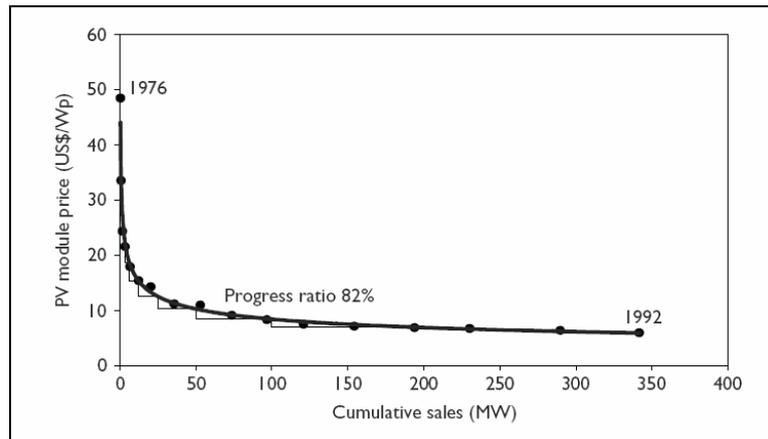


Figure 3-2: Linear representation of an experience curve for photovoltaic (PV) modules (IEA, 2000, p. 109)

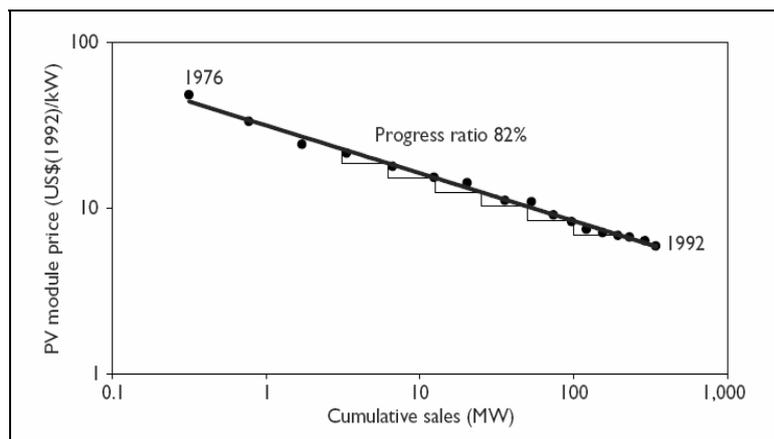


Figure 3-3: Double-logarithmic representation of an experience curve for photovoltaic (PV) modules (IEA, 2000, p. 109)

These curves show that as cumulative production/sales increase the cost per unit decreases. It can also be inferred that high initial investment are often necessary to initiate the progress of technology. Coupled with this the ability to predict the long-term costs of a particular technology can assist policy makers in choosing which technologies to encourage and provide with sufficient incentive to ensure their continued development.

### 3.2 Cost Development for Onshore Wind Energy – national studies

In terms of its comparability to other energy technologies, offshore wind farm technology is thought to be most comparable to onshore wind farm technology. A number of authors have considered the cost development for wind turbines where the trends observed show an exceptional fit to those expected. National studies utilising experience curve analysis to track the development of onshore wind include:

- Neij, (1997): Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology.
- Durstewitz and Hoppe-Kilpper. (1999): Wind Energy Experience Curve from the German "250 MW Wind"-Programme.
- Neij, Andersen, Durstewitz, Helby, Hoppe-Kilpper and Morthorst. (2003): 'Experience Curves: A Tool for Energy Policy Assessment.

These studies have been selected as being representative of typical result for the cost development of onshore wind farms. Additionally these case studies are based in Europe (Denmark, Germany, Spain and Sweden) similar to the vast majority of offshore wind farms. The findings of these studies, with emphasis on the cost development trends observed and the reasons behind such trends will be summarised in this section. This will be followed by a discussion of the comparability of the onshore and offshore wind energy industries in terms of cost development.

In an article published in 1997, Neij looks at the development of onshore wind turbines in Denmark from 1982 until 1995. The data used for Neij's analysis is based on turbine list prices sourced from the four biggest turbine manufacturers in Denmark; whom at the time accounted for 42% of the cumulative sales of wind turbines worldwide and over 80% of cumulative sales in Denmark. The results of this study showed that for turbines produced by Danish manufacturers, 55 kW and larger, the PR derived from experience curve analysis was 96%, see Figure 3-4. This PR corresponds to an LR of 4% indicating that the price per kW or turbine capacity is reduced by 4% with each doubling of cumulative sales ("experience").

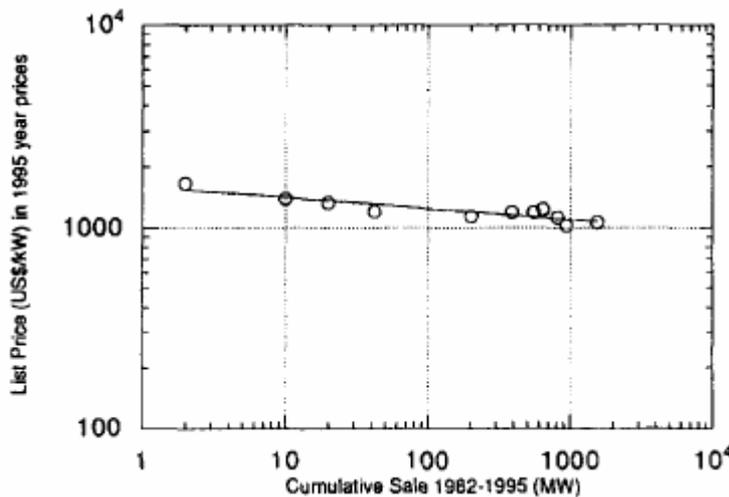


Figure 3-4: Experience curve for wind turbines produced in Denmark (1982 - 1995) (Neij, 1997)

Neij (1997) states that the cost reductions observed can be attributed to a continuous chain of incremental improvements rather than radical shifts to new designs. The main reasons for the improvements can be summarised as follows:

- The gradual scaling up of individual turbine capacity from 55 kW in the early 1980's up to 500 – 800 kW in 1985; and

- In order to achieve increases in capacity the rotor diameter has been increased while at the same time the weight per installed kW has been reduced saving both materials and costs.

Other sources of cost reduction are associated with electricity production and hence cannot be observed in Figure 3-4. These include:

- Increased efficiency of wind farms;
- Decreased down time and hence increased availability of turbines; and
- Improved location of wind farms through better assessment of wind resources.

In fact an experience curve constructed by Neij (1997) for the cost of wind-generated electricity from Danish wind turbines indicated a PR of 91%, a notably higher rate than that observed for the price of wind turbines.

Durstewitz and Hoppe-Kilpper (1999) studied the development of onshore wind turbines in Germany. The first onshore wind turbine installed in Germany and registered with the ISET was a 20 kW unit installed in 1982. By 1999 the installed capacity of onshore wind turbines had increased to 2855 MW; representing 17 doublings of capacity since the first registered installation. The associated prices for the wind turbines could only be tracked back as far as 1990 when there was 18 MW of total installed capacity.

For this study price data were gathered for 91% of the installed turbines representing 94% of the installed capacity. The data sources utilised were the ISET database together with officially available price lists; additionally the data was found to correlate well with manufacturer's invoice prices. The experience curve constructed using the described data is presented in Figure 3-5.

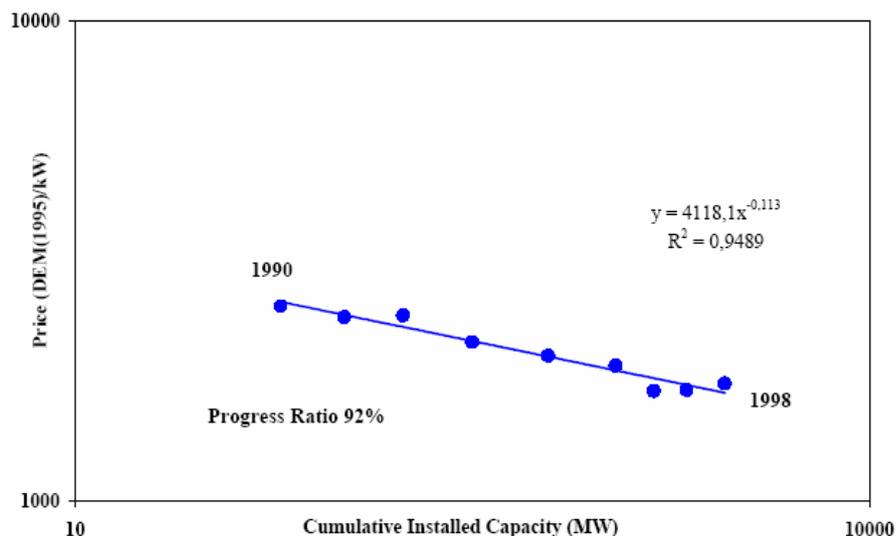


Figure 3-5: Experience curve for wind turbines in Germany (1990-1998) (Durstewitz & Hoppe-Kilpper, 1999)

This curve shows that with  $R^2=0.95^3$ , indicating a good level of fit, the PR for onshore wind turbines in Germany between 1990 and 1998 was estimated to be 92%. A PR of 92% is equal to a LR of 8% meaning that for each doubling of experience there was an 8% decrease in price. The results of this study are comparable to those of Neij (1997) for onshore wind turbines in Denmark.

A further study relating to the development of onshore wind energy was published by Neij, Andersen, Durstewitz, Helby, Hoppe-Kilpper and Morthorst (2003). This study considered the cost development for wind turbines in Denmark, Germany, Spain and Sweden. The data collected and the data sources can be summarised as follows:

- *Denmark:* Data were collected for 3226 turbines out of a total 6427 turbines. In terms of manufacturer the data collected represented 81% of all turbines installed in Denmark. Data for turbines made by small manufacturers, turbines sold in small quantities and unavailable or unreliable data were excluded from the study. There were two main sources of data: 1. Energi- og Miljødata (EMD), Denmark; and 2. Risø National Laboratory. Additional data from the mid-1980s up to the late-1990's was sourced from the Danish Technological Institute (DTI). Up until 2001 the EMD collected data on behalf of the Danish Turbine Owners Association with financial support from the Danish Energy Agency.

The data used have been reviewed by experts and have also been cross checked where multiple sources exist.

- *Germany:* For the German case study data from several existing databases together with additional published prices were verified and collated into a single database. The data collected were for wind turbines produced or installed in Germany from 1983 to 2000. Data was gathered for 5246 manufactured turbines and 9228 installed turbines. Turbine price data before 1988 were not available. Prices were able to be allocated to about 94% of the installed turbines in terms of both number and installed capacity.

Limitations regarding the data and method of data collection are stated to include:

- Prices are valid for single turbines and do not reflect discounts given for larger orders; some wind farms contain up to 50 turbines;
  - Installation and commissioning years may differ from the contracting year. This can lead to variances in cost that are not accounted for; and
  - The components of transport, installation and transformer are assumed to be included in the prices although this may not be the case.
- *Spain:* Total installation cost data as well as technical data were collected for Spanish manufacturers from 1984 to 2000. Data were mainly sourced from IDEA, a state-financed institute in Spain aimed at the promotion of renewable energy. Data covering 84% of the installed capacity were collected.

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<sup>3</sup>  $R^2$  is commonly referred to as the correlation coefficient. It is a statistical term that provides an indication of the level of fit of a trendline to a data set.  $R^2$  is always in the range of 0 to 1 where the highest level of fit is where  $R^2=1$ .

- *Sweden*: Data from 1994 to 2000 for Swedish onshore wind turbine installations were provided by the Swedish Government; this included both installation cost and technical specification data. Data prior to 1994 was unavailable. In terms of installed capacity data were gathered for approximately 91% of onshore wind turbines in Sweden.

Based on the data collected country specific experience curves based on cumulative installed turbine capacity as a measure of experience could be constructed as follows:

- Denmark & Germany- Price of installed wind turbines;
- Denmark, Spain & Sweden – Total installation cost for turbines; and
- Denmark and Germany – Specific production cost of electricity.

When utilised for experience curve analysis all data sets indicated showed good correlation to the expected trends. The results of the analysis in terms of PRs and LR are summarised in Table 3-1.

Table 3-1: *Wind turbine experience curve parameters: Denmark, Germany, Spain and Sweden (Neij et al., 2003)*

Country	Period	PR (%)	LR (%)	R <sup>2</sup>
<u>Price of wind turbines</u>				
<i>Denmark</i>	1981-2000	91	9	0.94
<i>Germany</i>	1987-2000	94	6	0.88
<u>Total turbine investment cost including installation</u>				
<i>Denmark</i>	1981-2000	90	10	0.92
<i>Spain</i>	1984-2000	91	9	0.85
<i>Sweden</i>	1994-2000	96	4	0.92
<u>Production cost of electricity</u>				
<i>Denmark</i>	1981-2000	83	17	0.97

Figure 3-6 and Figure 3-7 present the experience curves for price of wind turbines and total turbine installation cost respectively relating to Denmark. Denmark was the only country where the two data sets mentioned were available. In the Danish case the data pattern observed for both the price of wind turbines compared to the total installation cost for wind turbines installed in Denmark is almost identical; all turbines installed in Denmark were sourced from Danish manufacturers. The difference between the data sets is the cost of installing the turbines; the difference is small and looks to be a constant increment. The magnitude of the difference between the two experience curves indicates two things. Firstly that for onshore wind farms in Denmark the total installation cost tracks at constant increment above the turbine price, indicating that the cost for installing turbines is relatively constant and stable over time. Secondly the fact that the increment between the total

installation cost of turbines and the price of turbines is small indicates that the total installation cost for wind turbines is dominated by the turbine price.

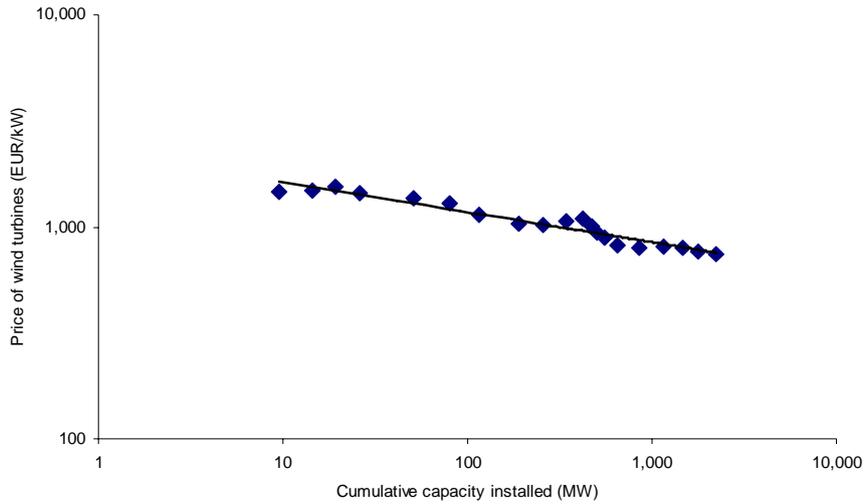


Figure 3-6: Experience curve for wind turbines produced by Danish manufacturers, 1981-2000 (PR=91%;  $R^2=0.94$ ). Prices are expressed in 2000 year prices. (Neij et al., 2003, p29)

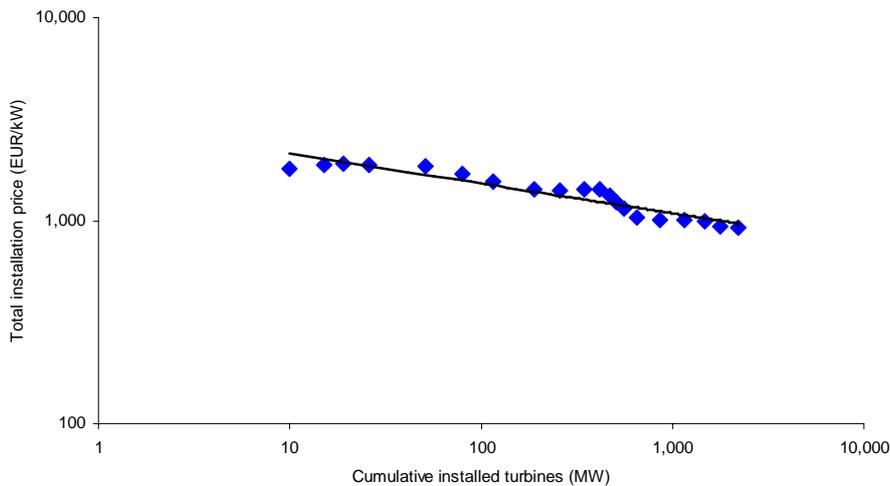


Figure 3-7: Experience curve for the total installation cost for wind turbines installed in Denmark, 1981-2000 (PR=90%,  $R^2=0.92$ ). Costs are expressed in 2000 year prices. (Neij et al., 2003, p30)

Perhaps an even more significant finding of the study by Neij et al. (2003) was the reduction potential calculated for the production cost of electricity from onshore wind farms in Denmark, a PR of 83%. The production cost for electricity encompasses the total installation costs together with operating and maintenance expenses spread over the total electricity produced over the life of the wind farm; generally assumed to be 20 years. This shows that the potential for improved efficiency together with operating and maintenance cost reduction is highly significant. In the case of onshore wind farms this result indicates that cost savings

relating to operations and maintenance as well as increased efficiency are more significant than the potential to reduce total installation costs.

### 3.3 Cost Development for Onshore Wind Energy – global studies

In Junginger's PhD Thesis (2005a), 'Learning in Renewable Energy Technology Development' – Chapter 3, an attempt is made to set up global experience curves for turnkey investment costs (referred to total installation costs in this study) for onshore wind farms worldwide. Extensive literature searches have found Junginger's (2005a) study to be the only attempt to construct global experience curves for onshore wind farms. The author considered setting up a number of different types of global experience curves relating to onshore wind energy, these included: individual wind turbine costs, wind farm costs and produced electricity costs. It was determined that there was only enough information to set up experience curves based on turnkey investment costs for individual wind farm projects using cumulative capacity as the measure of experience.

Junginger chose to base his study on data from the United Kingdom and Spain. This was both due to the availability of data as well as the perceived ability of the data to reflect global trends. The access to wind resources in both the UK and Spain is believed to remain stable due to the availability of windy sites. This is in contrast to both Denmark and Germany where it was stated that the availability of windy sites has substantially diminished over time; it was thought that in these countries that investment cost data may be affected by such factors as increasing hub height in order to access suitable wind resources. The experience curve resulting from the investigation is presented in Figure 3-8.

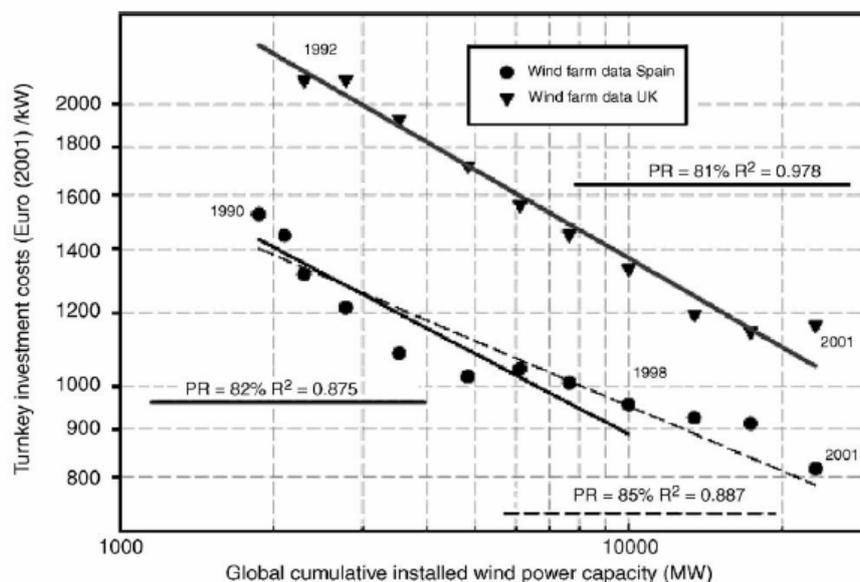


Figure 3-8: Global experience curves for onshore wind farms, using data for wind farms located in the UK and Spain. (Junginger, 2005a, p. 66)

These results show two distinct sets of data, one for the UK and one for Spain, with no observable overlap. As indicated the PR for the UK data is 81% compared to 85% for Spain. In the Spanish case it is mentioned that data post-1998 could be influenced by policy

measures, as a result a second PR of 82% was determined. Taking this into account the PRs for both the UK and Spain are highly comparable.

The distribution of average turnkey investment costs for onshore wind farm installations in Spain and the UK are summarised in Figure 3-9

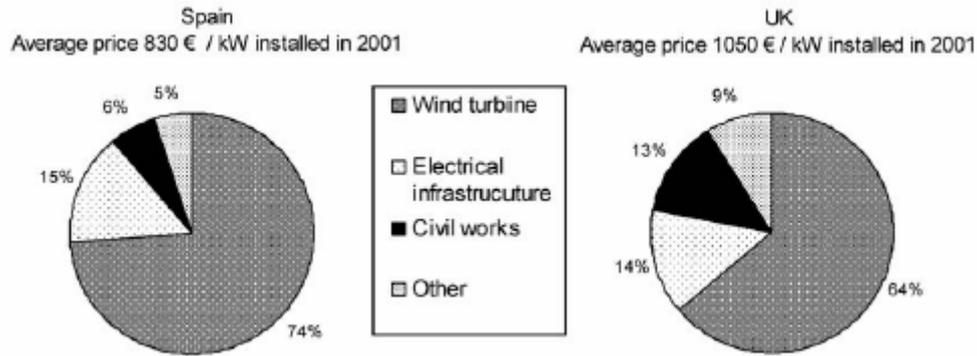


Figure 3-9: Average distribution of turnkey investment prices for Spanish and British onshore wind farms based on average wind farm sizes: UK – 5 MW and Spain – 20 MW. (Junginger, 2005a)

The incremental difference between the two data sets has been attributed to a number of reasons:

- There is a substantial difference between the average size of wind farms when comparing Spain to the UK, 20 MW and 5 MW respectively. Larger wind farms often have lower specific costs;
- Although the market for wind turbines is a global one it may be the case that cost components such as grid connection and civil work may be more dependent on local learning. This may explain the comparatively higher costs for wind turbines and other costs for the UK compared to Spain as detailed in Figure 3-9; and
- As the UK is a more densely populated area it is likely that suitable sites for the location of wind farms are more scarce and that the necessary permits are more difficult to obtain. This could explain the fact that civil work and other costs (e.g. project management and legal costs) make up a greater share of the total investment costs when compared to the Spanish case.

An additional reason for the differences, proposed by Neij (2006), is that the difference in cost is due to the use of different types of turbines in the UK compared to Spain.

In order to consider how the development of offshore wind farms may relate to the observed development of onshore wind farms it is important to have an understanding of the differences and similarities between the two. In terms of total installation costs a wind farm can be considered as consisting of the production and installation of three main components, namely turbines, foundations and electrical infrastructure.

The first turbines installed offshore were basically modified onshore turbines; this has been the starting point for the development of offshore wind turbines. Based on this it could be

assumed that the development of offshore wind turbines will be comparable to the development of onshore wind turbines. Although it is also the case that the first wind turbines installed offshore were already at an advanced stage of development compared to the first wind turbines installed onshore. This is due to the long-term development of wind turbines for the onshore industry. The basic wind turbine technology utilised for both onshore and offshore wind farms is the same and this is not likely to change. The cost of wind turbines is likely to reduce through the production of higher capacity turbines and also through economies of scale. More significant perhaps will be improvements in efficiency and availability, factors that affect electricity production costs. Based on these factors the cost reductions for offshore wind turbines will likely occur at a slower rate than for onshore wind turbines.

Foundations for onshore wind farms are completely different from those required for offshore wind farms. Similar to onshore foundations, foundations at sea utilise existing technology and expertise. As a result the development of foundations costs may be comparable to that observed onshore. Finally electrical infrastructure for offshore wind farms is again quite different from onshore wind farms as a result the costs of this component for onshore wind farms and offshore wind farms is difficult to compare.

Due to the fact that turbine costs dominate the total installation costs for both onshore and offshore wind farms is expected that the reductions of total installation costs for offshore wind farms are most likely to occur at a slower rate than that observed for onshore wind farms. However the development of electricity production costs for offshore wind farms could be equally significant to that of onshore wind farms as discussed by Neij et al. (2003); or perhaps of even greater significance.

### **3.4 Cost Development for off-shore wind energy**

There have been a number of studies carried out to date considering the development of the offshore wind industry. Some studies have considered the potential development of offshore wind farms in terms of capacity and location; see Beurskens 2003; BWEA, 1995; BWEA, 2006; and Delft University of Technology, 2001. The majority of the studies to date have been based on the proposed plans of individual countries rather than the cost development associated with offshore wind energy projects. Technical aspects and challenges and their potential to produce cost reductions have been explored to some extent; see Kooijman et al., 2003; Delft University of Technology, 2001.

Based on an extensive literature search the cost development associated with offshore wind deployment, 'learning-by-doing', has been considered in a limited number of studies. Lako (2002) considered the cost reduction potential associated with near shore and offshore wind farms up until 2030. The next notable study building on Lako's finding was that by Junginger et al. (2004) and later published by Junginger (2005b) as part of a PhD Thesis report that uses a bottom-up type analysis to explore the cost reduction potential for offshore wind energy up until 2020. The results of Lako's analysis will be presented briefly while the findings presented by Junginger (2005b) will be explored to somewhat greater detail.

Lako's (2002) analysis was based on data for a cumulative installed capacity of approximately 1200 MW. In Lako's work a distinction is made between near-shore and offshore wind farms with the analysis for near-shore wind farms representing only 150 MW of the installed capacity considered by the study. The data presented clearly shows a decrease in investment

costs (referred to as total installation costs in this study). The PRs and forecast investment costs determined by the study are summarised in Table 3-2.

Table 3-2: Progress ratios and specific investment cost forecast for near-shore and offshore wind farms according to Lako (2002)

Wind farm type	PR (%)*	Forecast specific investment cost for 2030 (EUR/kW)
Near-shore	92.5 – 97.5	755 - 885
Offshore	92.5 – 97.5	970 – 1140

\*Different PRs were used for turbines, construction, and cabling and grid connection. The same set of PRs were used for both near-shore and offshore cost forecasting.

Junginger (2005b) begins by presenting a graphical representation of turnkey or specific investment costs against time as displayed in Figure 3-10. This representation of data shows with reasonable clarity that the turnkey investment costs for offshore wind installations are decreasing over time.

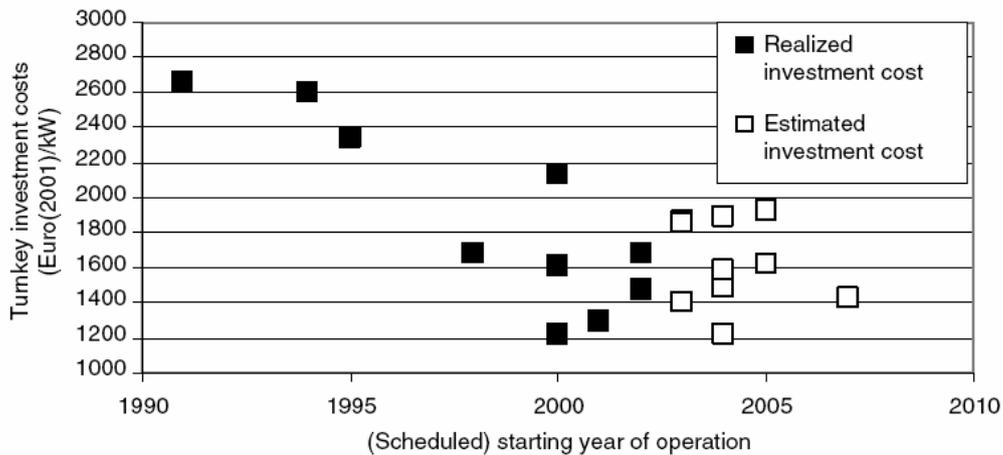


Figure 3-10: Development of turnkey investment costs of realised and planned offshore wind farms (Junginger, 2005, p. 74)

Based on the assumption that turnkey investment costs are decreasing Junginger (2005b) continues by carrying out a bottom-up analysis of the turnkey investment costs. This is done by disaggregating the turnkey investment costs into a number of major components. These components and the factors behind their cost reductions, as presented by Junginger, are summarised in Table 3-3.

Table 3-3: Overview of the relevant factors behind cost reduction for offshore wind farms (Junginger, 2005b, p. 85)<sup>4</sup>

	<b>Specific offshore wind developments</b>	<b>Exogenous developments</b>
Wind turbine	Upscaling Improved design Standardization Economies of scale	Further development of onshore turbines Steel price
Grid connection	Standardizing the design of HVDC cables Applicability of XLPE insulation to HVDC cables Advances in valve technology and power electronics	Further development and diffusion of submarine HVDC interconnectors
Foundations	Standardization Economies of scale Design regarding dynamic loads	Steel prices
Installation	Learning-by-doing Development and structural purpose-built ships Standardization of turbines and equipment	(Oil prices)

Building on this information a base case wind farm is used in conjunction with two cost reduction scenarios: sustained diffusion and stagnant growth. ‘Sustained diffusion’ utilises the high rates of diffusion observed for onshore wind energy, a 2%/year reduction in steel prices and a high growth rate for High Voltage Direct Current (HVDC) utilisation whereas for the ‘Stagnant growth’ scenario the parameters utilised are more conservative; a summary of the parameters utilised is given in Table 3-4.

Table 3-4: Summary of quantitative cost reduction scenario parameters (Junginger, 2005b, p.86)

	<b>Sustained diffusion</b>	<b>Stagnant growth</b>
Wind turbine	Annual growth rates of onshore wind and offshore wind capacity declining from 27% in 2003 to 15% in 2020 PR of 81%	Annual growth rates of onshore wind and offshore wind capacity declining from 27% in 203 to 10% in 2020 PR of 85%
Foundations	Cost of steel reduction 2% per year	Cost of steel reduction 1% per year
Grid-connection	High growth rates of HVDC converter stations and submarine cables PRs of 62 & 71%	Moderate growth rates of HVDC converter stations and submarine cables PRs of 62 & 71%
Installation	PRs of 77% (turbine erection) and 95% (other)	PRs of 77% (turbine erection) and 95% (other)

Based on this methodology experience curves are developed for the major components associated with an offshore wind farm as detailed in Table 3-3. The separate experience curves are then combined to build up an experience curve for the turnkey investment costs for an offshore wind farm. This aggregated experience curve is then used to forecast the turnkey investment cost reductions associated with offshore wind farms up until 2020. The result of the analysis is that the base case turnkey investment cost of 1600 EUR/kW for 2003

<sup>4</sup> XLPE = cross-linked polyethylene

costs will reduce to 980 EUR/kW for the ‘Sustained diffusion’ scenario and 1160 EUR/kW for the ‘Stagnant growth’ scenario by 2020. These forecast costs are comparable in magnitude to those forecast by Lako (2002) although Lako forecast that this level of cost reduction would not be achieved until 2030.

Although Junginger presented a graphical representation of the investment cost development with time for offshore wind farms, an experience curve based on this same data was not constructed. The study currently being presented will take this as a starting point. Initially a similar but more extensive data set than that used by Junginger will be independently gathered and verified. This will be followed by new experience curve analysis of actual cost data where it is expected that cost reductions will be in line with those observed and forecast by both Junginger (2005b) and Lako (2002) are expected to be determined.

## **4. New Experience Curves for Offshore Wind Farms**

Over time increasing levels of experience in the onshore wind energy sector have led to significant cost reductions. The electricity production costs for onshore wind farms are approaching a level where competition with electricity sourced from fossil fuels is becoming a reality. Both Lako (2002) and Junginger (2005b) have determined that there will be significant cost reductions associated with the continued deployment of offshore wind energy. In the case of Lako (2002) this analysis is based on a very small data set and for Junginger hypothetical experience curves are developed to determine the cost reduction potential for offshore wind farms although experience curves based on actual data are not developed.

Based on the studies presented in Chapter 3, experience curves for onshore wind have been developed up until 2000/2001. Studies where experience curves for offshore wind farms based on actual data were developed have not been located. Junginger's (2005b) work initially considered the development of total installation costs for offshore wind farms with time, his work showed that total installation costs decreased with time. The study then went on to utilise theoretical experience curve analysis to build a case for the potential investment cost reductions for offshore wind farms; however an experience curve based on actual data was not presented.

All studies to date analysing the cost development in both onshore and offshore wind energy have indicated that costs are reducing with increasing experience. The trends for onshore wind energy are long established trends where as the trends for offshore wind farms are based on a relatively limited data set. In this section new experience curves for offshore wind farms based on actual, verified data will be developed and the results observed will be detailed. It is the purpose of this analysis to ascertain if the expanded and verified data set will still exhibit similar trends to those observed in prior studies.

The accurate representation of the development of a technology is highly dependent on the quality of the data that is used. The high level of data verification used for this study is believed to be a significant strength that contributes greatly towards the development of meaningful experience curve analysis.

### **4.1 Construction of Experience Curves**

The construction of experience curves can be divided into three major steps:

- 1) Data collection and verification;
- 2) Data treatment and processing; and
- 3) Data utilisation and manipulation in the development of experience curves.

Once the experience curves are developed the trends observed can be analysed and interpreted.

In general, for a given technology, a large number of different experience curves can be developed. The extent to which experience curves can be developed is most often dependent on the data that can be accessed. Data can be gathered from both the investment and the

operating stages of a project to varying levels of detail, examples of this are summarised in Figure 4-1. For construction and installation stages experience curves can be constructed at all levels of the supply chain. For example experience curves can be used to track the development of components of a turbine, e.g. blades or drive shafts, as well as for the manufacture of completed turbines and foundations. At an even grander scale the learning system associated with the complete installation of a wind farm at company, national and global scales can also be modelled using experience curves.

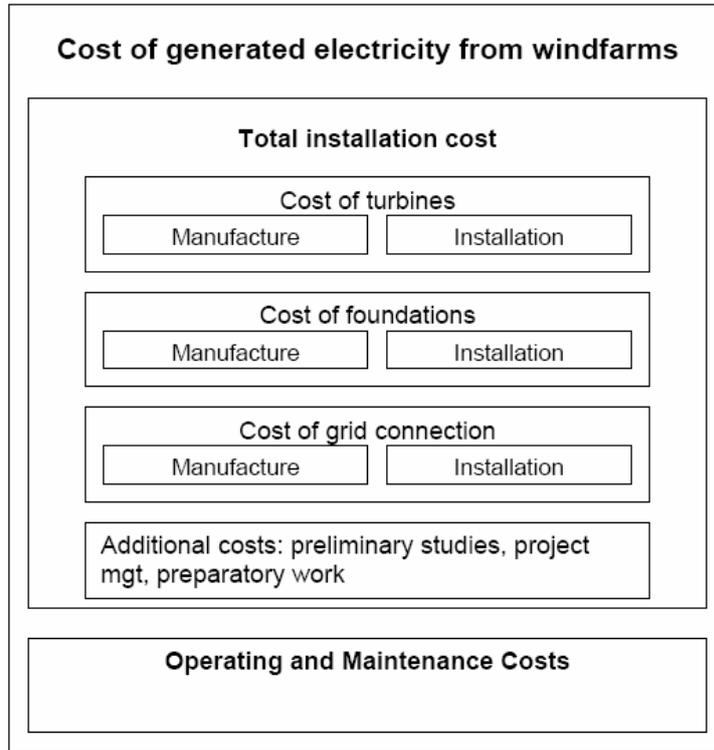


Figure 4-1: Basic components contributing to the cost of generated electricity from wind farms

The analysis performed for the purposes of this project will be to develop new experience curves for offshore wind farms at a global scale. The experience curves developed are intended to map the total installation costs as a function of cumulative capacity as a measure of experience. The experience curves generated for the purposes of this project have been calculated using the ‘output-weighting’ method as detailed by Neij et al. (2003).

## 4.2 Data Collection and Verification

The majority of cost and price data relating to offshore wind farms and their associated components are not readily available. Coupled with this the data that are available in the public domain are distributed through a vast range of publications often found in unexpected locations. Today’s offshore wind industry for the most part exists in the private sector and is an extremely competitive industry. An industry where wind farm developers and wind turbine manufacturers alike, consider price and cost data to be commercially sensitive and as a result go to great lengths to limit the sharing of this type of information.

A large part of this project was dedicated to the collection and verification of data. The initial data for this project were provided by Elsam who had expressed interest in cooperating with

IIIIEE, Lund University, on a project of this kind. The data provided by Elsam were, to a high level of detail and it was initially believed that Elsam's involvement would encourage the cooperation of other companies involved in the installation of offshore wind farms. This was the case to some extent although data to an equivalent level of detail as that provided by Elsam were not made available by any of the other companies involved.

Building on the data provided by Elsam, the first step in the data collection phase of the project was to identify all known offshore wind farm installations worldwide. A detailed search of both published and online material was conducted and a complete listing was developed. The wind farm developers and turbine manufacturers involved were identified for each project.

Following this, technical specifications for each of the wind farms identified were gathered. The technical information gathered for each of the wind farms was as follows:

- Year of commissioning (expected commissioning for 2006/2007);
- Installed capacity of wind farm including the number and capacity of the turbines installed;
- Average water depth and average distance to shore;
- Hub height and rotor diameter; and
- Type of foundation and grid connection.

This information although readily accessible was often difficult and time consuming to locate. In a number of cases there were discrepancies between different publications, in these cases the wind farm developer was contacted for clarification.

After confirming the technical specifications relating to each of the wind farms the next step was to gather the related cost data. This was by far the most time consuming step in the data collection phase. Initially an extensive search of both online and published data was conducted. This was followed up by making contact firstly with each of the wind farm developers and secondly with turbine manufacturers. Contact was made with approximately 15 companies with varying levels of success. Although responses were not received from all companies, in terms of installed capacity, 66% of the total installation cost data utilised in this study was confirmed with the wind farm developer.

Initially it was the intention of this project to collect total installation cost data as well as to breakdown the cost of each project into its main components, namely turbine purchase and installation, foundation purchase and installation, grid connections and other costs including preliminary studies, engineering and project management. Due to the highly competitive nature of the offshore wind industry and the commercially sensitive nature of this type of information, access to cost data to this level of detail was not possible. As a result an alternative approach was necessary.

It was decided that the total installation cost, a figure which was available for the vast majority of projects, would be the parameter that was utilised for the construction of experience curves. When in the initial process of collecting cost data for the offshore wind farm components mentioned, it was noted that in Denmark, at least, the cost for external

grid connection was covered by the relevant utility company. This meant that the total installation costs quoted for offshore wind farms in Danish waters often did not include the cost for the external grid connection that can account for at least 10% of the total project cost. In an effort to ensure the comparability of the total installation cost data it was ensured that the components included in the total installation costs were consistent across all projects; this was confirmed with the project developers where necessary. As a result all data utilised for the purposes of comparison have been confirmed to contain the cost for the external grid connection. All other components of the installation were observed to be included in the published costs as standard.

The limited number of data points for this project combined with the confidential nature of much of the data used limits the number of experience curves that could be developed. Nevertheless the experience curve developed is able to provide a powerful picture of the development of total installation costs for offshore wind farms and provides a basis for meaningful discussion.

### 4.3 Data treatment and processing

In order to develop a data set that could be utilised for the construction of experience curves. A certain amount of data treatment and processing was required. The two variables that were required to construct the experience curve were:

- 1) Total investment costs (EUR/kW); and
- 2) Cumulative installed capacity (kW).

The investment costs initially identified related to wind farms of varying capacity. In addition to this the costs were available in a range of currencies and in all cases related to the year of commissioning. In order to establish a set of comparable data points the data had to be normalised. The initial step was to calculate the total installation cost. Equation 1 provides the basic equation for the calculation.

*Equation 1: Specific Investment Cost*

$$P_t = \frac{Inv_t}{\sum_i c_i n_i}$$

Where:  $P_t$  = average investment cost (e.g. EUR/kW) for year t in published currency  
 $Inv_t$  = total investment cost for year t in published currency  
 $c_i$  = rated capacity of turbine in kW  
 $n_i$  = number of turbines

For each project the average investment cost  $P_t$  is calculated; this depends on the total installed cost of the wind farm,  $Inv_t$ , compared to the total capacity of the wind farm,  $\sum_i c_i n_i$ .

To allow the comparison of data, a reference year must be chosen and all cost data must be discounted to that year. This is done to eliminate the effects of inflation relating to the collected data. For this study this was done using a GDP deflator,  $k_{GDP}(t)$ , as detailed in Equation 2. Due to the discounting method being linked to GDP, GDP deflators are country specific. The GDP deflators used for this study are based on the reference year 2005, as published by IEA (2005).

*Equation 2: Investment Cost Inflation Standardisation*

$$P_{2005} = \frac{P_t}{k_{GDP}(t)}$$

Where:  $P_{2005}$  = inflation-corrected average investment cost for year 2005 in published currency

$k_{GDP}(t)$  = GDP deflator for year t for specified country

Finally all the data needed to be normalised to a reference currency in this case EUR was chosen. The exchange rates,  $k_{X,2005}$ , used for 2005 were 1 EUR = 7.45 DKK; 0.68 GBP; 9.28 SEK (European Central Bank, 2006). This standardisation is performed through the use of a simple equation as detailed in Equation 3.

*Equation 3: Investment Price Currency Standardisation*

$$P_{EUR,2005} = \frac{P_{2005}}{k_{X,2005}}$$

Where:  $P_{EUR,2005}$  = inflation-corrected average investment price for year 2005 in Euros

$k_{X,2005}$  = currency exchange rate

The experience curves for this project relate to the total cost of installing offshore wind farms, otherwise called the total installation costs. The method for developing the experience curves was to firstly calculate the total installed capacity for each wind farm in MW, this was done by determining the number and capacity of the turbines used as suggested in Equation 1 by the term  $\sum_i c_i n_i$  where  $i$  refers to the type of turbine. Once the capacity and number of each turbine type was established the total capacity of the wind farm could be easily calculated. The total investment price for each wind farm was also determined. Following this an average total installation cost was calculated, the total installation cost was then normalised to a reference year and currency, 2005 and EUR respectively; these adjustments were made based on Equation 2 and Equation 3. The resulting data set was used in the construction of experience curves.

#### 4.4 Development of Experience Curves

The first representation of the data presented in Figure 4-2, although not fundamentally an experience curve, tracks the development of the total installation cost for offshore wind farms over time; each data point represents an individual wind farm.

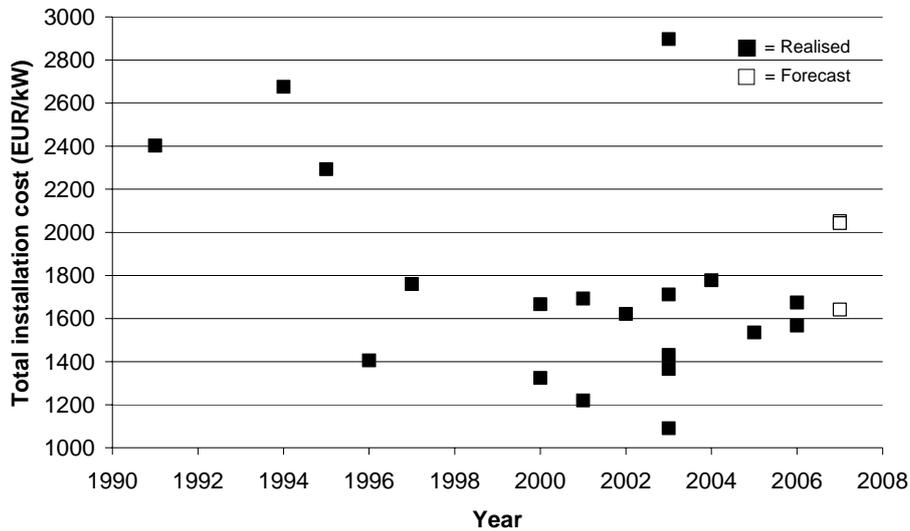


Figure 4-2: Total installation cost relative to time for offshore wind farms located globally (data adjusted for inflation and exchange rate)

This plot indicates that from the first wind farm in 1991 rapid cost reductions were achieved up until 2000, then from 2000 until 2003 costs remained somewhat stagnant then finally from 2003 onwards costs appear to be rising. Figure 4-2 is comparable to Figure 3-10, as developed by Junginger. This comparison shows a marked difference between the results of the two studies; this observation will be discussed further in Section 5.

The next plot to be developed was one considering the development of the total installation costs relative to cumulative capacity for offshore wind farms located globally. The curve illustrating this development is presented in Figure 4-3. This representation of data illustrates the development of total installation cost, EUR/kW, in relation to the total installed capacity, MW. Again this experience curve clearly shows that although total installation costs for offshore wind farm have reduced to some extent during the installation of the first approximately 300 kW, after this point costs have been steadily increasing.

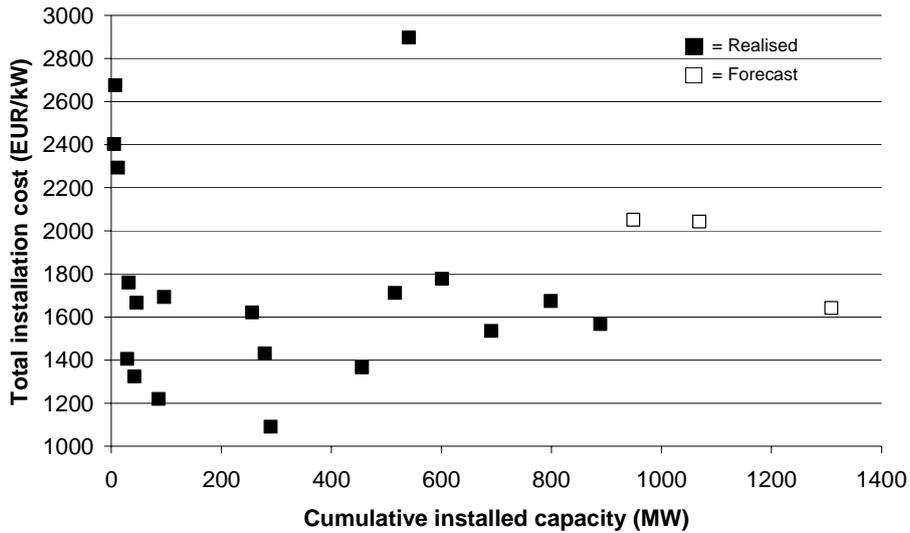


Figure 4-3: Total installation cost development relative to cumulative installed capacity for offshore wind farms located globally (data adjusted for inflation and exchange rate)

In order to determine a PR for the data set the first step is to construct the experience curve as presented in Figure 4-4. The PR is then calculated by fitting a straight trend line to the data set, as displayed in Figure 4-4; the PR is a function of the gradient of the line.

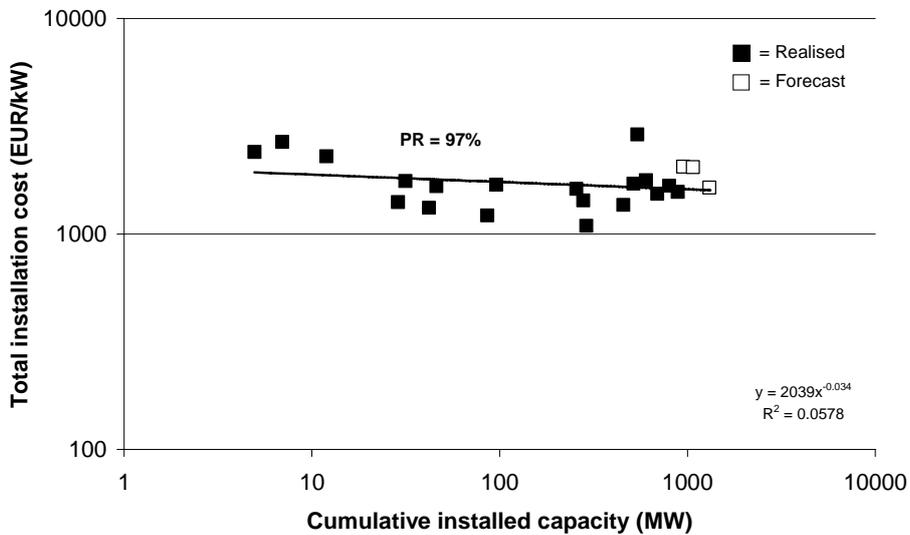


Figure 4-4: Experience curve for the total installation costs for offshore wind farms located globally (data adjusted for inflation and exchange rate)

Using this method of analysis a PR of 97% was calculated, although the fit of the trend line to the data is extremely poor indicated by a correlation coefficient ( $R^2$ ) value of 5.7%. The poor fit of the trend line to the data is more obvious when the exact same data set and trend line are plotted on a linear scale as presented in Figure 4-5.

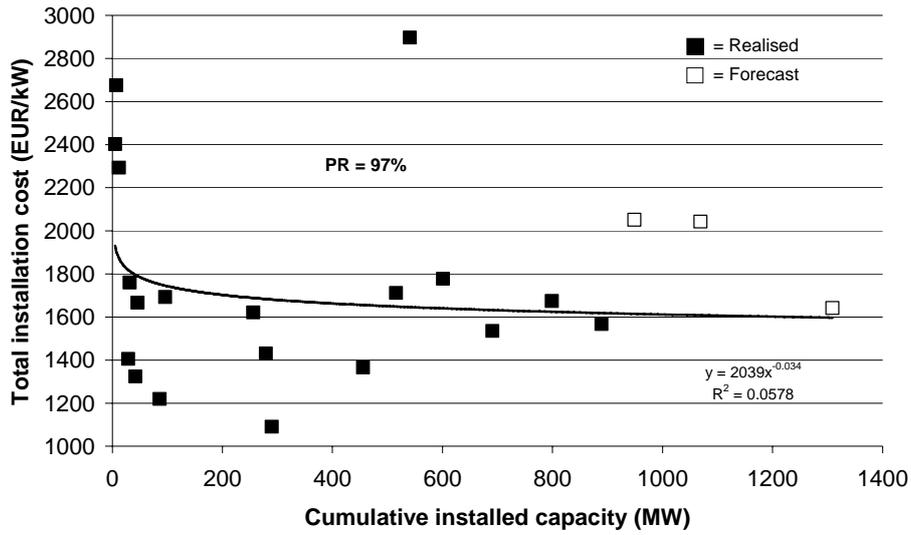


Figure 4-5: Total installation cost relative to cumulative installed capacity for offshore wind farms located globally, with fitted trend line (data adjusted for inflation and exchange rate)

A comparison between Figure 4-4 and Figure 4-5 shows that a poor level of fit of a trend line fitted to a data set can be somewhat disguised when the data are plotted on double-logarithmic scales. This issue will be further explored in Chapter 5.

## 5. Discussion of the total installation cost development of offshore wind farms

### 5.1 Comparison of results

It was initially hypothesised that the expected trend for the development of total installation costs for offshore wind farms would be comparable to onshore wind farms; a trend where as the cumulative installed capacity grows the total installation costs decrease. There was also an expectation that the relationship between the total installation cost and the cumulative installed capacity would follow the standard form of experience curves that have been developed for a large range of other energy technologies, particularly onshore wind installations, as discussed in Chapter 3. In fact the trends observed were the opposite; total installation costs were observed to increase with increasing cumulative installed capacity.

Analysis of the cost development of offshore wind energy has previously been performed by Junginger (2005b), the results of the initial investigation into the total investment cost are summarised in Figure 3-10 which provides a similar representation of information to that detailed in Figure 4-2, both Figure 4-2 and Figure 3-10 are repeated in Figure 5-1. While not experience curves, as such, Figure 4-2 and Figure 3-10, provide a basic level of insight into the development of total installation costs (turnkey investment costs) with time for offshore wind farms.

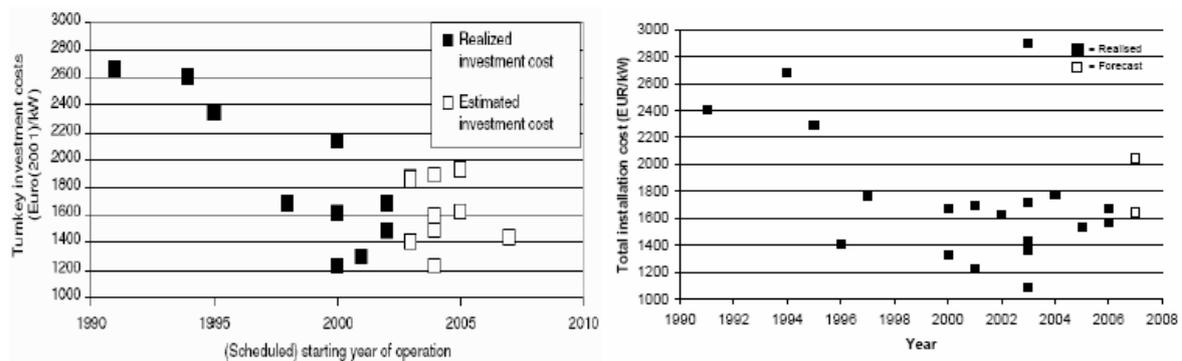


Figure 5-1: Total installation cost relative to time for offshore wind farms located globally (repeat of Figure 3-10(Junginger, 2005b) and Figure 4-2 respectively)

Junginger's (2005b) results clearly show a downward trend in the total investment costs for offshore wind farms with time. The upward trend that is observed in the results of this project (Figure 4-2), although possibly emerging in Junginger's results, are not obvious in Figure 3-10.

Due to the assumption in Junginger's (2005b) work that the total investment cost for offshore wind farms is decreasing the study goes on to identify cost reduction opportunities using a 'bottom-up approach' where the total investment cost is broken down into the components of wind turbines, foundations, grid connections and the installation process. Experience curves relating to onshore wind development combined with trends in commodity pricing are then used to estimate the magnitude of cost reductions that could be achieved. Junginger (2005b) has estimated that based on a 2003 total installation cost of 1600

EUR/kW that a total installation cost range of 980 – 1,160 EUR/kW could be achieved by 2020.

While the approach taken by Junginger (2005b) is reasonable based on the initial results of the study, it does not take into account that the overall price reductions observed in the offshore industry are not comparable to those observed for the onshore wind sector. This is especially important when the current trend for total installation costs for offshore wind farms is that they are increasing. Experience curve analysis, particularly regarding the use of trend lines, could also be used to overlook the observed increases in cost. This issue will now be considered in further detail.

### 5.1.1 Experience curves and the use of trend lines

As is mentioned the method of determining the PR for an experience curve is through the fitting of a straight line to the experience curve that is depicted on double-logarithmic axes. Double-logarithmic plotting of data compresses data points and can have the affect of making trends in data less noticeable when compared to linear plots. Leading on from this the fitting of trend lines to logarithmic data can disguise a bad quality of fit of the trend line to the data set. This is clearly shown through the comparison of Figure 4-5 and Figure 4-4 repeated in Figure 5-2. On first inspection the fit of the trend line to the data in Figure 4-4 appears to be reasonable although the correlation coefficient value,  $R^2=5.7\%$ , would indicate otherwise. If however the exact same data set and fitted trend line was depicted on a linear plot, the poor fit is much more obvious as shown in Figure 4-5. This is an obvious weakness of experience curve analysis that its users should be aware of.

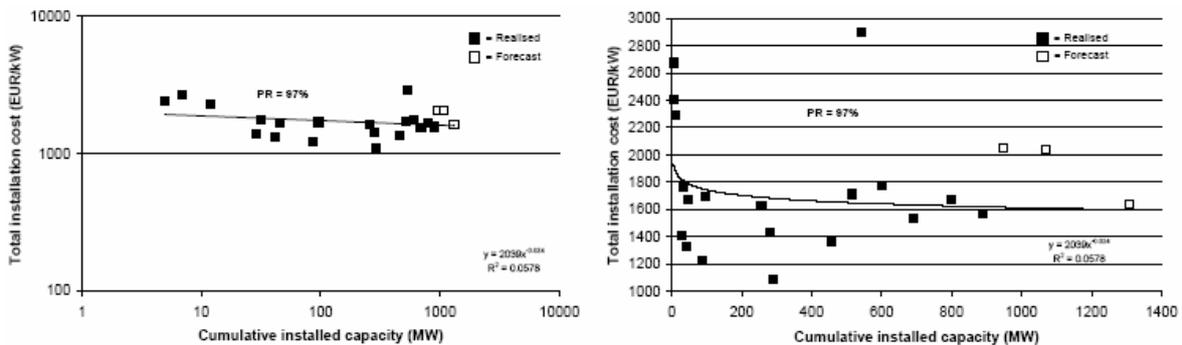


Figure 5-2: Total installation cost relative to cumulative installed capacity for offshore wind farms located globally (repeat of Figure 4-5 and Figure 4-4 respectively)

The data presented actually appear to occur in two distinct phases; an initial phase of cost reduction followed by a prolonged phase of gradual cost increase. These trends are graphically displayed in Figure 5-3.

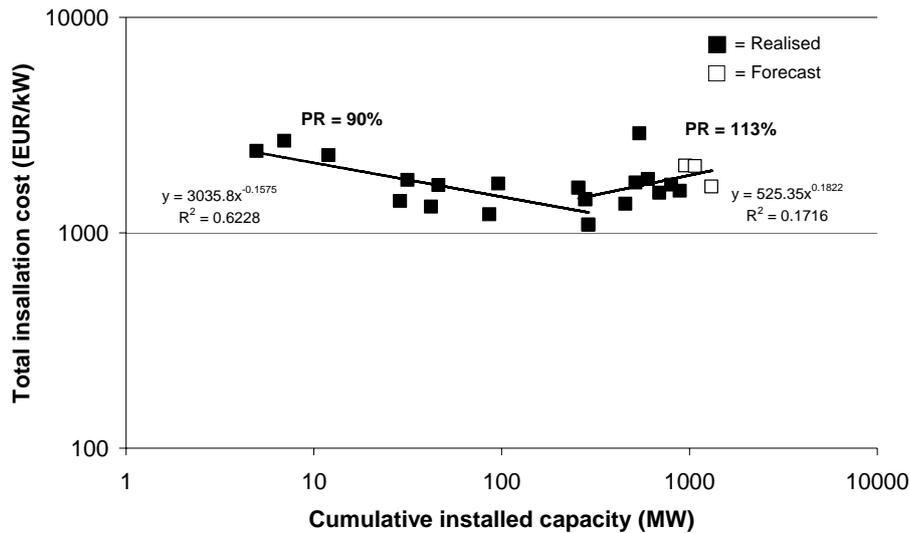


Figure 5-3: Experience curve for offshore wind farms located globally showing two phases of development, data adjusted for inflation and exchange rate

These trend lines indicate that for the initial development of offshore wind farms the total installation costs were decreasing based on a PR of 90%. Following the installation of approximately 300 MW of capacity the cost development took an upward turn and since that time costs have been increasing in line with an estimated PR of 113%. Based on the  $R^2$  values the level of fit has improved dramatically for the initial development phase although the ability of a trend line to fit the phase of increasing costs is still very poor. Again this representation of information can be somewhat deceptive. By comparison of the two phases indicated in Figure 5-3, the phase where costs are reducing appears to dominate the overall cost development for offshore wind farms, when in fact this cost reduction phase only spans approximately 25% of the total capacity of wind farms installed. This means, in terms of experience, the most recent 75% of experience relating to the development of offshore wind installation has resulted in increases in the total installation costs for offshore wind farms.

The continued development of offshore wind farms is dependent on overall cost reductions. As a result it is important to have an understanding of the reasons behind the observed trend of increasing total installation costs. The contrast between the expected and actual results of the experience curve analysis in this study highlighted the need for the use of complementary methods of analysis in addition to experience curve analysis.

First of all it is important to consider whether or not the experience curve developed provides an accurate picture of the progression of the total installation costs for offshore wind farms. Based on this the reliability of the data set will be discussed, the comparability of the data will also be considered.

Once it is established that the data used are in fact reliable and comparable it is important to have a thorough understanding of the type of data that are being used in this analysis. This will be done by discussing the relationship between cost and price and how this has the potential to affect the form of an experience curve.

## 5.2 Reliability of data

The reliability and comparability of data are core to performing meaningful experience curve analysis. The data used for the purposes of this study are believed to be both reliable and comparable; the reasons for this are as follows.

As detailed in Section 4.2, the initial collection of total installation cost data for this project was through the review of both online and printed publications. As far as possible the total installation cost data collected were verified with the wind farm developer. Where this was not possible the data used was taken from the publication that was judged to be the most reliable. Statistically, in terms of total installed capacity, 66% of the cost data were verified by the wind farm developer. This is a reasonably high level of data verification. Coupled with this the main sources of data used outside of wind farm developer verified data were wind farm specific websites (generally hosted by the wind farm developer) and IEA (2005) followed by Deutsche WindGuard GmbH, Deutsche Energie-Agentur GmbH (dena) & University of Groningen. (2005). Based on the high level of attention devoted to the collection and verification of data, the total installation cost data used for the purposes of this project are considered to be reliable.

Secondly, the issue of comparability was addressed by ensuring that the total installation costs included the same components namely the purchase and installation of: turbines, foundations and internal and external grid connections. In addition to this all offshore wind farms to date (with the exception of the 1.2 MW wind farm in Japan) are located in northern European waters as indicated previously in Figure 2-2. Another factor supporting the comparability of the data is that the supply of turbines, foundations, installation services and other components compete on the international market. This means that as well as being located in similar geographic locations the products and services for offshore wind farm installation are sourced from internationally competitive suppliers. Based on these factors the data for offshore wind farms from a global perspective are currently considered to be comparable. Depending on future development in the industry this may not always be the case.

## 5.3 Price data vs. cost data

In order to gain a more complete understanding of the trends observed in the experience curve developed, the type of data that are being utilised in this research project needs to be considered in greater detail.

A useful starting point is to consider the ability of the data set utilised to construct meaningful experience curves. As discussed earlier the ability of an experience curve to provide an accurate depiction of the development of a particular technology is completely dependent on the quality of data utilised for the analysis. In order to be certain of constructing an accurate picture of the development of an energy technology picture cost data must be used. Price data are said only to provide an accurate representation when the price/cost margin is consistent.<sup>5</sup>

The experience curve analysis made during this research project has been based on total installation cost data, as viewed by the wind farm developer. Total installation costs refer to

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<sup>5</sup> Price/cost margin is the margin between the cost to manufacture a good or provide a service and the price the good or service is sold for. Also referred to as the profit margin.

the costs incurred by the wind farm developer to access and utilise the goods and services required to install and commission an offshore wind farm. The installation of an offshore wind farm is generally completed in three main parts: 1) foundation purchase and installation; 2) turbine purchase and installation; and 3) electrical infrastructure (internal and external grid connections) purchase and installation. Additionally project scoping and design along with a range of other internal costs such as project management, administration; marketing, insurance etc. are part of the total installation cost. In simple terms the total installation costs for an offshore wind farm can be considered as the sum of the contracted prices of the major offshore wind farm components as detailed combined with additional costs incurred by the developer. This simplified view of the breakdown of total installation costs is presented in Figure 5-4; this is only one of many examples of how an offshore wind farm project can be structured, for example project scoping and design work may also be outsourced although the outsourcing of the major components of turbines, foundation and grid connections as depicted could be viewed as standard.

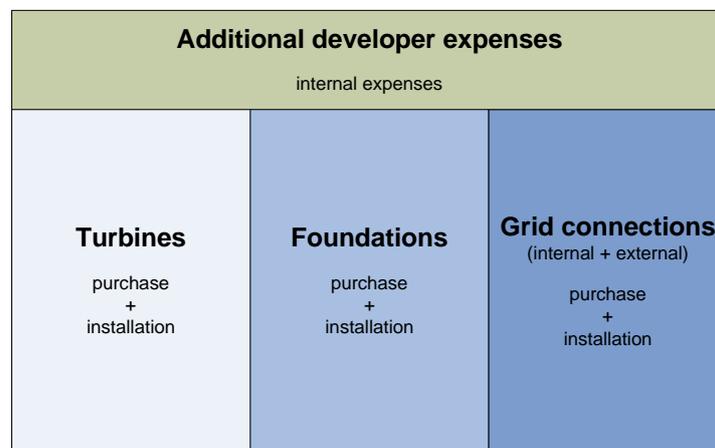


Figure 5-4: Breakdown of total installation cost for an offshore wind farm

In the breakdown of total installation costs presented in Figure 5-4 the costs for the purchase and installation of turbines, foundations and grid connections will be based on the contracted prices as determined by the producers and the installation contractors associated with these major components. In addition to this the wind farm developer will also have internal costs associated with such activities as project planning and management. These additional wind farm developer expenses are expected to be relatively stable from project to project and have been calculated as making up a small percentage of the total project costs, approximately 8% (Junginger, 2005b). As a result the total installation cost associated with an offshore wind farm is dominated by the prices for the purchase and installation of the turbines, foundations and grid connections. This means that in terms of experience curve analysis the total installation costs for offshore wind farms can be considered as price data; the total installation costs for wind farms will follow an extremely similar trend to that of the summed prices of the major components described.

The use of price data for the analysis of the offshore wind energy industry is somewhat questionable. It is an extremely competitive sector where manufacturers and developers alike are not prepared to give much away; manufacturers in terms of cost data and developers in regarding the breakdown of total installation costs. This leads to a situation where the price/cost margin is likely to vary significantly from project to project. As detailed by Neij et al. (2003) in order for price data to be comparable to cost data the price/cost margin must

remain consistent over time. Due to the highly competitive nature of the offshore industry this cannot be guaranteed. Adding to this the data gathered for the purposes of this study could be considered as price data at the highest level of the supply chain; the further up the supply chain, that is the further away from the production of the raw material, the greater the level of uncertainty associated with the accurate representation of a learning system through the use of experience curve analysis. This is due to the increasing number of actors in the supply chain all trying to maximise their own gain through the adjustment of the price/cost margin.

The price/cost margin is affected by the market forces of supply and demand and hence can vary somewhat independently of the cost of the good or service. The price experience curve is coupled to the cost experience curve to some extent although it is also a reflection of the structure of the market; it is affected by producers' strategies and consumers bargaining power. Experience curve analysis is ideally based on cost data, eliminating the affects of a varying profit margin. As indicated cost data are often considered to be confidential and are considered by companies to be part of their competitive edge; as a result it is very difficult to access. It is therefore often the case that analysts will need to measure the effects of experience through the use of experience curve analysis based on price data. An understanding of the potential relationship between price and cost over the development of a new product is therefore an important tool. Such methodological issues have been discussed in a report by IEA (2000). A potential relationship between cost-based and price-based experience curves as developed by the Boston Consulting Group (BCG) is presented in Figure 5-5.

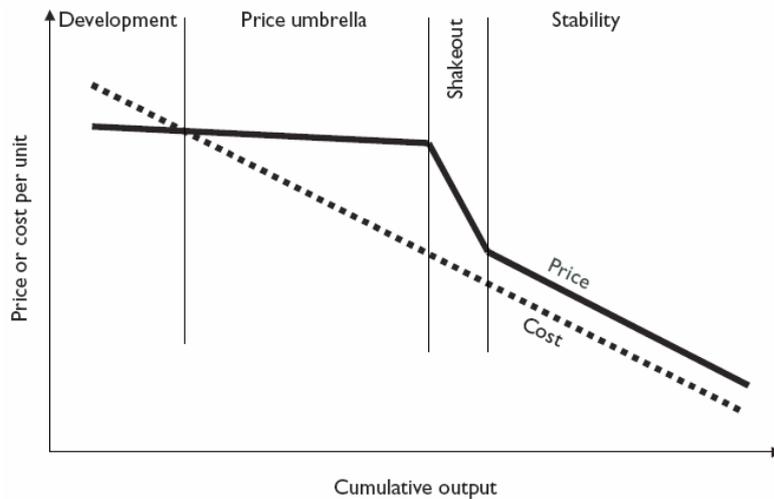


Figure 5-5: Relationship between price-based and cost-based experience curves for a new product (IEA, 2000, p. 35; based on: BCG, 1968)

As indicated in Figure 5-5 the relationship between the cost-based and price-based experience curves is considered to occur in four phases. The first phase labelled as the 'development' phase is where a new product is introduced to the market; here the producer sets the price of the good or service below the cost with the aim of establishing a market for the new product. Then as the relationship between price and cost data moves into the next 'price umbrella' phase the cost of the good becomes lower than the price due to experience

related decreases in cost. During this stage the first producer is a market leader and is able to maintain the higher prices due to a lack of competition.

It is under the 'price umbrella' phase that new producers are attracted to the market. Newcomers will enter the market and begin to gain experience. As the margin between price and cost grows the market becomes increasingly competitive and unstable. At this point the market enters the 'shakeout' phase where prices drop dramatically due to fierce competition. The PR during this period is high and will not be sustained. The final phase is the 'stability' phase where the market has become more stable and price/cost margin remains constant over time.

IEA (2000) then goes on to say that while technology related structural change can be observed from the cost-based experience curve, it is market structural change that is depicted by the price-based experience curve. As a result the trends observed in the price-based experience curve for the development of offshore wind farms are most likely due to issues relating to market structure. This is a view that is widely held by a large number of industry professionals including Hjelmsted (2006), Kouwenhoven (2006) and Winther (2006).

Potential explanations for the trends observed in the development of the total installation costs for offshore wind farms have been posed by Hjelmsted (2005) and the IEA (2005b). The development of the offshore wind industry can be looked at as occurring in three distinct phases. Firstly from approximately 1995 until 1997 a series of demonstration projects were constructed primarily in shallow waters. Then from 1997 to 2003 the industry moved into a more commercial phase where projects were more technically demanding, during this period companies became more interested in the potential development of the offshore wind industry and were vying for their place in its future. As a result investment prices were highly competitive, during this period the drive for companies to become established in the offshore industry meant that projects constructed during this period had uncharacteristically low investment prices and were possibly not viable when considered in isolation; as a result these prices could not be sustained, this is illustrated by the rise in costs observed particularly in the latter part of this phase. During the third phase which can be considered as from 2003 onwards costs have continued to increase due to a range of influencing factors including the high risk and uncertain future of the offshore wind sector in the face of a booming onshore industry as well as the fact that developments are moving further offshore.

It is also worth considering that the projects constructed up until 1997, including the Blyth development in the UK, as mentioned were considered as demonstration projects. These projects were constructed in relatively sheltered waters, in comparison to the waters of the North and Irish Seas; in combination with this the turbines used were much smaller than those planned for future projects. As a result this phase of projects may have little relevance to projects that have been developed since. This being the situation, the case for the increases in total installation costs for offshore wind farms becomes more convincing and relevant.

An important consideration also is the significance of the data considered for this project to the future development of offshore wind farms. The data set for this project relates to a total installed capacity of approximately 1300 MW. In 2005 the total installed wind capacity was estimated to be approximately 59 GW: of this total it was estimated that offshore wind farms accounted for approximately 0.7 GW, with onshore representing the remaining 58.3 GW; as detailed in Chapter 2. Further to this the potential for offshore wind energy has been estimated to be far in excess of onshore. If 65 GW is then considered as an extremely conservative estimate of the future potential for installed offshore wind farm capacity, then

the current data set would only represent approximately 2% of this. As a result the increasing trend observed in the current experience curve may be far less significant in the overall scheme of things; over a larger scale it is possible that the trend observed could be approximated using a relatively flat trend line, in line with the 'price umbrella' phase depicted in Figure 5-5. Nonetheless at this point there is still an apparent disconnect between the price (total installation cost) and the cost for offshore wind farms.

The total number of wind farms that have been used in this analysis is relatively small. It is also possible that the limited number of data points used in the development of the experience curve may limit the value of the study in terms of the potential to extrapolate future total installation costs for offshore wind farms. Perhaps as more and more projects are completed the patterns observed in the current data will become less significant. Additionally in terms of the number of wind farms the development of offshore wind farms is not expected to be as prolific as onshore wind farms due to the larger capacities and larger risks involved. As a result trends may take longer, in terms of both capacity and time, to emerge.

It is expected that the potential explanations for the trends observed are predominantly market based. It is most likely that the development of offshore wind farms is currently in the 'price umbrella' phase. The apparent disconnect between the price-based experience curve developed and the underlying cost-based experience curve would then be as a result of fluctuations of the price/cost margin. Discussion relating to market-based aspects that may be responsible for the price trends observed for the development of offshore wind farms will continue in more detail in Section 5.4.

This is not to say that production and installation costs relating to turbines, foundation and electrical infrastructure are not reducing. It is more of a case that the experience related production and installation cost reductions are not being passed on to the wind farm developers. Although not evident in the total installation cost data (essentially price data), the costs associated with the major components of offshore wind farms is most likely decreasing due to increasing experience. It is most likely that these cost savings are currently masked by the fluctuation of the price/cost margin. This trend of decreasing production and installation costs will only be visible in the price data once the development of offshore wind farms enters the 'shakeout' and consequent 'stability' phases depicted in Figure 5-5. Considering that cost reductions are occurring, the potential sources for these cost reductions are discussed in Section 5.5. Overall both a change in market structure bringing about increased competition coupled with continued experience related cost reductions for the production and installation of the major components will lead to a reduction of the total installation costs associated with offshore wind farms. It is only then that the ability of offshore wind farms to become a competitive energy technology will be demonstrated.

It has been established that the reason for the difference between the expected and actual development of the total installation costs for offshore wind farms is due to the use of price data. Based on this finding it is important to have an understanding of the reasons that the price data are in such contrast with the cost data. In order to do this a method of analysis in addition to the experience analysis must be used. The method used will be to consider the factors influencing the price development for offshore wind farm.

## 5.4 Factors influencing the prices of offshore wind farms

Experience curve analysis has often been criticised for its amalgamation of costs and its subsequent lack of attention to the underlying trends associated with a more detailed cost

analysis. Nevertheless experience curve analysis plays an important role in devising strategies regarding the future global energy supply. It has and will always be the case that overall price is the most important measure of performance for the utilisation of a new technology (IEA, 2000, p.9). This is not to say that more detailed analysis is not necessary, it is simply to say that the overall price development of a technology is a very important parameter that should not be overlooked. More detailed analysis will apply particularly in cases where the overall price development of a technology is not in line with expectation as is the case in this study.

The experience curve analysis utilised in the project shows convincingly that there is an observable disconnect between the price and cost of the major components necessary for the development of offshore wind farms; a trend that has been occurring for quite some time. In order to be confident that the existing trend will not continue and that cost reduction will occur it is important to have an understanding of the factors that are influencing the currently observed price development of offshore wind farms. It is highly likely that the trends observed are based on the market situation; as discussed in Section 5.3. If this increase in price is to be addressed then it is important to have an understanding of the parameters that have the potential to influence the future price development of offshore wind farms. Through both the review of literature and interviews with industry professionals a number of potential drivers for the trends observed have been identified and include:

- A low level of competition in the offshore industry due to the booming onshore industry;
- The high risk of investing in offshore wind farms leading to a lack of investors and lack of access to funding;
- A lack of competition amongst turbine manufacturers;
- Uncertainty relating to the stability of government subsidies and approval processes;
- A limited potential for experience related cost reduction, when compared to onshore wind farms; and
- A shortage of both installation vessels and experienced contractors.

These parameters and their relationship to the development of total installation costs for offshore wind farms will be discussed further in Sections 5.4.1 to 5.4.7. It is believed that decreases in the total installation costs for offshore wind farms may be brought about by addressing the issues identified through this analysis. Further discussion of potential production and installation cost reduction opportunities as well as other factors that may affect the competitiveness of offshore wind farms is located in Section 5.5.

#### **5.4.1 Booming Onshore Industry**

The onshore wind power sector is booming all around the world and particularly so in the USA and Spain (Westwood, 2006; Hjelmsted, 2006). As a result the demand for wind turbines for the construction of onshore wind farms is extremely high. In fact the demand for wind turbines for onshore wind farms is at a point where wind turbine manufacturers are producing at near capacity rates. The manufacturers of offshore wind turbines are the same as for onshore wind turbines; no manufacturer has currently dedicated their business to the

manufacture of turbines for offshore wind farms alone. This situation is in general pushing up the cost of turbines for onshore and offshore applications alike. With the demand in the offshore sector being for a relatively small number of larger more technically challenging units this price increase is much more exaggerated for onshore developments. This is further compounded by the fact that due to the high demand for turbines in the onshore industry many companies perceive the offshore industry as not worth investing in until the demand in the onshore industry decreases (Westwood, 2006). Manufacturing companies consider the manufacture of turbines for the onshore industry to be low risk and stable market compared with turbines for the offshore industry.

With the significantly high demand for turbines in the onshore sector the demand for components from the sub-suppliers (companies that supply components to manufacturers) is also at record levels. Due to the demand in some cases being in excess of the capacity of the sub-suppliers the cost of the components that are required to manufacture the turbines is also high. This trend continues up the supply chain ultimately contributing to a higher manufacturing cost for all types of turbines, particularly offshore turbines which could almost be considered as a non-standard specialised product when compared with the vast quantities of turbines being manufactured for the onshore industry.

Further potential reasons for the increase in costs for offshore wind farms were summarised in an article by Adam Westwood (2006). Westwood says that at present due to the high demand for wind turbines both onshore and offshore and the limited numbers of suppliers that premium prices are being demanded for all turbine units. This situation is expected to magnify as higher capacity units are produced, due to the non standard design and limited availability of such units.

#### **5.4.2 High risk**

Offshore wind farms are also considered to be high risk investments due to the high total installation costs compared to onshore wind farms. As a result it is essential that total installation cost reductions are achieved in an effort to lower this risk. Capital expenditure for offshore wind power is inherently high and is expected to become higher in the short-term due to plans to move further offshore and into deeper water. Recent experience has been that the total installation costs in many cases are increasing. Suggested reasons for this are: the high costs of providing back-up service for units with inadequate reliability; some serious faults in offshore turbines have occurred due to inadequate testing of new products and poor built quality; raw material prices have also increased mainly as a result of the growth of infrastructure in China; and costs have been driven up to more realistic levels due to the industry becoming more experienced with regard to the specification and construction of offshore units (BVG Assoc. et al., 2006). All of these uncertainties lead to an industry that is perceived as a high risk investment.

One of the factors demonstrating the current high risk of the industry and causing further increases in the prices of turbines is the fact that there have been many faults with offshore turbines. The repair of faults in turbines that occur within a certain period after installation, two up to five years depending on the terms of the purchase contract, are most often the responsibility of the turbine manufacturer. Faults with offshore wind turbines can incur substantial costs to the turbine manufacturer. There have been a significant number of technical faults associated with wind turbines installed offshore, resulting in significant expense for turbine manufacturers where it is standard to include a warranty period of between two and five years (Westwood, 2006; Hjelmsted, 2006; Kouwenhoven, 2006). In an

extreme case technical problems experienced at the Horns Rev wind farm in Denmark meant that the turbine manufacturer, Vestas, was forced to take all 80 turbines back to shore for modifications (Hjelmsted, 2006). Based on this risk the turbine manufacturer will react by increasing the price of offshore wind turbines across the board as a kind of insurance policy to reduce the potential impact of repair costs. This factor is also discouraging to turbine manufacturers that are considering extending their business offshore

Westwood goes on to say that another source of price increases is believed to be due to be the method of contracting and its associated risk. Initially the standard practice was for the development of an offshore wind farms to be conducted utilising a turnkey basis where the wind farm developer outsources the entire project development and installation to a single contractor. An approach also labelled as Engineering, Procurement and Construction (EPC) due to the fact that a single contractor is responsible for all three phases of the development of an offshore wind farm. In this way one contractor bears the majority of the risks for each project. Coupled with this the EPC approach generally means that each project is tendered for individually. Due to the frequent abandonment of projects, start-up problems and lack of continuous work, the costs that are being demanded by contractors under this protocol have increased to levels that are unjustifiable for project developers.

An approach with the potential to reduce costs, as suggested by Westwood (2006) is centred on the contracting procedure. He makes a point that current contracting procedures contract for one project at a time and in isolation from other projects, he believes that if contractors could be awarded multiple contracts that the certainty of continuing work would lower the risk for companies to invest in the development of offshore wind farms. The decreased risk of investment should then provide an incentive for companies to decrease their prices. As a result a multiple contract, where the same contractor is used for a series of projects, approach is now being trialled in the UK; this approach is expected to yield savings of up to 10%. An alternative approach as suggested by Hjelmsted (2006) takes this approach a step further. Hjelmsted's approach is based around multiple contracts for the same project where the contracts for the turbines, foundations and electrical infrastructure are separated and the interfaces between these contracts are managed by the wind farm developer; placing the risk of the project with the wind farm developer. Using this approach the awarding of multiple contracts to for example wind turbine manufacturers is still expected to reduce risks and decrease costs.

### **5.4.3 Limited competition amongst turbine manufacturers**

Experiences such as that at Horns Rev, although most probably an isolated incident, are discouraging to turbine manufacturers considering entering or building capacity in the offshore industry. The potential high risk associated with offshore projects combined with the rapid growth in the onshore industry has translated to a lack of interest from turbine manufacturers to enter the offshore wind farm market. This is evident through the comparison of Figure 5-6 and Figure 5-7 showing the market share of wind turbine manufacturers both in total and for the offshore sector.

**Wind Turbine Manufacturers - Total Market Share**

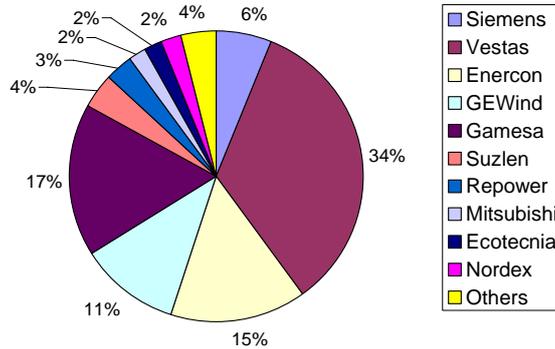


Figure 5-6: Wind turbine market share by manufacturer (Cameron, 2006)

**Turbine Manufacturers - Market Share Offshore Wind**

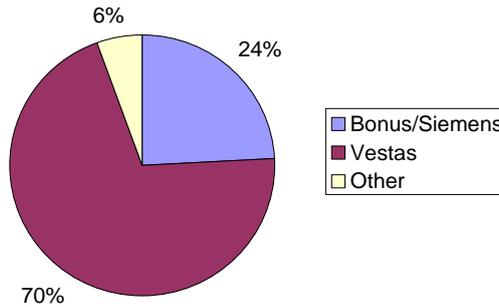


Figure 5-7: Offshore wind turbine market share by manufacturer (based on project data collected for this project)

The longer that the market for offshore wind turbines is dominated by a small number of suppliers the more difficult it will be for newcomers to enter the offshore market. This is due to the fact that the current manufacturers of offshore wind turbines are gaining skill and experience in production of offshore wind turbines ultimately leading to cost reductions. The expertise gained by these manufacturers during this period where other turbine manufacturers are simply not interested will be a big hurdle to overcome for newcomers to the offshore sector. Due to the higher cost and potential risks of investing in the offshore industry wind farm developers will also be more likely to buy from turbine manufacturers that have developed a reputation for producing reliable offshore turbines, not likely the newcomer. As a result the current market situation for offshore wind manufacturers is expected to be difficult to change. Although it is a change that is considered to be essential to the reduction of total installation costs for offshore wind farms.

Further to this it was proposed by Lako (2004) that the offshore wind turbine market could peak with an annual demand of 1,000 turbines of 5 MW each. This may mean that there will only ever be room enough for two or three suppliers of offshore wind turbines to the

European market. The result of this could be a lack of competition for offshore turbine manufacture for a long time to come.

#### **5.4.4 Uncertainty regarding government policy and approvals**

Jones and Westwood (2005) are of the opinion that recent success in the industry has been high although a number of promised projects have failed to go ahead, it is suggested that this has been due to a number of problems at both a project and governmental level. Strategies for the advancement of offshore wind energy vary between countries: an example of this is that in the UK progress has been gradual and based on forecast projects this trend is expected to continue. In contrast to this Germany has adopted a more high risk approach and is already progressing with a number of expensive deepwater projects. In the case of Denmark, a world leader in both onshore and offshore wind energy technology, a lack of long term strategy for offshore wind energy has already resulted in a loss of market share.

In 2003 it was estimated that by the end of 2006, the cumulative capacity of offshore wind power would be over 3 GW (Kooijman et al., 2003; Beurskens et. al., 2003). Based on the data collected for this report, this figure looks more likely to be approximately 1 GW. Kooijman et al. (2003) also went on to say that the main obstacle to this would be the insufficient policy support rather than due to technical barriers.

In a report published by IEA (2005b) a run down was given on a number of selected European countries regarding their policies that had the potential to encourage the offshore industry and also regarding the approvals required for offshore wind energy development. These factors can be summarized as follows:

In the UK the policy aimed at the support of renewable energy technologies is known as the “renewables obligation” where a target of 10% of generated electricity is to be sourced from renewables by 2010. The onus is on electricity companies to source an increasing percentage of their demand from eligible renewables; this is done through the purchase of Renewable Obligation Certificates (ROCs). No distinction is made among technologies; as a result the less expensive technologies such as onshore wind energy are favoured. As a result there was some uncertainty regarding what would happen post 2010, in response to this the target has been tentatively extended to 15% by 2015. The UK government recognized early on that onshore wind energy would be sufficient to meet the target. As a result additional capital grant support has been provided to the offshore industry to kick-start the sector for longer term development. Up to 2005 only projects that were in receipt of all of the necessary consents have been awarded these capital grants. This uncertainty in funding is thought to act as a deterrent to developers as the approval process is complicated, lengthy and expensive in itself.

In Belgium the market for renewable energies is driven by national and regional targets through obligations to increase electricity sources from renewables and tradeable green certificates. From an approvals perspective, a project requires two separate consents; an environmental permit and a domain concession from the electricity regulator, as well as two cabling permits. The granting of these consents has been somewhat unpredictable with some projects being granted one but not the other to the other extreme where a project has been granted both approvals that were subsequently revoked. The large C-Power, Thornton Bank offshore wind farm planned for Belgium has been granted all necessary permits, although the detail of the permits mean that this project is required to develop in three stages and is not expected to be completed until 2010 (C-Power n.v., 2006).

Denmark's energy policy, written in 1995, was based on a 20% reduction in CO<sub>2</sub> emissions by 2005 with a goal of 50% by 2030. In 1997 suitable areas for the development of 5 demonstration projects were identified to be developed by the utility companies under agreement with the government by 2007. Two of these projects have since been developed and the order from the government for the remaining three was revoked in 2002. This could be seen as a ramping down of the initiative or alternatively that there was better than anticipated growth in alternative renewable energy sources.

For Ireland the goal is to source 13.2 % of its electricity from renewable sources by 2010. Up until 2005 renewable energy was supported through a tendering process, from 2005 this has been replaced by a feed-in tariff system<sup>6</sup>. A number of foreshore licences have been granted, with most granted up to 2002, although the Arklow Bank project is currently the only project in operation. Approvals have also been an issue in Ireland where approvals are granted and subsequently withdrawn. In Ireland the grid connection is also considered a major obstacle.

Germany is thought to have possibly the most favourable long-running support system for renewable energy; technologies are supported by the feed-in tariff system. Changes made to the Renewable Energy Act in 2004 resulted in a separate price being paid for offshore wind making deeper and further offshore projects more attractive. In a report by Beurskens and de Noord (2003) a brief discussion of the status of approvals for a number of European countries is made. For example in Germany there are number of authorities that need to give permission for projects depending on the location. For those projects located within the EEZ (Exclusive Economic Zone) the issuing body is Bundesamt für Seeschifffahrt und Hydrographie (BSH), while for projects within the 12-mile zone local authorities are important (Landes-und Bezirksregierungen). A cabling permit also needs to be attained for the external grid connection for the wind farm; these permits are proving extremely difficult to get, this is resulting in significant delays to the progress of Germany's ambitious offshore wind programme where in 2003 it was estimated that there would be up to 25 000 MW of installed capacity by 2030.

Large scale offshore wind projects located in the Netherlands have also experienced lengthy delays, up to 4 years, due to legislative procedures. (Beurskens, 2003)

This uncertainty with regard to permits, licences and government subsidies leads to a situation where developers are hesitant to consider the development of offshore wind farms due to fears that permits and licences may not be granted and that the promised funding may be withdrawn. Stable growth in the installation of offshore wind farms is essential to the success of the industry and is dependent on greater certainty with regard to government policy and approvals.

#### **5.4.5 Difficulty of accessing funding**

In a report published by the New Energy Finance (Liebriech & Young, 2005) access to funding was indicated as a major barrier to the progress of offshore wind energy. The many uncertainties surrounding development costs, the cumbersome permitting process (where up to 14 agencies can be involved in a single project) and expensive external grid connection

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<sup>6</sup> A feed-in tariff is 'the price per unit of electricity that a utility or supplier has to pay for renewable electricity from private generators. The government regulates the tariff rate.' (EEA, 2006) The tariff rate can be consistent for all renewable energy types or vary depending on the energy source or technology used. In this way feed-in tariffs can be used to encourage the development of specific energy sources and technologies.

were cited as reasons that financial institutions are hesitant to finance upcoming offshore wind farm projects. It is rather stated that continuing government support is essential to the progress of the offshore sector.

Lack of access to government funding is a real issue in the UK. Offshore wind projects in the UK have been divided into a number of rounds or groups. Round 1 projects are eligible for government subsidies while Round 2 projects are not. Round 2 projects are mostly located further offshore in harsher conditions and economics now show that without government assistance, the Round 2 projects will not go ahead, this would severely hamper the development of the offshore wind sector in the UK. This future uncertainty could also act to increase the prices for the Round 1 developments.

The feed-in tariff system in Germany is also considered by this report to be the most progressive approach to date as there is a separate and high feed-in tariff assigned to offshore wind power.

The article goes on to say that across Europe over 54 GW of offshore wind is either proposed or in planning and that this level of development is likely to require funding of at least 91 billion EUR. This level of funding will only be achieved if governments actively support the industry to instil a certain level of stability regarding the ongoing development of offshore wind energy.

#### **5.4.6 Limited Potential for experience related cost reduction**

Technologies utilised in the offshore wind industry are not new technologies. It is simply the utilisation of existing technologies in a slightly modified manner. For example even though the turbines used offshore have the potential for significantly larger capacities they are still utilising many of the same technologies as those used onshore. Increases in the size of turbines does create some challenges particularly with regards to weight and ensuring the reliability of turbines in harsher conditions for offshore locations certainly does require the additional development of turbines. Experience in relation to these factors is expected to provide some potential for total installation cost reduction.

Both foundations and cabling have been utilised for a variety of offshore applications including harbour infrastructure and offshore platforms in the oil and gas industry. As a result the rapid reduction of costs as seen with new technologies will not likely be seen. It should be recognised, however, that the intensity of installation of both of these components for current offshore wind farms is higher than for previous more intermittent installations of similar components. As a result the average installation cost for both foundations and cabling can be expected to noticeably decrease with experience. Progress in the area has already been observed.

As a result, the level of experience related to total installation cost reduction for offshore wind farms cannot be expected to be as high as that observed for the development of onshore wind energy. Also limiting the potential for cost reduction in the offshore sector is that in the long term there will not be as many individual projects as for the onshore sector. This means that there will be less identification and utilisation of opportunities identified through experience. For example the installation of a total capacity of 500 MW may involve 50 onshore wind farms compared with only 5 offshore wind farms. This means that the frequency at which cost reduction measures identified through experience can be applied is far higher in the case of onshore wind energy. As a result a significantly higher cumulative

capacity of offshore projects would need to be installed to gain similar levels of experience as those observed for onshore developments. As a result the fact that there are relatively few offshore projects currently scheduled and approved, cost reductions relating to opportunities identified through experience will be at a much slower rate than observed in the onshore industry.

#### **5.4.7 Shortage of installation vessels and skilled contractors**

A limiting factor for the installation of planned offshore wind farms is considered to be a lack of specialist turbine and foundation installation vessels. Jack-up and heavy-lift vessels from the oil and gas sector can be used although it is expected that as the turbines become larger such vessels will be needed for whole seasons at a time; competition from the oil and gas industry will make this impossible. This will mean that installation vessels dedicated to offshore wind farms will be a requirement (Westwood, 2004b). Coupled with this is the availability of installation contractors, who will be in extremely high demand if the forecast increases in capacity for offshore wind farms are realised. In the long term, as this issue is addressed, the total installation costs for offshore wind farms are expected to decrease, although in the short terms costs could rise dramatically.

It has been noted by a number of experts including Hjelmsted (2006), Kowenhoven (2006) and Westwood (2006) that currently scheduled projects are likely to experience delays due to the limited availability of both installation vessels and experienced contractors. Currently there are only two purpose built turbine installation vessels available with only one capable of installing foundations in water deeper than 25m (Hjelmsted, 2006); this vessel already has a significant number of advance bookings. Bad weather at sea is also responsible for project delays. This is exacerbated by the fact that installation vessels and their operators will simply not be willing to wait for the weather to improve when they already have back-to-back contracts for other oil and gas and offshore wind farm developments. Competition from the oil and gas industry for installation vessels is also a major issue due to the fact that oil and gas companies can absorb much higher vessel day rates than an offshore wind farm can. As a result vessel operators will prioritise work in the oil and gas sector.

Again due to the uncertainty that exists regarding future development in the industry, new installation contractors are hesitant to enter the market much less invest in purpose built installation vessels. With a situation where there are a limited number of contractors in constant demand, contractors can demand premium prices for their services, carry on effects of this are increases in the total installation costs for offshore wind farms. The delays caused by the shortage of both vessels and contractors has the potential to increase total installation costs dramatically; in some cases offshore wind farms will have to suspend construction due to bad weather and wait for an appropriate installation vessel to become available. The process of stopping and starting construction operations can be a particularly expensive business.

### **5.5 Factors influencing the costs of offshore wind farms**

At present the economics for offshore wind farms are much less favourable when compared to onshore wind power; significant cost reductions are needed in order for it to become competitive. As discussed in Section 5.4 in order for cost reduction to begin to be observed it is important that measures are taken to both minimise and stabilise the price/cost margin. Once this is achieved, the cost reductions being realised by suppliers will be more visible.

Underpinning the prices of goods and services demanded by suppliers are the costs incurred by the supplier to enable the provision of such good and services. It is believed that increasing experience amongst suppliers of both goods and services to the offshore wind industry is resulting in a reduction in the incurred costs of providing these goods and services.

This section will begin by discussing the lifetime costs associated with an offshore wind farm in comparison to an onshore wind farm. The focus will then shift to the potential for cost reductions, beginning with a summary of the research of Junginger (2005b). As well as cost reductions relating to fixed assets, the potential for reducing operating costs is considered to be significant. Although operational expenditure has not been the main focus of this research the significance of this aspect and the potential for cost reductions will be discussed in Section 5.5.7 and Section 5.5.8.

The lifecycle cost breakdown for both onshore and offshore wind generated electricity is summarised in Figure 5-8. Approximately 75% of the electricity cost from offshore wind farms is attributed to the initial investment costs as indicated in Figure 5-8; as a result initial investment costs are perceived as having the highest potential for cost reductions.

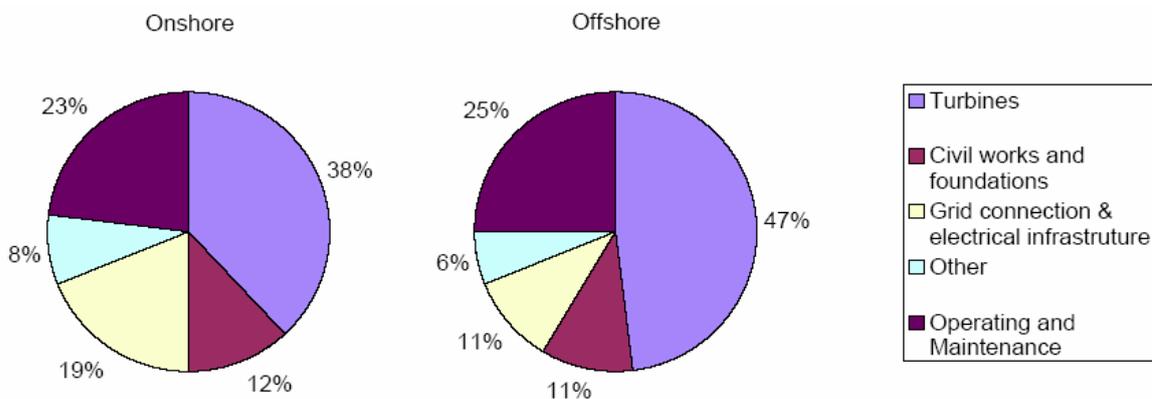


Figure 5-8: Lifetime cost breakdown comparing onshore and offshore wind energy (based on data from BWEA, 2006 and DTI, 2006)

One of the purposes of this study is to explore the potential for offshore wind energy to compete with other sources utilised for the production of electricity. To put things in perspective it has been estimated that the electricity produced from offshore wind farms could be up to 50% more than for onshore, based on equivalent capacity wind farms. Theoretically this means that all costs associated with an offshore wind farm could be up to 1.5 times those for onshore farms while still maintaining an equivalent generation cost i.e. EUR/kWh. Currently the range of electricity generation costs for onshore wind and offshore wind are 800-1100 EUR/kWh (Junginger, 2005b) and 1600-2600 EUR/kWh (Westwood, 2006) respectively.

If operating and maintenance costs are considered to be of a comparable magnitude then the capital investment (turbines, civil works and foundations, grid connection and electrical infrastructure and other) can be directly compared. By making this comparison it can be seen that at the high-end capital investment for onshore wind energy, 1100 EUR/kWh, becomes 1650 EUR/kWh (1100 EUR/kWh + 50%), for an equivalent capacity offshore installation. This is then comparable with the low-end capital investment required for offshore wind

energy, 1600 €/kW. Data collected for this study show prices as low as 1200 EUR/kW for offshore installations which would be comparable to the low-end capital investment required for onshore wind energy i.e. 800 EUR/kW + 50% = 1200 EUR/kW. Based on this high level analysis it can be seen that at some points through the development of the offshore industry there have been projects that have the potential to be competitive with onshore projects from a lifetime perspective.

### 5.5.1 Factors influencing the cost development of offshore wind farms

There are a number of influencing factors that have the potential to bring about cost reductions relating to offshore wind installation; in contrast to this there are also a number of factors that have the potential to further inflate costs. Data from the Netherlands suggests early ‘turn-key’ investment costs were as much as 2500 EUR/kW but in some cases have now decreased to as low as 1600 EUR/kW in 2005 (Junginger, 2005b; Westwood, 2006).

Junginger’s (2005b) work considers the initial investment or capital costs for an offshore wind farm by breaking it down into its major components. A summary of this breakdown and how offshore wind farm investment costs compare to onshore is presented in Table 5-1.

Table 5-1: Comparison of onshore and offshore wind farm initial investment costs (Junginger, 2005b)

Initial Investment Costs	Onshore	Offshore
Total turnkey investment costs 2005	800-1100 EUR/kW	1600-2600 EUR/kW <sup>c</sup>
Wind turbine	65-75%	30-50%
Foundation	5-10%	15-25%
Internal grid and grid connection to shore	10-15%	15-30%
Installation <sup>a</sup>	0-5%	0-30%
Others <sup>b</sup>	5%	8%

a In many publications, the installation costs are not listed separately, but are allocated to other components.

b Miscellaneous items such as engineering costs, project management, interest during construction, etc

c Westwood, 2006; using an exchange rate of GBP 1 = EUR 1.47.

The discussion regarding the influencing factors for the cost development of offshore wind farms will begin by using a bottom-up approach, based around the major components of wind turbines, electrical infrastructure, foundations and installation, similar to that detailed in Table 5-1; in line with the approach utilised by Junginger (2005b). The trend for wind farms to be located further from shore, as a factor for cost increases, will also be discussed.

Operating costs make up a significant proportion of the lifetime costs for offshore wind farms; estimated as 23-25% as summarised in Figure 5-8. For a developer operating costs for an offshore wind farm are recuperated through the sale of electricity. As a result the

operating costs per unit of electricity produced (e.g. EUR/kWh) is the most relevant basis for comparison. One of the strengths of offshore wind farms is expected to be the potential decreases in production costs. The operating costs for onshore wind farms have shown significant decreases as detailed in Table 3-1. A number of opportunities with the potential to decrease wind farm operating costs exist. These opportunities can be divided into two distinct categories: increase efficiency and increased availability.

In addition to these opportunities a development that is expected to increase the competitiveness of offshore wind energy, from an operations perspective, is the introduction or strengthening of CO<sub>2</sub> charges.

### **5.5.2 Cost reductions for wind turbines**

Offshore wind farms installed during the 1990s were basically only upgraded onshore turbines installed nearby to shore. Starting in about 2000 purpose designed units began to be installed, similar to onshore wind energy many of the cost reductions achieved in recent years have been due to increasing height, rotor diameter and capacity; the average size of turbines in 2004 was 2-3MW and it is expected that by 2008 this average will increase to 4MW (Jones & Westwood, 2005).

It is expected that the trend in offshore turbine development of increasing capacity will continue. The disadvantage of this is that in general as turbines increase in capacity the size also increases. Increases in size most often result in increases in weight, and thus a requirement for more substantial foundation structures. Historically the increase in the weight of turbines has been limited by the utilisation of lighter materials and the optimisation of design, although it is not clear if this trend can continue. Additionally there will be some limit to the upscaling of wind turbines but this is a yet to be determined constraint.

As with onshore wind turbines, as technology develops and designs become standardised significant savings are expected to be realised through the mass production of wind turbines. For onshore wind turbines savings through economies of scale have been significant. The largest order found by Junginger (2005b), an order for 1600 turbines, resulted in unit turbine price that was 45% less than the original list price. Offshore wind farms have the potential to involve large numbers of individual turbines; consequently economies of scale are expected to provide a significant opportunity for cost reduction. Junginger (2005b) is of the opinion that economies of scale will not be realised until turbines have reached a maximum size.

Junginger's (2005b) quantification for the expected cost reduction for wind turbines utilises an ambitious PR of 81%. This is justified by the fact that the offshore wind sector will most likely continue to develop as a global sector therefore, the development of offshore wind turbines should be in line with the global development of onshore wind turbines as presented in Figure 3-8. Due to the advanced level of development already achieved for onshore wind turbines it is also possible that the development for offshore wind turbines will be more gradual than that for onshore units.

### **5.5.3 Cost reductions for grid connections**

With regards to grid connections for offshore wind farms, HVDC (high-voltage direct current) or HVAC (high-voltage alternating current) connections are used. Over short distances HVAC connections are considered to be more economical although HVDC connections could be more attractive for use over the longer distances expected for offshore

wind farms (Junginger, 2005b). It has been estimated that HVDC connections will most likely be attractive for distances over 50 km, much further than existing wind farms and those planned for the near future (Kouwenhoven, 2006). Even so the cost associated with the use of HVDC could be significant and it has been estimated that the transmission costs associated with transporting wind power up to 2000 km could cost up to 1.2 ¢(€)/kWh<sup>7</sup> (DeCarolis & Keith, 2001).

Although currently none of the existing or planned offshore wind farms are utilising HVDC, Junginger's (2005) work assumes that cost reductions are possible for the utilisation of HVDC. Based on similar applications, excluding the cost of installation, Junginger (2005b) predicts that there will be a rapid decline in the cost of HVDC cable; PR of 62%. The converter stations required for HVDC transmission are also significant in terms of cost; for this component Junginger (2005b) assumes a PR of 71% based on technological advances. Costs for the internal grid connection are estimated to be constant and only contribute a minor share of the investment costs associated with an offshore wind farm.

#### **5.5.4 Cost reductions for foundations**

Two main types of foundation have been utilised for offshore wind farms; gravity based structures (GBS) and monopiles. Junginger (2005b) assumes that for future installations both monopole and tripod foundations are most likely to dominate. Junginger (2005b) envisages that savings will be made through economies of scale, reduced material consumption and reduced material cost. Elsam are also involved in research and development work aimed at reduction of material consumption through a more precise calculation of the stress loadings exerted by the turbine on the foundation. The cost of steel dominated the material cost for foundations. Junginger (2005b) estimates that steel costs will decline by 1-2%/yr resulting in a 5-10% reduction in overall foundation costs. Due to the high demands for steel, particularly from China, and its subsequent increasing scarcity, the assumption that steel prices will reduce is thought to be quite ambitious.

Regarding offshore wind farms there is a trend for the utilisation of wind turbines of increasing capacity. This is a trend that is expected to continue. It is expected that in the future higher capacity wind turbines will mean that fewer individual units will be required for a given capacity. As a result, although the cost of the turbines will be higher, the costs for installation, particularly for foundation work, will be lower.

#### **5.5.5 Cost reductions for installation**

The installation of offshore wind farms to date has often involved the use of installation vessels from the oil and gas sector. The cost of such vessels, most often day rates, is dependent on both oil prices and competing demand from the oil and gas sector. As a result Junginger (2005b) is of the opinion that the expectation of future price reductions may not be realistic. Junginger (2005b) goes on to say that the greatest opportunity for cost reduction in relation to installation vessels is the increased availability and utilisation of purpose built vessels dedicated to the installation of offshore wind farms. This is an opinion that is shared by a number of industry experts including, Westwood (2006), Hjelmsted (2006) and Kouwenhoven (2006). The use of dedicated vessels would mean that day rates would be far less dependent on oil prices. Currently there are a number of purpose built installation

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<sup>7</sup> Using an exchange rate of 1 GBP = 1.47 EUR

vessels; although based on the ambitious development plans for offshore wind farms these vessels are often reserved seasons in advance meaning that they are currently in short supply. Installation rates are also dependent on weather, that can be a real issue for offshore wind farms due to the fact the sites considered to be attractive for the location of offshore wind farms are those that are subject to extreme weather conditions.

An additional advantage of using purpose built vessels is that they are more suited to the demands of offshore wind farms. Junginger's (2005b) study has shown that these vessels need to be able to move quickly from site to site which is in contrast to the requirements of some oil and gas facilities. Also the cranes and lifting capacity are suited to the increasing size and weight of offshore turbines. These factors mean that increases in installation efficiency have the potential to decrease the installation costs for offshore wind farms. This fact was demonstrated at the Horns Rev project in Denmark where the average installation time was reduced from 3 days per turbine to 1.4 days per turbine. At both the Horns Rev and Nysted projects in Denmark the installation rates were observed to decrease by approximately 23%.

Junginger's (2005b) work considered the foundation installation as a separate component. In this case lower rates of cost reduction are assumed; PR of 95%. This is due to the lack of recently observed improvements but is based on the fact that there is still some room for reduction through both the standardisation of foundations and technological improvements. As mentioned for foundation the increasing capacity of turbines may also result in decreasing installation costs due to the decrease in the number of units requiring installation.

Another area for potential cost reductions that could be thought of as process improvement through learning effects is through both streamlining and greater interaction and communication throughout the supply chain. Greater interaction between contractors and project developers is also perceived as an area for potential cost reductions. At the same time contractors have to be confident of a consistent stream of upcoming projects to warrant the investment of both time and money into improvements. This is an issue that can potentially be addressed through policy measures.

### **5.5.6 Cost increases due to moving further from shore**

It is an observed trend that offshore wind energy projects are moving further offshore. Reasons for this include maximising electricity generating capability through the utilisation of stronger and more consistent winds and also reduced societal opposition as the wind farms are far enough from shore so that visual obstruction and noise related issues are drastically reduced.

Moving further offshore also means having to contend with more extreme conditions; conditions that are unfamiliar and somewhat unpredictable. As a result for the initial developments moving further offshore into subsequently deeper water development prices are expected to be significantly higher due to the associated risk; high prices will continue until adequate experience is gained.

### **5.5.7 Cost reductions due to increased efficiency**

One of the main strengths of offshore wind farms is their ability to obtain increased capacity factors when compared to equivalent capacity onshore installations; the capacity factor is used to estimate the energy output for a wind farm based on its capacity. Without

significantly increased capacity factors over those achieved by onshore projects the economics of offshore wind energy become questionable.

The capacity factor for a wind farm is highly sensitive to the average wind speed at the location. As a result an increased certainty of wind patterns will lead to better site selection and ultimately result in the development of projects with maximised capacity factors; the optimal selection of development sites is of utmost importance. A great deal of effort has gone into mapping wind patterns across Europe by companies such as Douglas Westwood Ltd. By maximising the capacity factor the per unit electricity generating costs are minimised. Even for current developments potential offshore sites undergo extensive monitoring as the achievable calculated capacity factor for a particular project will be critical to deciding whether or not the project will go ahead.

An additional factor is that offshore wind patterns and strengths in specific areas remain largely unmapped (Westwood, 2005a). There is a considerable amount of work being done in this area. Once more comprehensive information is available the optimal location and potential energy generation will be able to be more precisely calculated leading to more robust project economics. This in itself has the potential to initiate significant cost reductions through boosting industry confidence. A focus on more comprehensive wind mapping both across Europe and extending to other areas of the globe, where the development of an offshore wind industry is likely, has the potential to increase the viability of offshore projects in general. Increased access to wind pattern information will have the affect of maximising yield and hence minimising generation cost.

### **5.5.8 Cost reductions due to increased availability**

In order for wind farms to maximise their energy output the availability of individual turbines needs to be maximised. Increased unit availability will result in significant decreases in operating costs, particularly maintenance costs (Hjelmsted, 2005; Kouwenhoven, 2006). This makes sense as the energy produced by a wind farm is dependent on the energy output of the individual units which in turn is dependent on the availability of the unit.

The trend for the installation of higher capacity turbines could be seen as a risk due to down time for individual units resulting in greater losses of energy output when compared to smaller capacity units. The expectation is that the availability of units will actually increase. This is due to the fact that the use of higher capacity turbines means that for a given wind farm capacity a smaller number of units will be required. This means that maintenance efforts can be dedicated to a smaller number of turbines; this provides the opportunity to carry out more preventative maintenance that should improve both the reliability and availability of the units. In addition to this when a turbine malfunctions unexpectedly the affected unit can be given immediate attention and brought back online in as short a time as possible. As a result the installation of higher capacity turbines is expected to result in increased availability and decreased maintenance costs. Improvements in technology, where offshore wind turbines are more suited to offshore conditions, are also expected to reduce maintenance requirements and increase unit availability.

## **6. Concluding remarks**

The potential for offshore wind as an energy resource has been assessed as being far in excess of that for onshore wind. Currently the most effective technology for the utilisation of offshore wind energy has been through the use of wind turbines. The costs associated with offshore wind farms are high and at their current levels are prohibitive to the continued development of offshore wind farms. Experience curve analysis for the historical development of the total installation costs for offshore wind farms have shown that the total installation costs are actually increasing. This result is in contrast with the expected cost development for a new technology and places some concern over the continued development of offshore wind farms.

Experience curve analysis of offshore wind farms has shown that the experience curve method of analysis, on its own, is not particularly robust. As a result although experience curve analysis is a powerful tool for considering the cost development and future costs for an energy technology it should be used with care. In particular the practice of plotting data on double-logarithmic axes can be misleading. As a result of these factors additional methods of analysis were used to compliment the experience curve analysis and explain the trends observed.

Investigation of the trend of increasing total installation costs showed that the main reason for the increases observed was due to the type of data being used. Ideally cost data should be used to develop experience curves; when price data are used, experience curves will only provide an accurate representation of the development of a technology if the price/cost margin is constant. This study considered the total installation costs for offshore wind farms as incurred by the wind farm developer. The total installation cost for an offshore wind farm is set by the sum of the price of turbines, the price of foundations, the price of electrical infrastructure and the price of installation. As a result, total installation costs are most appropriately labelled as price data with respect to experience curve analysis.

If the total installation cost data are considered as price data then the trends observed are indicative of a market failure. The main cause of the market failure in this study has been found to be a lack of competition, particularly amongst turbine manufacturers. This is exacerbated by the fact that the onshore wind turbine sector remains in a period of rapid growth, providing little incentive for turbine manufacturers to consider the production of 'high risk' offshore wind turbines. It is still anticipated that cost of producing and installing the main components of an offshore wind farm are decreasing based on increasing experience; although these benefits will not translate to reductions in price until the market situation is addressed. It is also the case that the longer that the current situation continues, the more difficult it becomes for newcomers to initiate business in the offshore sector.

Newcomers to the sector have also been discouraged by the uncertainty of planned projects actually going ahead. In 2003 it was estimated by Beurskens et al. that by the year 2006 there would be between 3.2 GW and 3.4 GW of installed offshore wind capacity, in reality there will only be 0.9 GW. As recently as February 2005, Westwood (2005) forecast that 304 MW of offshore capacity would be installed in 2005, this was made up by two 90 MW projects in the UK, one 120 MW project in the Netherlands and a demonstration unit off Germany. In reality only one of the UK projects was completed with the remainder being pushed back at least one year. The same article estimated that a further 747 MW of additional capacity would be installed during 2006, this figure is looking more likely to be approximately 260 MW

including one of the 90 MW UK projects pushed back from 2005. With only 7 full scale projects scheduled for the next ten years it is important that these projects run smoothly to stimulate further growth in the offshore wind energy sector.

The potential for decreases in electricity production costs for offshore wind farms is perceived to be great. It is after all the electricity production costs that are the most important consideration for an energy technology. Electricity production costs are based on the total capital and operating costs distributed over the total produced electricity over the lifetime of the project. As a result reductions in electricity production costs can be achieved through both cost reductions and increased electricity production.

Although not currently visible it is anticipated that cost reductions for the production of wind turbines are being achieved. This is also expected to be the case for foundations and electrical infrastructure, although to a lesser extent. It is believed that the main reasons for these cost reductions are increasing experience and economies of scale. Increases in individual wind turbine capacity should also create opportunities for total installation cost reductions. Increased wind turbine capacity will mean that for a wind farm of a defined capacity less individual units will be required, this will in turn reduce the costs associated with the foundations and electrical infrastructure required to install the turbines. A decrease in the total requirement for foundations and electrical infrastructure may be of greater relevance than decreases in the costs of producing these components. A decrease in the number of individual wind turbines needed for a wind farm is also expected to bring about decreases in operating and maintenance costs due to the attention that can be devoted to individual units.

Increased electricity production from a wind farm of defined capacity can be achieved through increases in both efficiency and availability of turbines. Improvements to the efficiency and availability of offshore wind turbines is believed to hold significant potential, perhaps even greater potential than reductions in the total installation costs for offshore wind farms. Improved mapping of wind patterns and the subsequent better location of wind farms will improve the efficiency of offshore wind turbines. In this way the capacity factors and hence the efficiency of offshore wind turbines will be maximised. There is also potential for increases in the availability of offshore wind turbines. Improvements in technology are one factor that will increase the availability of offshore wind farms. Additionally the installation of higher capacity turbines should also bring about availability improvements; where more attention can be given to the operation and maintenance of individual units.

An externality that has the potential to benefit wind energy is CO<sub>2</sub> emissions. An estimate of the potential increases in cost due to a high-end cost of £30/tonne CO<sub>2</sub> emissions is presented in Table 6-1, this amount corresponds to the reported cost of CO<sub>2</sub> sequestration (RAE, 2004a). Based on this comparison it can be seen that with rising CO<sub>2</sub> emission costs renewable wind energy becomes competitive even at current costs. With the energy demand across the globe expected to increase by 60% by 2030 (GWEC, 2005) wind energy is set to play an important role as an energy source for electricity production.

Table 6-1: Comparative costs for electricity from different energy types (RAE, 2004a)

Energy Type	¢(€)/kWh <sup>8</sup>	
	No CO <sub>2</sub> cost	CO <sub>2</sub> cost €44/tonne CO <sub>2</sub>
Onshore Wind	5.4	5.4
Offshore Wind	8.1	8.1
Coal	3.6-4.7	7.3-7.6
Gas	3.2-4.6	6.3-7.1

Lako (2002) has stated that: 'No single country has the potential to create an offshore wind market on its own'. The continued development of the offshore wind sector is dependent on increased competition in the market place. This in turn depends on confidence in the continuing development of the industry that can only be demonstrated through long-term stability demonstrated by the completion of planned projects and government policy aimed at stimulating the growth of offshore wind farm developments. It is likely that cost reductions for offshore wind farms will occur at a slower rate than for onshore wind although this will be compensated by an increased energy output per unit of installed capacity. Continued government support and the completion of planned projects should ensure that offshore wind farms achieve their potential as an energy technology.

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<sup>8</sup> Using an exchange rate of GBP 1 = EUR 1.47

## **7. Recommendations for Future Work**

Most of the analyses and discussion in relation to this study have been from a qualitative perspective. A number of influencing factors relating to both price increases and cost reductions have been discussed. It would be interesting to attempt to quantify these factors. This type of quantitative analysis would require the collection of cost data. As indicated due to the highly competitive nature of the offshore sector, cost data are extremely difficult to access.

From the perspective of this thesis, in order to access more detailed financial information relating to individual projects an official project with confirmed cooperation from the majority of offshore wind farm developers and turbine manufacturers would be necessary. This would give the companies confidence in the objectives of the project, and should ensure greater transparency and access to cost information. If such a project could be established it is believed that much of the qualitative analysis presented in this study could be reinforced through quantitative assessment.

It would also be interesting to further explore the reasons that national plans for the development of offshore wind farms are not being achieved. Some of the reasons mentioned are uncertainty of long-term support due to potential changes in government policy and also the difficulty of attaining the necessary permissions. These are reasons that could be further investigated. Building on this, once the most likely reasons have been identified, recommendations regarding the most appropriate way of encouraging continued development of the offshore wind industry could be made.

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