Experience Curves: A Tool for Energy Policy Assessment

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Project title: Experience curves - a tool for energy policy programmes assessment (EXTOOL)
Summary

The objective of the project, *Experience curves: a tool for energy policy assessment (EXTOOL)*, was to analyse the experience curve as a tool for the assessment of energy policy measures. This is of special interest, since the use of experience curves for the assessment of energy policy measures requires the development of the established experience curve methodology. This development raises several questions which have been addressed and analysed in this project. The analysis is based on case studies of wind power, an area with considerable experience in technology development, deployment and policy measures. Therefore, a case study based on wind power provides a good opportunity to study the usefulness of experience curves as a tool for the assessment of energy policy measures. However, the results are discussed in terms of using experience curves for the assessment of any energy technology.

The project shows that experience curves can be used to assess the effect of combined policy measures in terms of cost reductions. Moreover, the result of the project shows that experience curves could be used to analyse international “learning systems”, i.e. cost reductions brought about by the development of wind power and policy measures used in other countries. Nevertheless, the use of experience curves for the assessment of policy programmes has several limitations. First, the analysis and assessment of policy programmes cannot be achieved unless relevant experience curves based on good data can be developed. The authors are of the opinion that only studies that provide evidence of the validity, reliability and relevance of experience curves should be taken into account in policy making. Second, experience curves provide an aggregated picture of the situation and more detailed analysis of various sources of cost reduction, and cost reductions resulting from individual policy measures, requires additional data and analysis tools. Third, we do not recommend the use of experience curves to analyse learning investments and cost effectiveness of policy measures. Our analysis illustrates too many shortcomings for such analysis using experience curves.

Due to the limitations of experience curves, we believe that complementary methods are required for the assessment of energy programmes. However, we recommend the traditional use of experience curves as a tool to support strategic decisions. Based on experience curves, strategies and policy measure of relevance for new emerging energy technologies could be discussed, e.g. R&D measures to effect radical innovations versus market based policy measures to effect learning and incremental cost reductions. Used in the right way, experience curves can assist several actors, such as financial analysts, researches and policy makers, in analysing and assessing strategies and policy measures.
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1. Introduction

The transition towards a sustainable energy system will require the development and deployment of new and improved energy technologies. This, in turn, calls for methods of analysing the dynamics of energy systems in regard to technical change and policy instruments for effecting and accelerating technical change. Such methods are limited and the development and assessment of complementary methods are important.

Experience curves may provide a tool for analysing technical change and policy measures for implementing and promoting technical change. In general, experience curves are used to analyse the trend of cost reduction of new technologies. Experience curves have also been used as a tool for production and strategic analysis in industry. In recent years, experience curves have also been used for energy technology analysis.

1.1 Objective

The objective of the project, *Experience curves: a tool for energy policy assessment (EXTOOL)*, was to analyse the development of the experience curve methodology for the assessment of energy policy. The analysis includes the development of experience curves, analyses of different sources of cost reduction, and analyses of the effect of different energy policy programmes in relation to the experience curve e.g. the effect on the ride down the experience curve, the effect on the experience curve itself, and the cost effectiveness of different programmes measured by the experience curve. The result of the project describe the advantages and disadvantages, the potential and limitations and the relevance of using experience curves as a tool for different energy policy programmes assessment.

In the project, the development of the experience curve methodology is based on case studies of wind power and analysis of cost reduction due to different wind policy programmes. The wind policy programmes in Europe in the 1990s have resulted in a major development and deployment of wind turbines. Therefore, a case study based on wind power makes possible the development of experience curves and the analysis of the assessment of policy programmes. However, the results are discussed in terms of using the experience curve for the assessment of any energy technologies, with the focus on renewable energy technologies, and policy programmes in general.
1.2 Experience curves

1.2.1 State of the art

Experience curves have been used for several decades to analyse the cost reduction of new technologies (experience curves are described in Box 1.1). The concept of experience curves is based on learning curves, which have been used to analyse the reduction in man-hours (or cost) per unit of a standardised product produced by an individual company. (For the first publication on technological learning, see Wright (1936), and for a recent survey, see Argote and Epple (1990)). Experience curves have, however, come to be used in a more general way than learning curves, and refer to cost reductions for non-standardised products produced globally, nationally, or by an individual company. The cost reduction refers to the total cost (labour, capital, administrative costs, research and marketing costs, etc.), and sources of cost reduction include cost reductions due to changes in production (process incremental innovations, learning effects and scaling effects), changes in the product (product incremental innovations, product redesign and product standardisation) and changes in input prices.\(^\text{19}\)

An experience curve describes the cost reduction of a technology as a function of cumulative experience in terms of units produced, units sold, etc. However, experience per se does not lead to cost reductions, but rather provides opportunities for cost reductions. The cost reduction, and the experience gained, will depend on market demand and market enlargement. Market demand, in turn, will depend on the cost and performance (e.g. quality, function, user-friendliness, efficiency and durability) of the new technology relative to existing technologies. In the long term, cost reduction will be limited by physical limits on technology development, cost limits and market potential. In the short and medium terms, cost reduction, and the rate of cost reduction, may be limited by market barriers such as high initial cost, limited product performance, limited information, limited product availability, limited access to capital etc. and the rate at which manufacturers are able to reduce costs through increased production. Cost reduction, and the rate of cost reduction, can be affected by policy instruments that stimulate technology development and market demand. Thus, the development of the experience curve will depend on policy measures.

\(^{19}\) It is open to debate whether scaling effects should be included in the experience effect or not. The overlap between experience and scaling effects is, however, so great that it is difficult to separate them. In this report scaling effects are considered part of experience.
Box 1.1 Experience curves

Experience curves describe how cost declines with cumulative production, where cumulative production is used as an approximation for the accumulated experience in producing and employing a technology. A specific characteristic of experience curves is that cost is reduced by a constant percentage with each doubling of the total number of units produced, see figure below. The observed cost reduction for different technologies covers a range from approximately 65% to 100% for each doubling of the total number of units produced.

![An experience curve on (a) linear and (b) log-log scales. The experience curve shows a 20% cost reduction with each doubling of the total number of units produced.](image)

Generally, an experience curve is expressed as:

\[ C_{\text{CUM}} = C_0 \cdot CUM^b \]

where \( C_{\text{CUM}} \) is the cost per unit as a function of output, \( C_0 \) is the cost of the first unit produced, \( CUM \) is the cumulative production over time, and \( b \) is the experience index. The experience index is used to calculate the relative cost reduction, \((1-2^b)\), for each doubling of the cumulative production. The value \((2^b)\), which is called the progress ratio (PR), is used to express the progress of cost reduction for different technologies. A progress ratio of 80%, for example, means that costs are reduced by 20% each time the cumulative production is doubled.

In theory, an experience curve is a straight line on a log-log scale and cost reductions are based on incremental improvements. However, an experience curve represents the combined effect of a large number of parameters, that may fluctuate on a short time scale. Thus, only after many doublings of production can the underlying pattern or trend be distinguished. Moreover, and in practise, the cost reductions illustrated by an experience curve do not always follow a straight line. It has been observed that some experience curves show discontinuities, or a distinct break. Such discontinuities may be the result of a pricing strategy (e.g. price reduction levels off at a different rate than the cost reduction, see, for example, BCG, 1972; Ayres and Martinás, 1992). Discontinuities may also be the result of major technological changes (radical improvements). It could be argued that such a break calls for the use of two separate experience curves. One problem is that the distinction between incremental and radical changes is subtle and often somewhat arbitrary.

*For each doubling of the cumulative production \((CUM_2 = 2CUM_1)\) the relative cost reduction will be

\[ \frac{C_{\text{CUM}_2} - C_{\text{CUM}_1}}{C_{\text{CUM}_1}} = 1 - \frac{C_0 (2CUM)^b}{C_0 \cdot CUM_1^b} = 1 - 2^b \]
Experience curves have traditionally been used to analyse the historical trend in cost reductions. Moreover, experience curves have been extrapolated and used to analyse future cost reductions in strategic decision making. Experience curves are often based on price data and not on cost data. The use of price data will, however, only be accurate if price/cost margins remain constant over time or are considered in the analysis.

1.2.2 The development of the experience curve methodology

In recent years the experience curve methodology has been developed within energy analysis, and experience curves have come to be used to analyse cost trends of various energy technologies. Moreover, experience curves have been extrapolated and used to analyse future energy costs and the potential of the commercialisation of new energy technologies. Experience curves have also come to be used for analysing the effect of policy measures on the development and commercialisation of new energy technologies.

The experience curve methodology used in energy analysis today is complex. As described in Section 1.2.1, the experience curve concept includes non-standardised products produced globally, nationally or by an individual company. This is also the case when experience curves are used for energy analysis. As products, not only energy technologies (wind turbines, solar cells, combustion facilities etc.) but also energy carriers (electricity, oil, biomass etc.) are considered. Experience curves are developed both in an industrial perspective (based on technologies produced by an individual company, in a specific country or globally) and in a market perspective (based on technologies installed in a certain region).

Experience curves have also come to be used for analysing future energy costs and the potential of commercialisation of new energy technologies. Such analyses provide policy makers with important information on the trend of cost reduction of new energy technologies. The extrapolation of experience curves has also been integrated into complex energy modelling for future energy scenarios. Moreover, the use and the potential use of policy measures have been assessed using experience curves. The importance of RD&D measures has been analysed, the cost effectiveness of incentives has been evaluated, and the possibility of boosting markets for new energy technologies through incentives has been analysed by the use of experience curves. However, several questions arise when using experience curves with these new applications. These questions are addressed in this report.

Although the experience curve shows a simple quantitative relationship between price and cumulative production or use of a technology, the curve must be seen as the
combination of several parameters that effect cost reduction. The weakness of many experience curve analyses has been the neglect of several parameters that effect cost reduction. Instead, cost reduction has been treated as a variable that depends only on the cumulative production. The strength of this report is that it includes the analysis of several parameters that effect cost reduction. The results will show how different energy policy measures effect cost reduction and how they effect the experience curve in different ways.

Moreover, the use of experience curves for the assessment of energy policy programmes has to be put in a framework of other methodologies. This is only briefly done within the scope of this report, see next Section (1.2.3).

1.2.3 Other methods of analysing and assessing policy measures

As mentioned above, the objective of the EXTOOL project was to analyse the applicability of the experience curve methodology for the assessment of energy policy programmes. It is thus natural to compare the experience curves with other approaches used for the assessment of energy policies. We have considered both the assessment of energy policy measures in a historical perspective (“ex post”) and the assessment of energy policy measures as decision support for new energy RTD programmes.

In recent years a number of studies have been carried out within the European Union on methodologies and approaches for assessing and designing policies in science and technology. In a European review of methodologies and experience in science and technology policy planning, three distinct groups of approaches are mentioned (Kuhlmann et al., 1999).

I. Science and Technology Foresight
II. Technology Assessment
III. Policy Evaluation

Another review adds a fourth approach to this list (Holtmannspötter and Zweck, 2001); namely:

IV. Technology Forecasting

Science and Technology Foresight (I) has been defined as: “systematic attempts to look into the longer-term future of science, technology, economy, and society with a view to identifying emerging generic technologies likely to yield the greatest economic and social benefit" (OECD, 1996). Similar definitions are to be found in other studies, but there is a general consensus that foresight concerns the impact of technological development on society, with the focus on the identification of broad future trends and
socio-economical aspects of emerging technologies. A broad cross-societal dialogue is an important trait of foresight exercises. Here, experience curve studies may play a limited role as foresight exercises often take a very broad approach and utilise several methodologies.

*Technology Forecasting (IV)* also concerns emerging technologies and their implications, but compared with Science and Technology Foresight (I) it involves less (or no) dialog between the stakeholders. Technology Forecasting primarily focuses on technological and economical aspects. Here, experience curve studies can play an interesting role in forecasting or predicting the future. Techno-economical development is a central issue in the prospective use of experience curves. Technology Forecasting is often mentioned together with similar approaches such as Monitoring, Early Warning, Technology Radar, Key Technologies Lists and Emerging Technologies Lists.

*Technology Assessment (II)*, as Science and Technology Foresight (I), deals with the impact of new and emerging technologies on society, and cross-societal dialogue is essential. Technology Assessment tends to focus on the risks of technologies and secondary implications for society, and the examination of norms and values is important. Consequently, it seems that experience curve analysis can not play an important role.

In several European countries, and especially in Scandinavia, an “evaluation culture” has been developed in science and technology policy planning. *Policy Evaluation (III)* approaches vary from country to country and from issue to issue. A central issue in Policy Evaluation is the impact of the policy in question. Here historical experience curves for the technology in question might be a relevant tool provided that relevant data are available. This will be discussed in more detail later in this report.

Table 1.1 gives an overview of the role of experience curve studies in the different approaches used in science and technology policy planning discussed above.

In general, experience curves can be considered a complementary tool for the assessment of energy policy measures. However, in the prospective use of experience curves (trend extrapolation) we believe there is a need for additional tools, see Table 1.2. It is not possible to directly foresee changes in technology or markets by the extrapolation of experience curves. For this reason it is necessary to combine experience curve studies with methodologies designed for dealing with the future, such as scenarios or Delphi studies. Furthermore, it appears to be natural to focus on expectations
regarding the future development of science, technology and markets when making decisions in energy research policy.  

Table 1.1. Overview of the role of experience curve studies in a number of different approaches used in science and technology policy planning.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Timeframe</th>
<th>Role of experience curve studies</th>
<th>Disadvantage(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science and Technology Foresight</td>
<td>Future development is a central issue.</td>
<td>Not an obvious tool, since societal dialogue is the essential feature.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>Technology Forecast</td>
<td>Future development is a central issue.</td>
<td>One important tool together with other trend extrapolation methodologies such as regression analysis and s-curve analysis.</td>
<td>Reliable technological data seldom available. Can only be used for a series of incremental changes. Major shifts in technology can not be predicted. Must be combined with scenarios or Delphi techniques.</td>
</tr>
<tr>
<td>Technology Assessment</td>
<td>No or limited focus on future developments.</td>
<td>Not an obvious tool since societal dialogue and assessments of the consequences of new technologies are essential.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>Policy Evaluation</td>
<td>Primary focus on historical analysis.</td>
<td>One among several tools for analysing the impact of S&amp;T policies in a historical perspective.</td>
<td>Reliable technological data seldom available. Must be combined with interviews, case studies, etc.</td>
</tr>
</tbody>
</table>

Moreover, it is important to note, that the use of experience curves, and similar trend analysis tools, is only suitable under conditions of low uncertainty, for series of incremental innovations, in short time ranges, and on a highly aggregated level. On the other hand, trend analysis tools cannot be used for prospective analysis under conditions characterised by high uncertainty, shifts in technology or market situation and long time ranges. We are then left with judgemental methodologies such as interviewing experts, expert panels, Delphi surveys, etc. Finally, it is important to emphasize that processes aiming at strategic decisions must include combinations of methodologies and participation of central actors in the domain in question. Here, scenarios and road mapping are often useful methodologies.  

20 Nevertheless, there is a long-lasting tradition within the scientific community to make priorities based on historical results instead of prospective expectations. It is common to grant public support for scientific research on the basis of the historical academical performance of individual scientists and groups of scientists. This has been described as the Model1/Mode2 discussion in recent contributions to the science sociology literature. For further details see Gibbons et al. (1994) and Nowotny et al. (2001).

21 For further discussions on trend analysis and other prospective methodologies in RTD policy making see Jantsch (1967) and Martin (1995).
Table 1.2: Overview of approaches to and methodologies used in prospective RTD policy assessment.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Technology Foresight</td>
<td>- Monitoring and mapping historical data</td>
</tr>
<tr>
<td>- Technology Forecasting, Monitoring, Early Warning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o etc.</td>
</tr>
<tr>
<td></td>
<td>- Trend analyses</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o s-curve analyses</td>
</tr>
<tr>
<td></td>
<td>o experience curve analyses etc.</td>
</tr>
<tr>
<td>- Judgmental methodologies</td>
<td>- Multiple techniques (strategy oriented)</td>
</tr>
<tr>
<td></td>
<td>o interviews</td>
</tr>
<tr>
<td></td>
<td>o expert panels, focus groups</td>
</tr>
<tr>
<td></td>
<td>o consensus conferences</td>
</tr>
<tr>
<td></td>
<td>o Delphi surveys</td>
</tr>
<tr>
<td></td>
<td>o etc.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o road-mapping</td>
</tr>
<tr>
<td></td>
<td>o etc.</td>
</tr>
</tbody>
</table>

Recently, a great deal of literature has been published on the use of experience curves for forecasting the diffusion of energy technologies and for designing energy policies. This literature is often related to operations analysis and econometrics. Hence, there seems to be only a limited focus in recent energy-policy-related literature on combining experience curves with judgmental methodologies. A further analysis of this may prove fruitful but is outside the scope of this study.

1.2.4 Different actors’ use of experience curves

Experience curves can assist different actors in evaluating and analysing the development of technology systems, services etc. However, the shape of an experience curve must be interpreted and conclusions drawn with caution. Which actors can take advantage of the experience curve method? According to the historical development of the experience curve the following actors can be distinguished.

- Financial analysts e.g. in industry: The task of an industrial analyst is to examine methods, strategies and insights with regard to certain goods or services of relevance to the business segment of his company. His advice to the company management will influence strategic decisions, for example, whether or not investment in new products or production facilities will be profitable. The classical example for an evaluation of whether, and under which conditions, a new product will be profitable for a company using the experience curve method is the study of T.P. Wright (Wright, 1936). The analyst can derive figures regarding the necessary (learning)
investments or initial losses, the expected break even point and of course the expected future gains. These figures will be used, among others, to decide in favour of a certain technology or product or not.

- **Researchers:** The value of experience curves for researchers varies, depending on the specific research area. In relation to energy policy and decision making, the experience curves are used for technology assessment, forecasting, scenarios, the development of energy models, etc. Researchers will use values reflecting prices, progress ratios, etc., of technologies in their energy models. Using “real” data concerning historic and expected cost development of energy technologies will influence and improve the output of energy models.

- **Policy makers:** Policy makers make use of both individual experience curves for energy technologies and projected data for future growth and development obtained through scenarios by energy modelling or other methods. Experience curve tendencies can be used to obtain a rough estimate of the development of individual technologies or services. Policy makers may also want to use experience curve for the design and evaluation of policy measures.

### 1.3 Outline of this report

In the EXTOOL project, experience curves have been developed and applied to analyse the applicability of the experience curve methodology for the assessment of energy policy measures. In Chapter 2 we present the experience curves developed for wind power and wind turbines; as will be seen there is not one experience curve for wind power but many. In Chapter 3 we then describe the sources of cost reduction identified, and analyse several parameters that effect cost reduction. In Chapter 4 policy measures applied for wind power development are presented, and in Chapter 5 each policy measure is analysed in relation to how the programme has effected technology development (a push effect on the experience curve) and market penetration (a pull effect on the experience curve) and how these have effected the ride down the experience curve and the observed cost reduction. Moreover, the effect on the experience curve itself is analysed; the effect on the experience curve due to policy measures that limit cost reduction or jeopardise technology quality. In Chapter 6 we analyse the wind power system as national and international learning systems, and in Chapter 7 the cost effectiveness of wind policy measures is calculated. We then consider cost efficiency as policy programme investments in relation to the theoretically required cost identified by the experience curve. In the conclusions of Chapter 7 we discuss the relevance of such cost-efficiency calculations. In Chapter 8 we conclude the report by presenting the synthesis and conclusions of our work.
2. Experience curves for wind power

In this chapter we will present the experience curves constructed and applied in this project. The goal of the project was to develop experience curves for countries in Europe that have made important contribution to wind power development and deployment. Relevant and reliable data were available for the development of experience curves for Denmark, Germany, Spain and Sweden, see Appendices 1 and 2. We also tried to find data for the Netherlands and the UK, but relevant and reliable data could not be found, see Appendix 3. A comparison of the installed wind power capacity in Europe with that worldwide shows that Denmark, Germany, Spain and Sweden account for approximately 85% of the capacity in Europe, and 62% of the global wind power system, see Figure 2.1.

![Figure 2.1 Wind energy capacity installed at the beginning of 2001, expressed as percentages for different countries (based on data from Wind Power Monthly (2002)). During the course of the two-year project wind energy capacity has increased, but the proportions have not changed.](image-url)
2.1 Construction of experience curves

The construction of experience curves for arbitrary technologies or services can be divided into three major steps: (1) data acquisition and verification, (2) data processing, i.e. the construction of experience curves and (3) interpretation of the results. The most time-consuming part of this process is usually the search for reliable data on the process to be analysed. Such data include number of units produced, sold or installed and the cost development of each unit.

Once data acquisition has been completed and all data have been checked and verified the calculation of experience curves can begin. As can be intuited by the term “experiences curves” this implies that more than one experience curve can be derived from the existing data. To clarify this it is useful to recall a simple cybernetic model of experience curves, see Figure 2.2.

![Figure 2.2 Cybernetic model of the experience curve (OECD/IEA, 2000)](image)

An experience curve provides a measure of the performance of a system which (continuously) produces certain products. One can regard the system as a black box with an input and an output. The input is usually measured in monetary terms (e.g. euros). The production system transforms the input (material, know-how, manpower, energy etc.) into a product (e.g. wind turbines, electricity, etc.) which is defined as the output. The output can be measured in various ways e.g. physical units. The transfer function – input to output – describes the performance of the system, e.g. euros/unit. In the case of wind power, the performance of the system could be measured as e.g. euros per unit, euros per megawatt, euros per square metre of rotor area, euros per kWh, etc.
Since there is an interaction between output and input this can be described as a feedback signal. This feedback influences the activities and the performance of the conversion system (black box, production system). The loop back from output to input is defined as “experience”, and characterises the dynamic properties of the production system. The experience is measured by the progress ratio (PR), as described in Box 1.1. The lower the value of the progress ratio the more learning and experience will be gained in the system. For a description of the learning system of wind power, see Chapter 3.

2.1.1 Different types of experience curves

As described in Chapter 1, the methodology of experience curves used has developed. In this context we divide experience curves into different types of curves. First, the experience curve can illustrate two different experience perspectives, the production perspective and the market perspective. The production perspective describes the experience process (learning process) based on production and includes, for example, wind turbines produced by different manufacturers, specific production cost of electricity by turbines produced by different manufacturers etc. Moreover, a market perspective has come to be used, which describes the market, or different countries, as the basis for the experience process. Experience curves based on the market perspective include, for example, wind turbines installed in different countries, electricity generation by wind turbines installed in different countries etc.

Second, we can classify experience curves according to the different system approaches that can be used, describing different parts of the wind power system such as components, wind turbines, installed wind turbines, wind-generated electricity etc. When analysing cost reduction of wind power it is important to realize that the learning system of wind power is an aggregated system of several individual learning systems, see Figure 2.3. One system is the learning system of wind turbines. However, this system can be divided into learning systems of components such as blades, towers etc. Moreover, the learning system of wind turbines can be extended to a learning system of installed wind turbines including foundations, installation, site preparation, land acquisition, necessary infrastructure such as roads, transmission lines etc. Another dimension is the learning associated with wind turbine performance and the expected increase in wind capture and electricity generated. The learning system of wind power is thus an aggregated learning system including the learning systems associated with wind turbines (as described above), siting and wind capture and maintenance.

The development of different types of experience curves will give rise to different progress ratios. Therefore, the development and use of experience curves will require
in-depth understanding and knowledge of which experience curves are relevant. In this study we focused on experience curves for wind turbines and wind-generated electricity.

![Cost of generated electricity](image)

**Figure 2.3** Aggregated system of wind power divided into several sub-systems. Experience curves can be constructed for each sub-system.

### 2.1.2 Calculation of experience curves

When calculating experience curves different methods can be used. The experience curves developed in this project were calculated using an “output-weighting” method, as described by the following equation:

\[
p_t = \frac{\sum_{i=1} p_i \cdot n_i}{\sum_{i=1} c_i \cdot n_i}
\]

where:
- \( p_t \) = average price for year \( t \)
- \( p_i \) = unit price of turbine \( i \)
- \( n_i \) = number of turbines \( i \)
- \( c_i \) = rated capacity of turbine \( i \)
For each year, an average price is calculated, $p_t$, which depends on the unit price, $p_{i}$, of each individual turbine of model $i$, the number of turbines sold, $n_{i}$, and the rated capacity of each turbine, $c_{i}$. Each turbine type is defined by its manufacturer, rated power, rotor diameter and hub height and year of installation. The parameter $c_{i}$ should be regarded a measure of the output quantity. Depending on the definition of the system the output quantity could be described in other terms. For wind turbines, this could also be e.g. the area of the rotor blades or kilowatt-hour of electricity generated.

The resulting average nominal prices, $p_{t}$, must be corrected by a factor – the GDP deflator, $k_{GDP}(t)$ – for each year in order to eliminate the effects of inflation on the collected price data. The GDP deflators used in this project for the countries studied are based on the reference year 2000, published by the IEA (2001). The transformation of nominal price to real price is achieved with the following equation:

$$p_{t,real} = \frac{p_{t}}{k_{GDP}(t)}$$

where:

- $p_{t}$ = average nominal price for year $t$
- $k_{GDP}(t)$ = country-specific GDP deflator for year $t$
- $p_{t,real}$ = inflation-corrected (real) price for year $t$

Finally, the data can be transformed to a reference currency if necessary, e.g. euros, dollars etc. This will be useful in comparisons between international markets. Normalisation to a reference currency $p_{t,ref}$ must be done using the relevant conversion rates $k_{curr}(t)$, which of course usually vary over time. In this project, the euro was chosen as the reference currency and the exchange rate of year 2000 was 1 EUR = DEM 1.96; DKK 7.45; ESP166.4; SEK 8.45 (Swedish National Bank, 2002). Conversion was achieved using the equation below:

$$p_{t,ref} = \frac{p_{t,real}}{k_{curr}(t)}$$

where:

- $p_{t,ref}$ = average nominal price for year $t$ in reference currency,
- $k_{curr}(t)$ = currency conversion factor,
- $p_{t,real}$ = inflation-corrected (real) price for year $t$. 
The experience curves for wind turbines developed in this project were developed as described below.

- The total number of sold and installed turbines, in MW per year, was calculated.
- The average price was calculated, as described above.
- The data for different years were plotted on a log-log scale.
- The data were fitted using a linear regression.
- The progress ratio was calculated.

2.2 Data collected

Technology, production and price data were collected for wind turbines produced and installed in Denmark, Germany, Spain and Sweden. New data were collected and existing data in databases maintained by ISET and Risø National Laboratory were verified. A database including data for approximately 17,000 wind turbines was set up. The records in the database include the following information:

- year (of production/installation)
- name of manufacturer
- turbine type
- rated power (kW)
- rotor diameter (m)
- hub height (m)
- annual production at a reference site (ref. wind speed (m/s), ref. height (m))
- number of units installed
- unit price (in national currency)
- data source

The price information provided is usually provided in local currency and given as nominal value. Recalculation to real prices for the year 2000 was done using the national GDP deflators, as described above. The data collected are based on price-list data and data reported to authorities. In all, an enormous amount of data has been collected. In theory, these data is not sufficient to describe the true cost development of wind power. In reality, however, the data should be considered very good and are the best data available for cost (price) development analysis for independent research. The data collected regarding wind power in Denmark, Germany, Spain and Sweden are described in more detail below.
2.2.1 Data for Denmark

The Danish data collected include data for turbines produced and installed in Denmark from 1978 until 2000. The data for Danish wind turbines include some of the largest wind turbine manufacturers: Bonus, Kuriant, Micon, Nordtank, Vestas, Windworld and NEG Micon (a merger between Nordtank, Micon and WindWorld). The data include year of installation, manufacturer, turbine type, rated power, rotor diameter, hub height, annual production, number of units installed, turbine prices, cost of foundation etc.

A total of 6427 electricity-producing wind turbines have been installed in Denmark until year 2000. Of these 3226 turbines were included in this project, which is equivalent to 50% of the turbines installed in Denmark. Expressed in terms of manufacturer this study cover 81% of all turbines installed in Denmark. We have excluded data for turbines made by small manufacturers, turbines sold only in small numbers and turbines for which data were unavailable or unreliable. The final data are representative of the wind turbines produced and/or installed in Denmark.

The Danish data have been collected from two main sources. Technical data and the number of turbines were obtained from the company Energi- og Miljødata (EMD) in Aalborg, Denmark. EMD collected data on behalf of the Danish Wind Turbines Owners Association up to 2001 with a grant from the Danish Energy Agency. These data have been combined with list prices from different sources. The Danish Energy Agency has, over the years, financed information on list prices of wind turbines from Danish wind turbine manufacturers. From the late 1970s up to the mid 80s data were collected by the Test Station for Wind Turbines at Risø National Laboratory. Between the mid 80s and the late 90s data were collated by the Danish Technological Institute, and in recent years data have been collated by EMD in Aalborg. Information on list prices for foundations, grid connection, insurance etc. has been included in recent years.

Manufacturers usually treat data on exported wind turbines strictly confidentially. However, from an annual statistical report issued by the firm BTM-Consult we were able to estimate the total production of a number of companies from 1989 to 2000. Based on our knowledge on domestic sales from the above mentioned source, we were able to estimate the exports over the period 1989-2000.

Most technical data are unquestionable, and since 1990 electricity production data have been certified by independent authorities such as the Risø National Laboratory, Germanischer Lloyds and Det Norske Veritas. Information on prices is more uncertain. There are no Danish regulations obliging manufacturers or owners to publish data or inform public authorities about actual project costs. Publicly available list prices (ex works) of wind turbines are dependent on the information the manufacturers offers. Therefore, potential problems of validity and reliability are primarily concerned with
cost and prices. The following measures were taken ensure the validity and reliability of the data in the study:

- All data have been scrutinized by experts who would be expected to be able to identify inconsistencies.
- The two sources of data: the database containing price lists and technical data, and the database including number of turbines installed and technical data, were compared and checked.
- List prices were compared with other sources of information. Data from a study carried out for the Danish Energy Agency in 1997 were utilised. The study comprised questionnaire data (collected by EMD) on 17 turbines (500 kW) installed in the period 1993 - 1997 and 33 turbines (600 kW) mostly installed in 1996.

Average actual ex works prices of these turbines have been compared with similar average list prices. In Table 2.1 actual prices and list prices are given together with standard deviations for the two types of turbines. For the 500 kW turbines the difference is almost zero and for the 600 kW machines the difference is only 2.5%. Furthermore, the standard deviations of the prices are only 3% and 5%. This indicates good validity and reliability of the data used in this study. All prices included in the databases are nominal prices, which mean that no deflation has been applied.

Table 2.1. Prices of wind turbines in actual projects and list prices. The values given are in thousands of EUR.

<table>
<thead>
<tr>
<th>Turbines type</th>
<th>Actual projects</th>
<th>List prices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave. ex works price (thousands of EUR)</td>
<td>SD</td>
</tr>
<tr>
<td>500 kW</td>
<td>366</td>
<td>79</td>
</tr>
<tr>
<td>600 kW</td>
<td>422</td>
<td>161</td>
</tr>
</tbody>
</table>

2.2.2 Data for Germany

The data collection for Germany was very successful, however, not all the required data could be retrieved. Data were collected for almost all turbines installed in Germany and produced by manufacturers from Germany or abroad (Denmark and the Netherlands). The most successful German manufacturers regarding manufactured capacity and units are: Enercon, Tacke/Enron (now GE Wind), DeWind, Südwind, HSW, Fuhrlander and Jacobs.
The data for turbines was retrieved from several existing databases e.g. EUWINet, the 250 MW Wind Programme, and the IWET-Betreiberdatenbank. The data were checked, verified, reorganized and compiled into a new database. Turbine data together with officially published price lists and price information for wind turbines on the German market resulted in a database that includes a considerable amount of information on the majority of turbines.

The data include wind turbines produced or installed in Germany from 1983 to 2000. In all, data were collected for 5246 turbines produced, and 9228 turbines installed, in Germany. The acquisition of historic price data before 1988 was not possible in most cases. However, prices could be allocated to 8675 out of 9228 turbines. With respect to installed capacity, turbine prices could be allocated to 5667 MW out of 6056 MW installed capacity. Thus, the success rate of price allocation is about 94% in both cases. A comparatively low allocation rate of prices with values between 55 and 85% of registered turbines was achieved for the years 1987 to 1990 and 2000. No price information at all could be retrieved for the years 1982, and 1984 to 1986.

The allocation of market prices to turbines installed in Germany was achieved in two steps. In the first step, a query was submitted which collates the number of turbines as well as all relevant turbine data sorted according to year of installation, manufacturer, turbine type, rated power and hub height. In the next step turbine prices, published in freely available market overviews, magazines etc. were used to find official list prices of installed turbines for each year, according to construction parameters e.g. rotor diameter, hub height etc. This method of price allocation gives only an estimate of the prices paid in the real business world. Therefore, the data include some constraints and errors which should be kept in mind when working with the data. These constraints are listed below.

- The price references are valid only for single turbines. Wind turbines are often installed in clusters or wind farms with up to 50 turbines. Depending on the size of the installation a significant price reduction can be assumed.
- The year of installation and commissioning of the turbines can differ from that when contracts between operators and manufacturers were signed. This will result in a difference between real and assumed prices if the price of the turbine changed in the meantime.
- An error in the price will arise if extra costs, which are not included in the delivery price, are not specified in the price lists, e.g. transport, installation and transformer. All price allocations assume that prices are on-site prices including transport, installation and transformers (if necessary).
• In order to determine the development of the cost of complete wind power installations a survey among developers was launched in a parallel ISET project. More than 100 companies were contacted and asked to send copies of their marketing brochures for wind park projects to ISET. The feedback from the developers was quite positive. Almost 30 percent of those contacted responded. In total, they submitted material which is estimated to represent a few hundred megawatts of installed wind power capacity. However, the time of commissioning of these projects only goes back to about 1996.

• The acquisition of historic price data was found to be extremely difficult or almost impossible. There were several cases in which inconsistent data were found in various publications. There were also problems in obtaining some actual data on turbines. In one case the marketing department of a successful subsidiary of a Danish turbine manufacturer officially refused to cooperate in to the project by not giving any information on current prices.

2.2.3 Data for Spain

Data for the Spanish manufacturers was obtained from year 1984 to 2000. The data cover the Spanish manufacturers NEG Micon, Ecotecnia, ACSA Aerogeneradores Canarios S.A, Gamesa, Iazar, Abongoa/Desarrollos Eólicos S.A. Wind power, Ecotecnia and Made. The source of the data was mainly IDAE, an institution financed by the state with the aim of promoting renewable energy in Spain. Complementary and verified information was obtained from several manufacturers. The data represent historical data of turbines sold including technical data and total cost of installation.

In total, the data collected for Spanish manufacturers covers 2,382 MW. To this, an exported wind turbine capacity of 19.7 MW (0.7% of turbine production) should be added. However, price data are not available for these turbines. Moreover, data were not available to calculate the price of electricity generated at a reference site.

As mentioned the data collected cover 2,382 MW. This figure should be compared with the total installed capacity in 2000 in Spain, which was 2,836MW (BTM, 2001). The difference between the figures can not be explained. The data collected thus cover 84% of the installed capacity. No data were available on the price of wind-generated electricity in Spain.
2.2.4 Data for Sweden

Data for wind turbines installed in Sweden cover the years 1994 to 2000, and was provided by the Swedish Government. The data include wind turbines that have been granted subsidies by the Swedish Government. No data were available for wind turbines installed before 1994. The data for the turbines include technical information on, for example rotor diameter and hub height and rated power, number of units installed, and total cost of installation. The data cover 221 MW wind power. The total installed capacity in Sweden in 2000 was 241 MW of which 25 MW was installed before 1994. Some of the wind turbines that received subsidies in 2000 will be installed in 2001. No data were available on the price of wind-generated electricity in Sweden.

2.3 Experience curves constructed

In this project we have constructed more than 60 experience curves for wind power, see Appendix 1. The experience curves illustrate two different experience perspectives, the production perspective and the market perspective, as described in Section 2.1.1. The systems studied were wind-generated electricity and wind turbines, produced and installed. We intended to give priority to experience curve for wind-generated electricity, but this proved not to be possible as there was a general lack of data in this area. The types of experience curves developed are presented in Table 2.2. The development of the different types of experience curves is discussed below. The development of experience curves using alternative benchmarking alternatives is discussed in Box 2.1.

The results show that the progress ratio of the experience curves developed is in the range of 83-117%, see Appendix 1. The range depends on the system chosen, the perspective selected, the variation within the data, the manufacturer included, the time frame used and the sizes of turbines included. In the following sections we present some selected experience curves. The figures behind these curves can be find in Appendix 2.

[22] A progress ratio less than 100% indicates a cost reduction, as described in Chapter 1. A progress ratio greater that 100% indicates that the total cost cannot be reduced by product standardisation, process specialisation, scale effects, labour rationalisation, etc., as fast as costs are added through design changes and product performance improvements. Experience curves with increasing progress ratios have been identified in this project for individual wind turbine manufacturers.
Box. 2.1 Benchmarking of energy technologies

The traditional method of benchmarking the performance of energy technologies, in cost per kW, is also being used for experience curves for wind turbines. However, some question the applicability of this traditional method in relation to wind energy technology (DWTMA, 2002), (Molly, 2002). They claim that due to the specific technological nature of wind turbines the traditional method is not adequate and leads to an incorrect evaluation of the performance and success of this modern kind of energy conversion system. According to their point of view, performance should be measured in more appropriate terms, e.g. by price per square meter of rotor area or per unit weight of the rotor head. However, the latter seems not to be suitable for comparisons with other kinds of energy conversion systems. In this project we have of course analysed this approach as well.

From our point of view, the best way to measure the performance of the system is to follow the development of cost reduction of wind turbines in relation to the power produced (kWh). However, the collection of statistically relevant data for this is almost impossible. For the development of a correct experience curve investment data, long-term production data and O&M cost data is required for a very large number of operators. Furthermore, the data would have to be sorted according to different turbine technologies, wind conditions at different sites, investment and financing parameters, etc. However, we consider that using prices of the wind turbines, corrected for the improvement in the turbines efficiency and O&M cost development is a reliable measure for experience curve analysis.

Price per unit capacity. Benchmarking of conventional energy conversion systems is traditionally performed by using unit price per capacity. However, a certain capacity can be obtained with different combinations of hub heights and rotor diameter, depending on the site-specific wind conditions where the turbine operates. The hub height and the diameter of the rotors will have a significant effect on the price of the turbine since the reinforcement of the turbine, due to higher loads, increases non linear with increasing hub height or rotor diameter.

Price per unit rotor area. The amount of wind energy developed depends on wind speed and rotor area. Therefore a larger rotor will provide more electricity than the same generator with a smaller rotor. A larger rotor will naturally be subjected to greater loads than a smaller one. Consequently, the turbine must be constructed so as to withstand this extra load. This usually requires reinforcement of components such as bearings, frame, tower, foundations, etc. which of course increase the cost. If the earnings from the increased energy harvest can cover the extra costs, this will be a profitable investment for the operator. Thus, in the case of wind turbines the specific price per unit rotor area seems to be appropriate. However, this would make comparisons with other energy technologies rather difficult. In this project an experience curve showing price per unit rotor area on the y-axis and cumulated rotor area produced has been developed. However, this experience curve shows very similar tendencies to the corresponding curve for cost per unit capacity of turbines installed in Germany from 1990 to 2001. The progress ratio is about 97%, compared with 94% for price per unit capacity, see appendix 1.

Price per unit power produced. Another way of benchmarking conventional energy technologies is to compare the cost of annual energy production. Traditionally, the annual energy cost per kWh is given by a typical number of full load hours, which can also be a design parameter for power plants. This figure can also be calculated for wind turbines, however, the annual energy yield depends very much on the site and the specific wind conditions. These vary widely, not only on a global level, but also within relatively small distances. Thus the energy harvest can vary significantly. One way of circumventing this problem is to calculate the theoretical value of each turbine using the results of energy yield predictions related to the power curves and a reference wind speed. By doing this, the price efficiency of different types and models of turbines can be compared. Charts showing the trend in price per kWh are compliant with the experience curves of category II (see Section 2.3.2). In experience curves of category III we also include estimated cost development of O&M costs (see Section 2.3.3).
Table 2.2. Types of experience curves developed.

<table>
<thead>
<tr>
<th>Category</th>
<th>Experience curves</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production perspective</strong></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Experience curves for wind turbines (WT) produced by different manufacturers</td>
</tr>
<tr>
<td></td>
<td>- Experience curves for WT produced in each country</td>
</tr>
<tr>
<td></td>
<td>- Experience curves for WT produced in each country, during various time periods</td>
</tr>
<tr>
<td></td>
<td>- Experience curves for WT produced in each country, different sizes</td>
</tr>
<tr>
<td>II</td>
<td>Experience curves for the specific production cost of electricity in each country *</td>
</tr>
<tr>
<td>III</td>
<td>Experience curves for levelised production cost of electricity in each country **</td>
</tr>
<tr>
<td><strong>Market perspective</strong></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Experience curves for wind turbines installed in each country</td>
</tr>
<tr>
<td></td>
<td>- Experience curves for wind turbines installed in each country, during various time periods</td>
</tr>
<tr>
<td>V</td>
<td>Experience curves for cost of wind-generated electricity in each country</td>
</tr>
</tbody>
</table>

* The specific production cost of electricity was calculated by dividing the average wind turbine list price by the number of full load hours. The number of full load hours is, in turn, determined by dividing the average production in roughness class 1 by the average turbine size.

**The levelised production cost of electricity (see Trade and Hunter (1994)) is based on the specific production cost of electricity for wind turbine produced in Denmark (at roughness class 1), the cost reduction in the installation of wind turbines in Denmark, a lifetime of 20 years, an interest rate of 6%, and a model for O&M costs based on surveys of actual O&M costs (see Redlinger, et al., 2002).

2.3.1 Category I: Experience curves for wind turbines

The experience curves of wind turbines describe the price reduction per kW as a function of the total capacity produced in MW. The experience curves developed indicate rather small price reductions. The progress ratio was found to be 92% for turbines produced by Danish manufactures and 94% for turbines produced by German manufactures, see Figures 2.4 and 2.5.

The experience curve in Figure 2.4 is based on the Danish wind turbine industry’s cumulative global sales in the period 1980 to 2000 and price data for a representative selection of Danish turbines. The companies included in the data account for approximately 50% of all turbines (expressed as in both number of units and capacity) installed globally during the past two decades. It is important to note that this experience curve only reflects the decrease in the cost of equipment. Improvements in equipment efficiency are not included. This is taken into account in categories II and III.

The experience curve in Figure 2.4 gives the Danish average price reduction of wind turbines produced by Danish manufacturers. Corresponding experience curves for individual manufacturers result in progress ratios in the range of 89-117%, see
Appendix 1. The average price reduction over different time periods results in progress ratios in the range of 88-95%, see Appendix 1. In Box2.2 the experience curve of Danish wind turbines has been divided into three periods, each with a specific progress ratio.

**Figure 2.4** Experience curve for wind turbines produced by Danish manufacturers: 1981-2000 (PR=92%, $r^2=0.84$). Prices are expressed in 2000 year prices.

**Figure 2.5** Experience curve for wind turbines produced by German manufacturers: 1987-2000 (PR=94%, $r^2=0.74$). Prices are expressed in 2000 year prices.
Box 2.2 Experience curves for Danish wind turbines during three periods

Experience curve for Danish wind turbines can be divided into three periods according to the theory of the BCG (1972).

Period 1 covers the years 1980 to 1984: the conceptualisation and development phase. From the mid 1970s until the early 1980s several wind turbine concepts were tested and produced by small companies entering the awakening wind energy industry. First of all the classic concepts such as the multi-bladed “wind rose”, the two bladed concept, the Darreius concept, the gyro concept, etc, were tried. Of these only the multi-bladed wind rose obtained a significant market share. But already from 1981 the whole Danish wind turbine industry based its production of one concept: the upwind, three-bladed, stall-regulated, grid-connected, horizontal axle concept. Over the years a number of incremental changes to this concept have been introduced. The period 1981 to 1984 was characterised by further development of the Danish wind turbine concept and of the industry’s manufacturing capability. On the market side, the period was characterised by steadily increasing sales in Denmark and rapid growth of exports to California. From a level of less than 5 MW in 1981 exports peaked in 1985 to 243 MW.

Period 2 covers 1985 to approximately 1990; the shakeout phase. During the period 1984 to 1989 a number of new companies entered the wind turbine industry due to the Californian “wind turbine export boom”. A great deal of money was earned during this boom and a number of newcomers were attracted by this business opportunity. From the peak in 1985 the Californian wind turbine market collapsed in 1986 and 1987 and only 88 MW was exported in 1987. As the Californian market collapsed so did most Danish wind turbine manufacturers. Only one Danish company (Bonus) did not file for bankruptcy. The strongest firms were reconstructed with new capital, but newcomers with a short track record were not able to enter the market place again. After a very high progress ratio in the mid-1980s an almost flat experience curve can be observed in the years 1988-1991. One reason for this may be that prices fell rapidly due to the fierce competition within the industry after the decrease in the Californian market and the introduction of several newcomers onto the market. Hereafter, the industry needed some years of reconstruction.

Period 3 covers approximately 1990 until 2000; the stable growth phase. Since 1991 the world market for wind turbines has experienced relatively steady growth. In Denmark a recession in the wind turbine market was observed during 1992 to 1994, especially 1993 with only 36 MW installed in Denmark; the lowest annual installation between 1988 and 2000. These difficulties on the home market could have influenced the Danish wind turbine manufacturers’ global business.

The experience curve in Figure 2.5 was calculated from data from seven German manufacturers that had sold the highest number of turbines, domestically or abroad. The time span ranged from 1989 to 2000. The data were taken from manufacturers that were active on the market during the whole period analysed, “newcomers” who entered the market after 1989, and those who disappeared from the market before 2000. The individual progress ratios for each company show values between 90% and 102%, see Appendix 1. Moreover, the average price reduction during different time periods shows progress ratios in the range of 94-101%, see Appendix 1. When dividing the turbines into different sizes, we find that the progress ratio is only 98-102%.

The minimum value in Figure 2.5 is roughly 894 EUR/kW from 1996. After that time megawatt size turbines, with increased hub heights and rotor diameter, especially
designed for inland sites with lower wind speeds, became more and more important on the market. The production cost of these turbines increased non-linearly with the hub height. Furthermore the generator size was comparatively small in these types of turbines, which increased the price per unit capacity. However, it must be also noted that the situation on the German wind turbine market was, and still is, booming. This means that prices are kept relatively high, customers are willing to pay almost any price for this product.

2.3.2 Category II: Experience curves for the specific production cost

Wind turbines have been improved in more ways than by cutting the costs of ex works turbines. Wind turbines have also been developed to improve wind capture etc. When such improvements are included the price reduction increases. The price development of wind turbines can be expressed as a specific production cost of electricity, which is calculated by dividing the average wind turbine list price by the number of full load hours. The number of full load hours is in turn determined by dividing the average production in roughness class 1 by the average turbine capacity. The reference site selected is a so-called roughness class 1 site, according to the Beldringe data in the European Wind Atlas (Troen and Petersen, 1989). This is slightly better than the average site in Denmark. During the 1980s and 1990s the average roughness class for the sites of new turbines was typically between 1.2 and 1.5.

The progress ratio for the specific production cost of wind power was found to be 86% for turbines produced by Danish manufacturers and 88% for wind turbines produced by German manufacturers, see Figures 2.6 and 2.7. The curves illustrate a higher cost reduction than in category I. This indicates that learning regarding turbine improvement, including annual energy yield, is more progressive. The customer can thus buy a higher degree of wind energy capture from the manufacturer.

The roughness of a land surface is defined by the size and distribution of roughness elements the surface contains. For land surfaces these elements are typically soil surface, vegetation, buildings, etc. The higher roughness the lower the annual average wind speed and the lower the annual electricity production from wind turbines.

For the sake of reproducibility of this study it is important to point out, that by 1991 the definition of roughness classes had been changed from referring to the Danish Wind Atlas to the European Wind Atlas (Riso National Laboratory, 1980) using Beldringe wind data (Troen and Petersen, 1989). A simple formula for transforming old data to the new definition can be derived from the two references mentioned. In the case of roughness class 1, the scaling factor (with which the annual production is multiplied) as function of the hub height, $z$, is calculated as: $\text{factor}_{\text{class 1}} = 0.0023z + 0.8059$, while data for roughness class 2 are recalculated as: $\text{factor}_{\text{class 2}} = 0.0019z + 0.8428$
Figure 2.6 Experience curve for specific production cost of electricity from wind turbines produced by Danish manufacturers 1981-2000 (PR=86%, \( r^2 = 0.97 \)). Costs are expressed in 2000 year prices.

Figure 2.7 Experience curve for specific production cost of electricity from wind turbines produced by German manufacturers 1991-2000 (PR=88%, \( r^2 = 0.87 \)). Costs are expressed in 2000 year prices.
2.3.3 Category III: Experience curves for levelised production cost

In this project we not only calculated the specific production cost of electricity, including improvements in wind capture, but also the levelised production cost of electricity. The levelised production cost of electricity, expressed as cost/kWh is based on the specific electricity production of wind turbine produced in Denmark (at roughness class 1), cost reduction of installation of wind turbines in Denmark, a lifetime of 20 years, an interest rate of 6%, and O&M costs calculated according to a model developed from the results of a number of questionnaires surveys (Redlinger, et al., 2002, pp 77-80). The levelised production cost of electricity is not the same as the actual cost of the electricity generated. In the levelised production cost variables (such as interest rate, O&M costs, and annual wind resource) that change over a wind turbine’s lifetime are levelised to an annual average. The levelised production cost thus provides a reasonable estimate of the actual cost of electricity over a turbine’s 20-year lifetime. The progress ratio for the experience curve of the levelised production cost of electricity is 83%, see Figure 2.8. This indicates that the greater the number of sources of experience (learning) included in the experience curve, the larger the cost reduction. For a more detailed description of different sources of cost reduction see Chapter 3.

Figure 2.8 Experience curve for levelised production cost for wind turbines made by Danish manufacturers, 1981-2000 (PR=83%, \( r^2 = 0.97 \)). Costs are expressed in 2000 year prices.
2.3.4 Category IV: Experience curves for wind turbines installed in different countries

In this project we have also developed experience curves for wind turbines installed in different countries. For Denmark and Germany we were able to develop experience curves describing the price of the wind turbines alone, see Figures 2.9 and 2.10. For Denmark, Spain and Sweden we were also able to develop experience curves for the total installation cost, including the cost of the turbines, foundations, ground preparation, grid connection etc, see Figures 2.11-2.13.

The experience curves for the cost of wind turbines alone, installed in Denmark and Germany, show that the progress ratios are almost the same as those for wind turbines produced in those countries. The Danish data included are based on the accumulated installations in Denmark and the ex works prices of wind turbines on the Danish market. All turbines installed in Denmark have been produced by Danish firms. Although several of these companies have been sold to foreign interests over the years (investment banks) or the shares floated, and although many vital components of the turbines (such as the generators and gearboxes) are manufactured in other countries, the turbines and the manufacturers are usually referred to as Danish.

The German data include turbines manufactured by German companies as well as turbines bought from their competitors abroad. The supply to the German market is almost 60% domestic, while nearly 40% of the installed turbines are manufactured in Denmark. About two percent of the installed turbines has Dutch origin. The major part of this Dutch market share can be identified as small or medium sized turbines (50 kW up to 250 kW) installed in the early 1990s. The few remaining turbines were supplied by manufacturers from the UK, Belgium and Japan. Thus, the experience curve shown in Figure 2.10 represents a combination of German and Danish wind turbine manufacturing experience. However, the progress ratios for turbines installed in these two countries show little difference (Germany 94%, Denmark 91%). One reason for this could be that the Danish manufacturers charge the “German” prices, which are above those of the Danish market. Furthermore, economic and legislative conditions are often quoted by Danish turbine salesmen as the reason why a turbine installed on the German side of the Danish-German border is more expensive than the same turbine installed a few kilometres away on the other side of the border. A tendency towards real price stagnation since 1996 can also be observed in this experience curve.
The experience curves for wind turbines installed, based on total installation cost, including the cost of the turbines, foundations, ground preparation, grid connection etc., in general indicate larger cost reductions than those for the cost of wind turbines alone. The experience curve for wind turbines installed in Denmark has a progress ratio of 91% and an $r^2$ of 0.94. Prices are expressed in 2000 year prices.

Figure 2.9 Experience curve for wind turbines installed in Denmark, 1981-2000 (PR=91%; $r^2=0.94$). Prices are expressed in 2000 year prices.

Figure 2.10 Experience curve for wind turbines installed in Germany, 1987-2000 (PR=94%; $r^2=0.88$). Prices are expressed in 2000 year prices.
90% and for Spain the figure is 91%. The progress ratio for wind turbines installed in Sweden is 96%. However, the Swedish data available are limited to a short time period, and if the first data point of the Swedish experience curve is excluded the progress ratio is only 89%.

**Figure 2.11** 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.

**Figure 2.12** Experience curve for the total installation cost for wind turbines installed in Spain, 1984-2000 (PR=91%, $R^2=0.85$). Costs are expressed in 2000 year prices.
Figure 2.13 Experience curve for total installation cost for wind turbines installed in Sweden, 1994-2000 (PR=96%, r²=0.32). Costs are expressed in 2000 year prices.

2.3.5 Category V: Experience curves for cost of electricity

In this study we intended to develop experience curve for the cost of the electricity generated by wind turbines. However, such data were not available for any country. The only data available were the tariff price of wind-generated electricity. The experience curves for the tariff of wind-generated electricity in Denmark and Germany show a progress ratio of 98% in both countries, see Appendix 1. This does not indicate the cost reductions illustrated by the other experience curves developed in this project. The progress ratio of tariff prices does not even indicate the price reductions of turbines. Moreover, the cost reductions indicated by tariffs do not come close to the cost reductions illustrated by the experience curve of the levelised production cost of electricity (category III). Experience curves based on tariffs for the electricity are thus not relevant for the analysis of wind power development.
3.  Analysis of sources of cost reduction

In this chapter sources of cost reduction will been analysed. Firstly, we will consider sources cost reductions theoretically. Secondly, we will analyse the sources of cost reduction in the wind turbine technology innovation systems in Denmark and Germany. If the nature of the technology in question and the industrial structure surrounding that technology are not correctly understood, the development and use of experience curves will be fraught with many pitfalls. We believe that much valuable insight can be gained by trying to understand and model industrial learning processes a little better, and our aim was to establish such an understanding. Data from the Danish and German technology innovation systems was found to be less comparable than anticipated. Despite this, useful insight can be gained from the material available.

3.1 Theory of technology and innovation revisited

To open up the black box of industrial learning and innovation with regard to the wind turbine industry it is necessary to consider theoretical considerations on technology and knowledge and their dynamic counterparts innovation (change in technology) and learning or experience (change in knowledge).

3.1.1 Some terms and definitions

Technology in its widest meaning contains both means (knowledge, techniques, organization, etc.) and objects (tools, results or products)\(^\text{25}\), but in order to construct an operational technology model we will define technology more narrowly, so that technology has two sides: artefacts and knowledge. The American Heritage Dictionary explains the term artefact as: “An object, esp. a tool produced by human workmanship.

Another common view is to consider technology as either a product or a process. This has often been done by scholars when studying the artefact side of technology. Other scholars focusing on the knowledge part of technology tend to use other terms, such as conceptual knowledge and manufacturing or processual knowledge. The first refers to the knowledge necessary to design or construct a certain artefact, for example making

\(^{25}\) For a much more elegant discussion of the relationship between technology, science, art, knowledge, etc, see Layton (1974).
the blueprint. The latter refers to knowledge applied in producing the actual artefact from the blueprint.

When writing about learning, Rosenberg (1982) introduced this distinction through the terms “learning-by-doing” and “learning-by-using”. “With respect to a given product, I want to distinguish between gains that are internal to the production process (doing) and the gains that are generated as a result of subsequent use of that product (using). For in an economy with complex new technology, there are essential aspects that are a function not of the experience involved in producing a product but of its utilizations by the final user. This is particularly important in the case of capital goods” (Rosenberg, 1982, p122). In the following, these aspects will be referred to as manufacturing or processual knowledge and utilisation knowledge.

Knowledge on manufacturing and producing is divided into design knowledge and production knowledge by Vincenti (1984). Design knowledge is based on either production requirements or mechanical requirements, that is the drawing up of the blueprint. Production knowledge is concerned with how the blueprint is transformed into the actual devices or artefacts. Another commonly used categorisation concerns whether knowledge is codified/explicit or tacit. Tacit knowledge, according to Vincenti is “the implicit, wordless, pictureless knowledge essential to engineering judgement and workers’ skills” (Vincenti, 1984, pp.574).

Rosenberg (1982) introduced the terms: embodied knowledge and disembodied knowledge. Rosenberg’s definitions of those terms are somewhat ambiguous, but they are connected to the knowledge acquired through learning in the early stages of an innovation process and then embodied in the product. Embodied knowledge is revealed as constructive changes in an artefact, i.e. a wind turbine. Disembodied knowledge is seen as changes in how an artefact is manufactured or used.

3.1.2 A theoretical model for sources of knowledge and experience

Based on the above terms and considerations we have constructed a model for the sources of accumulated knowledge and learning, see Figure 3.1. The core of the model contains the three types of knowledge in the industrial innovation process: conceptual knowledge, processual knowledge and utilisation knowledge. This follows a generic pattern of the life cycle of a product: design, manufacturing and use.

Experience-based knowledge can be created in three ways. However, through this process, new knowledge is created, which is directly embodied into the design or redesign of the machine. This new knowledge may, for example be improved knowledge on the use of computer codes for design or stress calculations. Targeted
research activities creating codified knowledge are also used this way. We are, however, not concerned with research here but with the learning processes creating tacit knowledge affiliated to development and design.

![Model for knowledge and learning](image)

**Figure 3.1** A theoretical model for types and sources of knowledge and learning.

Secondly, at the centre of the model is the kind of learning Wright observed in the aircraft industry and the kind of learning that the Boston Consulting Group (BCG, 1972) deals with. Learning through manufacturing will lead to improved or cheaper manufacturing of the same product. The product will not be exposed to visible changes due to these improvements; we are talking about disembodied knowledge. In wind turbine technology this could comprise better logistics in purchasing and distribution, outsourcing of production, improvement in the speed of welding robots, etc. Some of the experience gained from manufacturing might lead to suggestions for changes in the design of the product. This kind of new knowledge will be embodied in the product as artefactual changes that will improve the manufacturability of the product.

Thirdly, experience can be gained through the use of a product as pointed out in the above quotation from Rosenberg. Rosenberg might primarily focus on learning gained through the use of a machine, leading to an improved or more efficient use of the machine. This new knowledge is disembodied since it will not cause artefactual changes
in the machine. But if what is learnt is fed back to the design of the machine the new
knowledge can be embodied in the machine. Several heads of R&D departments in
wind turbine manufacturing companies acknowledge that they receive a great deal of
input to their new product development process from the company’s O&M staff. In the
largest companies, this has been formalised into regular meetings between R&D staff
and O&M staff.

As indicated above, models of learning usually only include knowledge affiliated to
design, manufacturing and use of technology. In recent years, however, there has been
an increased focus on the adverse effects of the technology life-cycle impact on the
environment. This includes environmental affects after end use. Therefore, an element
could be added to the model concerning knowledge on dismantling and recycling. Wind
turbines, as other machinery, should be designed with recycling in mind. Alloys might
not only be selected to fulfil certain stress and strain criteria but also to fulfil the
demand for recycling after end use. Also, thought must be given to components that are
difficult to recycle such as electrical cables and hydraulic tubing. For the purpose of this
study, however, we need not include this type of knowledge.

3.2 Historical development of wind turbines

Wind energy technology has progressed considerably from the beginning of modern
wind energy application, in the middle of the 1970s, until today. Amongst other
indicators, this progress can be noted in the increase in plant size, from small plants
rated at about 15 to 30 kW with rotor diameters of less than 15 m, in the early 1980s, to
wind turbines rated at 2 to 3 MW, with rotor diameters of more than 90 m in recent
years.

In 1961 a United Nations conference on new sources of energy was held in Rome. One
of the technologies discussed was wind energy. Surprisingly many topics of discussion
were the same in 1961 as they are in 2002. In Rome in 1961 the cost of wind energy
was discussed. Different concepts and designs were discussed, including simple designs
(such as the Danish design of Juul) and more sophisticated designs (such as the German
design of Hütter). The number of blades was discussed (1, 2, 3, 4 and multi-bladed
designs), as were the advantages of direct-driven generators. Almost all imaginable
concepts of wind turbines were presented in Rome in 1961. Only few new concepts
have been developed since then, and only very few concepts have a significant market
share today.

In the mid-1970s several wind turbine concepts were tested and produced by small
companies entering the awakening Danish wind energy industry. First, classical
concepts such as the multi-bladed wind rose, the two bladed concept, the Darreius concept, and the gyro concept, but also more experimental concepts such as the Ulrik Poulsen windmill were produced commercially. Of these different concepts only the multi-bladed wind rose obtained a significant market share. The 10 kW version with a 5.7 metre rotor diameter became the most sold turbine in 1980, with approximately 12% of the total market (measured in numbers of turbines). From 1981, the whole Danish wind turbine industry developed its technology within a certain concept or paradigm: the upwind, three-bladed, stall-regulated, grid-connected horizontal axle concept. Over the years a number of incremental changes to this concept have been introduced. One company, Vestas, introduced pitch-regulated turbines during the 1980s and in the 1990s variable-speed turbines were also introduced by Vestas. During the 1990s other companies introduced variable-speed turbines.

The development of wind turbine technology has been slightly different in Germany. Table 3.1 shows the degree to which typical construction features can maintain their place in the German market. The percentages given describe the proportion of wind turbines with each particular feature, in relation to the total number of plants installed in each year (ISET, 2001).

Table 3.1 Specifications for wind turbines installed in Germany from 1988 to 2000. The figures given are percentages. (ISET, 2001).

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The clearest development is the combination of three-bladed and up-wind rotors. Other rotor forms have practically disappeared from the market. Manufacturers are concentrating on power control and speed characteristics, with essentially three different construction principles, as before. However, the share of variable-speed turbines has
increased considerably in the past five years. Only turbines with a range of 70-100% of the rated speed are considered to be variable-speed turbines.

Speed variability is increasingly being realised by manufacturers with double-powered asynchronous generators. This type of construction was established about 20 years ago in German “GROWIAN”, but was long thought to be too expensive. Of the plants built in Germany up to 2000, 20% were equipped with double-powered asynchronous machines, which constitute 40% of the variable-speed turbines.

The development of the key characteristic of average turbine size (expressed as rated power and rotor diameter) from 1980 to 2000 is shown in Figures 3.2 and 3.3. It should be noted, that values for the year 1980 to 1985 are based on relatively few machines – especially for Germany, the data cover very few machines and have a large deviation for this five-year period. The figures indicate that the average turbine has increased in size during this 20-year period, and recent data confirm the continuation of this trend in 2001 and 2002. The reason for this development is that larger turbines are more cost effective than smaller ones, and that customers usually wish to buy the most up-to-date products if there are no other technological limitations, e.g. grid capacity. The figures also reflect the differences in market structure in Denmark and Germany. Since the mid
1990s Germany has provided a market for large turbines. Large turbines were thus first installed in Germany and then in Denmark.

With the development in plant size, the inevitable introduction of newer, bigger models has also occurred. The division of these plants into rated power classes, and the annual installation rate of wind power in each class, shows that new models with higher power classes have quickly superseded their smaller predecessors. The current power class has dominated the market for several years, accounting over 50%.

Machines in the megawatt class, established on the market since 1996, have increased their share of the German market for new machines to nearly 80%, leaving the class dominating until now (500/600 kW rated power) clearly behind them (21%). Smaller machines are not usually installed in commercial wind farms in Europe any more. Fifteen plants with rated powers of 2 MW or more were installed in Germany alone in 2000. As wind turbines from 3 to 5 MW are planned for offshore use, it can be expected that the power class of 2 to 3 MW will become established in the coming years, and that experience with these machines will aid the optimisation of offshore wind farms.

3.2.1 New generations of turbines

As mentioned above up-scaling within a technological paradigm is a key process in the technological development of Danish and German wind turbines. Each generation is larger than the preceding generation, measured as rated capacity, swept rotor area, etc. But also within each generation incremental up-scaling has taken place. Typically, each new generation of turbines is designed conservatively with broad safety margins. After some experience of turbines had been gained, these safety margins could be narrowed down. Typically, the experience gained has not been used to produce the same design cheaper but to increase the electricity output by means of a slightly larger rotor diameter, a change in pitch angle, etc.

From 1984 to 1989 a number of new companies entered the Danish wind turbine industry due to the Californian wind turbine export boom in the early and mid-1980s. When the Californian wind turbine market collapsed so did most Danish wind turbine manufacturers. Only Bonus did not go through a bankruptcy process. The strongest firms were reconstructed with new capital but newcomers with a short track record were not able to enter the market place again. That is the explanation of the dip below 75% in Figure 3.4 in second half of the 1980s.

The first generation of industrially produced turbines was based on a 5 metre blade, for example the blade produced by the company “Økær Vind-Energi” in Denmark. The turbines had rotor diameters of 10 to 11 metres and they were equipped with a 15 kW or
a 30 kW generator. This generation of turbines was primarily sold from 1978 to 1981. The most sold machines of this generation were the 15 kW and 18 kW machines manufactured by Kuriant in Denmark, both equipped with a 10.9 metre rotor. WindMatic sold a 22 kW machine with a 10 metre rotor. Also, Vestas and Nordtank sold 30 kW machines, the former with a 10 metre rotor and the latter with an 11 metre rotor.

![Figure 3.4](image.png)

*Figure 3.4* Annual share of the Danish wind turbine market for each generation. The data included cover only manufacturers with a significant market share over several years: Bonus, Micon, Nordtank, NEG-Micon, Nordex, Vestas and WindWorld. For the early 1980s the manufacturers Kuriant, Kongsted and WindMatic are included as they had a considerable market share. The turbines included represent, on average 86% of all the turbines installed (in Denmark) and almost 90% of the turbines installed in the 1990s.

The second generation started as the very popular 55 kW machine with a 15 metre rotor, and the platform was scaled up to a 75 kW machine with a 17 metre rotor. This generation of turbines was developed in the late 1970s. The first versions were designed with a 45 kW generator, but very few of these early 45 kW versions were actually sold. The second generation of turbines was based on a 7.5 metre blade manufactured by Alternegy, and it dominated the Danish and the international wind turbine markets in the first half of the 1980s. Vestas started producing its own blades from the 7.5 metre generation. Vestas produced the, by far, best selling machines in this generation. The Vestas 55 kW turbine with a 15.3 metre rotor was scaled up to a 75 kW machine with a 17 metre rotor. WindMatic also produced 55 kW turbines in different versions that were
scaled up to a 75 kW version. The 55 kW versions were first sold in 1980 and the 75 kW versions were introduced in 1983, but sales of both versions peaked in the same year, 1985. Nordtank entered the market with a 45 kW/15 metre rotor version and this was scaled up to first to a 55 kW machine with 15 and 16 metre rotors and later to a 65 kW machine with a 16 metre rotor. Also, a 75 kW version with a 16.5 metre rotor was sold in limited numbers. Bonus and Micon also produced machines in the 55 kW generation.

The third generation consisted turbines based on a 9 metre blade with generators in the range of 90 to 130 kW. The rotor diameter was between 18 and 21 metres. From this generation onwards LM Glasfiber A/S has been the dominating blade manufacturer supplying all Danish wind turbine manufacturers except Vestas. (Vestas has developed its own blade manufacturing capability). For private wind turbine owners the maximum allowed machine size was limited to 100 kW in the late 1980s. This is why several manufacturers sold 95 kW and 99 kW turbines during this period. Sales for this generation peaked in 1987. The Bonus 95 kW machine with a 19.4 metre rotor was the best selling turbine of this generation. Another best-seller was a turbine made by Nordtank with a 20.5 metre rotor. This was initially sold with a rated capacity of 99 kW, but later the generator was increased to 130 kW while the rotor and generator remained the same. Also available were the WindMatic 99 kW, Nordtank 99 kW and Micon 95 kW turbines with different rotor diameters.

The fourth generation of Danish wind turbines cover turbines between 150 and 250 kW and was based on 11 and 12 metre blades. This size range dominated the market from the late 1980s to early 1990s. The 150 kW turbines (23–25 meter rotor diameter) and the 200–250 kW turbines (25–29 metre rotor diameter) have been among the best selling turbines over the years. Vestas had three machines in this generation: the V25 (150 kW, 25 metre rotor), the V27 (150 kW, 27 metre rotor) and the V29 (225 kW, 29 metre rotor). Especially, the V27 and V29 were very popular machines. Other popular machines were the Bonus 150 kW with a 23.8 metre rotor and the Nordtank 150 kW with a 24.6 metre rotor; both equipped with 11 and 12 metre blades made by LM-Glasfiber A/S. WindWorld, WindMatic, Micon and Nordex also produced machines of this generation.

An intermediate fifth generation of turbines covers the range 300-400 kW with a rotor diameter of 30-31 metre based on 13 and 14 metre blades also made by LM Glasfiber. Only Bonus, Nordtank and Micon manufactured turbines in this size range. The most sold turbines were the Micon 400 kW with a 31 metre rotor and three versions of Bonus 300 kW in three versions with 31.0, 33.0 and 33.4 meter rotors. Nordtank sold a 300 kW with 28, 31 and 35 metre rotors.
The sixth generation took place with 500 kW turbines based on 37 metre to 39 metre diameter rotors in the early 1990s. During the mid 1990s this generation was scaled up to first 550 kW or 600 kW machines with rotor diameters of 43 and 44 metre and later to 660 and 750 kW machines with 44 to 48 metre rotors. All Danish manufacturers now have 600 kW machines in their range. This generation actually started with the early Bonus 450 kW turbines with a rotor diameter of 35 metre in the late 1980s, but these were only sold in limited numbers compared with the following 500 kW to 750 kW turbines.

This sixth generation of turbines has been the workhorse during the rapid growth in the international wind turbine market, and the generation that has been affected by the mergers and acquisitions leading to the company NEG-Micon and the introduction onto the stock exchange of first Nordtank and Vestas and then of NEG-Micon. NEG-Micon has been formed through mergers and acquisitions of the three Danish companies Nordtank Energy Group A/S, Micon A/S and WindWorld A/S, the Dutch company Nedwind the British company Aerolaminates. Also, a number of vendors have been acquired by NEG-Micon. Among the best-selling machines in this generation are those based on Micon’s so-called “20 ton platform”. This was initially a 500 kW machine with a 43 metre rotor, sold in very few numbers, but the platform was scaled up to a 600 kW machine with 43 and 48 metre rotors and to a 750 kW machine with 44 and 48 metre rotors. These NEG-Micon turbines were still based on a traditional “Danish concept” with fixed rotational speed and stall control. More recently, NEG-Micon has developed new versions of the 20 ton platform and is now producing a 900 kW version with a 52 metre rotor diameter and a 950 kW version with a 54 metre rotor diameter. According to NEG-Micon (2002) these machines are totally new, and include new features such as “Power Trim” technology that equals pitch regulation in other makes. Today, NEG-Micon markets five versions on the same platform: NM43/600, NM48/600, NM44/750, NM48/750 and NM52/900. In an experience curve perspective it is interesting to note that the same nacelle mass (20 tons) used for a 500 kW machine with 43 metre rotor can now, 10 years later, be used for a 950 kW machine with a 54 metre rotor. The manufacturing cost of the nacelle has probably not increased significantly, and this has led to an improvement in overall cost efficiency. In this generation Vestas produced a V39 machine with a 500 kW rated capacity and a 39 metre rotor. This was scaled up to first to 600 kW versions with 42 and 44 metre rotors and then to a 660 kW machine with a 47 metre rotor. The Vestas V47 was also equipped with more advanced pitch control and a variable speed solution for the European market.

Based on the sixth generation an intermediate size range (a seventh generation of technology) has been developed between the 500-750 kW generation and the offshore MW size turbines. These are turbines with 800 kW-1000 kW generators and 50 to 54
metre rotor diameter. From this generation new characteristics of wind turbine technology appear. Until this stage quite a narrow range of turbine sizes constituted the “state-of-the-art” technology. But as the world market grows it is becoming possible to design a higher variation in wind turbine designs other than just upscale. New machines are being designed for special markets in the size range between 800 kW and 1500 kW.

The eighth generation of wind turbine technology consists of the first MW turbines designed for offshore market for wind turbines. These are turbines of 1300-2000 kW with rotor diameters of 60-76 metres. In Denmark, the first machines in this generation were the Nordtank 2 MW turbine with a 72 metre rotor and the Vestas 1650 kW turbine with a 66 metre rotor. Together with the Bonus 1000 kW turbine, these machines were developed with support from the European Union’s 5th Framework programme. Only a few of these turbines have been installed on land in Denmark due to planning restrictions, but Germany is the most important market for this generation of turbines. This generation has been on the commercial market in Denmark since around 1998, and is expected to provide machines for the first large-scale offshore wind farms in Denmark and other countries in Europe such as Germany, Sweden, the UK, and the Netherlands. Vestas markets a V80 machine with a 2000 MW rated capacity and a rotor diameter of 80 metre. During 2002 this machine will be erected on the Horns Reef offshore wind farm in the North Sea. NEG-Micon has two turbines in this size range: the NM72/2000 and a NM80/2500 based on the so-called 50 ton platform. Several manufactures have even larger machines on the drawing board with rated capacities up to 5 MW and with rotor diameters of 100 metre and above.

3.3 Sources of reduction in the cost of machines and installation

Cost reductions can be defined in different ways. Looking back at the early uses of experience curves, cost cutting was associated with cutting manufacturing costs for a certain component, see Chapter 1. Much of the recent literature on experience curves for energy technologies uses the cost of the turbine as a measure—often expressed in USD/kW of installed capacity.

This approach gives an erroneous picture of industrial learning, as we will show in the following. For wind turbine technology, the competition in the marketplace is not based on comparisons of the cost of equipment offered by different manufactures. Competition is based on the ability of the equipment to produce electricity. Several issues indicate this.

Firstly, from the model for knowledge and learning, see Figure 3.1, it is obvious that if we choose to study the experience curve for equipment cost we will only include
learning that is embodied in the design of the machine or disembodied in the manufacturing process. Learning-by-using disembodied in the utilisation of turbines will not be included. This theoretical consideration strongly suggests that if we wish to include improvements due to learning-by-using in our analysis of experience curves we must choose a measure that includes this type of learning.

Secondly, it may be of interest to examine what the industry considers important in the marketplace. In a survey carried out by the Danish Association of Wind Turbine Manufacturers on the industry’s need for government-financed research, development and demonstration one of the main conclusions was, that the most important driving factor behind technological development was decreasing the cost of the energy produced. Krohn (1995, p.8): "Danish wind turbine manufacturers operate in markets characterized by very strong competition. In the end, the most important competition parameter is the cost per kWh produced".26

Thirdly, the ability of wind turbines to produce electrical energy per unit of installed capacity has improved over time, see Figure 3.5. Improvements are primarily due to higher towers and better aerodynamic design. This improved efficiency of the technology will not be reflected in experience curves based only on the cost of the equipment. The relationship between the rated capacity and the ability of the turbine to produce electricity also depends of the relationship between the rated capacity and the diameter of the rotor. Basically, the area swept by the rotor and the rotor’s aerodynamic efficiency determine the electrical output. The optimum design has changed slightly with time. Today, most wind turbine manufacturers use numerical optimisation tools (large computer codes) to make these design decisions. The key design criterion for numerical optimisation is minimal cost per kWh electricity produced. As knowledge concerning design criteria, material properties, etc. improves, does the relation between rotor diameter and rated capacity.27 This improved knowledge is always reflected in the ability of the turbines to produce electricity but not always in the machines rated capacity.

The measure would be the actual production cost of electricity for wind turbines. Since this information is very difficult to find, the next best approach be to try to include as much learning-by-using in the analysis.

Minimisation of the cost of each kWh produced is the key driving force behind innovation in the wind turbine industry, but there are naturally other design criteria. Because the land available is limited in Denmark (as well as in Germany) and because of limitations on how many turbines a private owner may own, the size of the turbine

26 Author's translation.
27 For a short introduction to wind turbine engineering and design see Redlinger et al. (2002), pp.48-51.
(measured in rotor diameter or rated capacity) is also a competitive parameter. If you can own only one turbine, it should be as powerful as possible, provided that the net income from the machine is optimal. The “best” turbine (and thus manufacturer) is that which can produce the cheapest electricity at the site in question.

![Figure 3.5](image)

**Figure 3.5** Development in the ability of Danish wind turbines to produce electrical energy (measured in annual production in kWh) per unit installed generator capacity (measured in kW). A standard site characterised as roughness class 1 was selected.

Which components are responsible for the reduction in cost of each kWh produced? As a starting point, one could consult the manufacturers. In an earlier cited report from the Danish Wind Turbine Manufacturers’ Association the following is stated: ".. the cost per kWh produced ... depends partly on the costs of the wind turbine itself, partly on costs covering foundations, erection, network connection, operation and maintenance. Last, but not least, the size and character of local wind resources are of importance to the energy turnover. Furthermore, financing, guarantee, insurance and service are competition parameters between the manufacturers" (Krohn, 1995, p. 8).  

This by and large reflects the components determining the cost of the energy provided by turbines (see Tande and Hunter, 1994).

### 3.3.1 Sources of cost reduction of wind turbines

From the above overview of generations of Danish wind turbine technology lessons can be drawn on types of industrial innovations. Three types of technological innovations can be identified.

---

28 Authors translation
1) Innovation in one size of machines

The first type of innovation concerns improvements to the same type of turbine or machine platform while maintaining the rated capacity. Most innovations of the type can be referred to as learning through manufacturing, and technological changes are not necessarily embodied into the design of the machine. Components such as the gearbox or generator may be replaced by similar ones from other vendors, but the overall specifications remain the same. In several cases, learning is embodied in incremental technical changes to the machine. If we consider one version of a wind turbine, for example a Bonus 150 kW turbine, we can see that its overall technical specifications remained almost the same from its introduction in 1987 until the mid 1990s when it was withdrawn from the market. It is a 150 kW machine with a 23 metre rotor, a 150 kW primary generator and a 30 kW secondary generator, and it produced 369 MWh electrical power annually, in roughness class 1. The ex works list price with a 24.5 metre tubular tower was 105,000 EUR in 1987. In 1990 the same turbine was sold with a 30 metre tubular tower for 126,000 EUR. As a result of the higher tower the machine was able to produce 395 MWh per year in roughness class 1. In 1990 a Mark II version of the machine was marketed with the following technical specifications. The rated capacity remained the same, the rotor diameter was increased to 23.8 metre, the annual production with a 30 metre tower was 413 MWh in roughness class 1 and the ex works price was 133,000 EUR. This version remained in the company’s product portfolio at the same price until 1995, while inflation over the period was approximately 10%.

2) Up-scaling on a platform

The second type of innovation concerns the scaling up of a machine platform – primarily slightly increased rated capacity and rotor diameter. This is called “improvements within a generation”.

Industry often refers to generations of wind turbines as “platforms”, and labels these platforms with the mass of the equipment expressed in tons. Especially NEG-Micon uses this term in product planning and marketing. NEG-Micon is currently marketing turbines on three platforms of 20, 30 and 50 tons. A platform consists of the machine bed on which components such as the generator, gearbox and main bearings are mounted. The top of the wind turbine is referred to as the nacelle. The 500 to 750 kW size range is often referred to as the 20 ton platform. NEG-Micon has also designed a 950 kW machine on their 20 ton platform.

New manufacturing and logistics facilities are usually built to handle a new platform. These manufacturing facilities include welding robots, cranes etc. Based on this platform up-scaling or other variations in versions can be made. This is to some extent analogous to automobile manufacturing where large manufacturers, such as Volkswagen build different cars with names such as VW Golf, Audi A4, Skoda or
SEAT on the same basic platform. This affords cost advantages related to accumulated experience during development phases. Manufacturing learning can be applied directly (disembodied) to a new size of machine. The more the same platform can be scaled up the more cost efficiently the wind turbines can be manufactured as the fixed costs of the manufacturing facilities have been paid.

Up-scaling on a platform is a competitive development and design process since only incremental changes are made to the design of a machine and all the experience from earlier designs can be embodied into the scaled up design. The first machine on a new platform is usually conservatively designed (i.e. it includes extra safety factors) with respect to mechanical strength. When the first practical experience of the practical operation of the design has been gained this can be embodied into the platform in the form of a less conservative design, closer to the limits of the material characteristics. This experience is not embodied into the machine as the use of less material, but typically as a larger rotor and consequently a greater annual production of electricity.

3) Introduction of a new platform.

The third type of innovation concerns the development of to a new machine platform – including significantly increased rated capacity and rotor diameter, but also the introduction of new technological features, such as new drive-train solutions. This heralds the introduction of a new generation.

In NEG-Micon’s annual report for 2001 the company defines some success factors for their R&D efforts over the years to come. With regard to existing machine types, an annual cost reduction of the order of 3-5% per kWh is expected. NEG-Micon does not elaborate further on whether this will result from elements to a particular machine or up-scaling on the same platform. For a new generation of turbines NEG-Micon expects a 5-10% reduction in cost per kWh generated (NEG-Micon 2002, p. 13).

Above we have focused on innovation within wind turbine manufacturers. In the early 1980s most commercial wind turbines were assembled from a number of standard components, such as gearboxes, generators, hydraulic motors for yaw systems, standard bearings for the main shaft and yaw rim etc., Only blades and control systems were especially tailored for the wind turbine industry. Because of the relatively small volume in the wind turbine industry, no vendor was prepared to tailor special components (e.g. bearings). However, as the total market volume has increased scope has arisen for specialised suppliers to the wind industry. Large international corporations such ABB, VALMET and FAG now focus much more on designing components for wind turbines, and they also carry out targeted R&D on these components. Hence, a great amount of both engineering - based and experience-based knowledge is being created within the vendor companies and this knowledge is being embodied in the components.
3.3.2 Sources of reduction of additional costs

Additional costs comprise items such as foundations, electrical installations, grid connection, electronic surveillance (via phone or Internet), financial costs (initial costs of financial packages, financing building period, etc.), civil engineering planning and consulting, roads and other less important costs. The costs for foundations, road construction, grid connection and so on, decrease significantly with the number of turbines in each project. However, these additional costs are dependent on the conditions at each individual site.

A significant decrease can also be detected in the additional costs. As with the ex works costs, it is difficult to distinguish between cost reduction due to experience and that due to up-scaling. A Danish questionnaire study on the cost of wind energy concluded that the decrease in the relative cost of additional costs is primarily due to up-scaling, and that there might be learning effects, but such effects cannot be determined from the data available.

Additional costs, expressed as a percentage of the total cost, have decreased during the past 20 years. Danish investigations indicate that in 1989 almost 29% of the total investment cost was related to costs other than that of the turbine itself. By 1996 this had declined to approximately 20%, a level that been maintained over the past five years.

In this study we have estimated the additional cost based on Danish data from comprehensive questionnaire surveys carried out in other projects (Redlinger et al., 2002). The data were interpolated and extrapolated to cover the size of turbines included in this study. In Figure 3.6 and 3.7 the decrease in additional costs, expressed as EUR/kWh, is shown as a function of time and as an experience curve.

3.3.3 Sources of reduction in the cost of process development

Over the years, a number of smaller companies have specialised as suppliers for the wind turbine industry which facilitates the professionalisation of and learning within this sector. Such companies have specialised in areas such as transporting wind turbines (blades, nacelles and towers) around Europe, in service and maintenance, and in the insurance of wind turbines, etc.

Sources of cost reduction include:
- improved skills of craftsmen in the production line, e.g. manual generator construction, turbine assembly, and
- experience in engineering know-how.
Figure 3.6 Estimate of the development of average additional costs for wind turbine projects in Denmark. Deduced from data available in Redlinger, et al. (2002, p.76).

Figure 3.7 Data in Figure 3.6 presented as an experience curve.
3.3.4 Sources of cost reduction due to changes in input prices

As the wind turbine industry uses components such as bearings, gearboxs, generators, blades, etc. from vendors, the main part of the cumulated learning is made by these vendors. However, we are not able to quantify this further from the data available in this study.

Only anecdotal evidence has been found on the relation between changes in input prices of raw materials and cost reduction for wind turbines. One anecdote concerns the use of carbon fibres in blades. The world market for carbon has fluctuated considerably with rebates varying between 20% and 80%. This has led to reluctance in the same use of carbon fibres in wind turbine blades. If the wind turbine industry were to become a large customer of carbon fibres one might expect prices to become more stable and the use of carbon fibres to increase.

3.3.5 Sources of cost reductions due to scale effects

Based on our analysis of the data available it appears to be almost impossible to distinguish between reductions due to technological learning and those due to scale effects. In the middle of the 1980s development started from the bottom, in small and medium sized companies. This path finally led to the expected success. Legislative measurements intended to open up reliable markets, such as the German Electricity Feed Law and the Renewable Energy Law, have contributed significantly to wind turbine development.

The decision to scale up turbines was made although this did not initially lead to significant reductions in price, expressed as the cost per turbine produced or per unit rotor area. One important reason for this is the high increase in the annual energy yield. No one can say today that the technical and economical limits of turbines will be. In the future turbines will be specially designed for special conditions. At present, the largest turbines being developed are in the 5 MW range, for application mainly in offshore wind farms. However, small plants in the kW range will also find growing markets, for example, as integrated supply modules in hybrid systems for power supply in remote areas.

The experience curve for wind turbines in Germany generated showed that the progress ratio is comparatively low in comparison with other technologies. Similar figures were also found for other countries. The question is, why? Competition on the market has forced manufacturers to construct new and bigger turbines, one after the other, leading to costs for new production lines and facilities, R&D, testing, approval etc. This can be illustrated by the production cycle of turbines made by the leading German
manufacturer Enercon. Since 1986 they have sold almost 3,600 turbines. The workhorse E 40 was first sold in 1993. This turbine was a best-seller with almost 1,800 turbines being sold in Germany and abroad. Looking at the sales figures for the E 40 for Germany shows that sales culminated in 1997 and then fell steadily to almost zero. The E 40 was succeeded by the E 44 in 1999 and then by turbines in the megawatt range.

3.4 Sources of reduction of the cost of electricity production

3.4.1 Sources of cost reduction due to improved wind capture

The wind capture of a wind turbine depends on the air density, wind velocity, effective area and the aerodynamic ability of the rotors to transform the energy of the wind into rotational energy. Since the air density and wind velocity cannot be influenced, and since aerodynamics can only be improved incrementally, an increase in wind capture and thus increased output is only possible by increasing the rotor area of the turbines or by using greater hub heights. However, larger rotors and higher towers cost more and require reinforced foundations, which also cost more.

Furthermore, the total cost of energy produced by a wind turbine depends on the wind resource (annual average wind speed), on the site, and the ability of the developer to “micro-site” the turbine exactly where the wind conditions are optimal. As numerical tools for micro-siting have improved, gains of a few per cent have been made over the past two decades regarding the cost of electricity.

3.4.2 Sources of cost reduction due to reduced O&M costs

Operational and maintenance costs are related to a limited number of components: insurance, routine maintenance, repairs, spare parts, administration, land leasing or purchasing costs. Based on a number of Danish statistical surveys O&M costs have been estimated as percentages of the investment cost, according to turbine age and size, see Table 3.2.

Prior to and during the 1980, banks and other financial institutions had little experience of wind projects and the discount rate was consequently above the average for similar projects. But as financers gained experience in wind projects they were able to offer lower relative discount rates. The same applies to insurance – as experience is gained the financial risks are better understood and insurance has become cheaper. In this sense, an important source of experience comes from the financial sector, although the quantitative effect of this is difficult to estimate.
Table 3.2. Development in annual O&M costs as a percentage of investment cost, according to the age and the size of turbine (Redlinger, et al. 2002)

<table>
<thead>
<tr>
<th>Turbine size (kW)</th>
<th>Years after installation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-2</td>
</tr>
<tr>
<td>150</td>
<td>1.2%</td>
</tr>
<tr>
<td>300</td>
<td>1.0%</td>
</tr>
<tr>
<td>600</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

According to German operator reports, O&M costs are initially low at the start of operation and increase in the years following. After a few years O&M costs seem to stabilise at a certain level, depending on the size class of the wind turbine, as shown in Figure 3.8. However, O&M costs of large turbines are significantly lower than those of smaller turbines.

![Figure 3.8](image_url) Specific O&M costs for wind turbines in Germany (ISET, 2002)
4. Wind energy policy

Policy measures for the development and deployment of wind power have been applied in many countries in Europe. Evaluation of these measures using experience curves requires information about the measures. In this chapter we present the policy measures applied in those countries for which experience curves for wind power could be developed, i.e. Denmark, Germany, Spain and Sweden. The policy measures are described and their budgets presented to the degree possible based on data available.

The policy measures are presented under the following headings:

- RD&D subsidies from the national budget
- Investments and price subsidies from the national budget
- Price support from other sources
- Other forms of support

The development of wind power in the countries considered here has been subsidised by a multitude of sources. This chapter focuses on government subsidies, i.e. on subsidies from the national budget and legislation dictating special prices for wind power to be paid by electric utilities and their consumers. Some remarks concerning other means of steering the development of wind power are included for some countries.

All data were recalculated to give prices for the year 2000 using the GDP deflator used and published by IEA (IEA, 2001), see Chapter 2.

4.1 Wind energy policy measures in Denmark

Danish wind power programmes took off in the early 1970s and since then various forms of RD&D subsidies, direct subsidies and regulatory incentives have been implemented. The wind measure has been stable over the years providing a steady home market for wind power. The emphasis has been on technology reliability, and subsidies were combined with certification already from the start. Financial support has moved from turbine investment subsidies to electricity price subsidies and from governmental support investments to private support.
4.1.1 RD&D subsidies from the national budget

The Danish Government has sponsored several RD&D programmes on wind energy over the years. The three most important areas have been:

- The Energy Research Programme (EFP)
- The Renewable Energy Development Programme (UVE)
- The Test Station for Wind Turbines at Risø National Laboratory

The funding of the EFP programme and the UVE programme for the period 1976-2000 was EUR 82 million, see Figure 4.1. The resources provided for the Test Station at Risø National Laboratory from 1984-2000 were EUR 18 million (Data is not available before 1984). Figures regarding funding for RD&D by Danish companies are not available.

The first wind energy research projects were initiated and financed by the former Ministry of Trade. The two Nibe turbines and the establishment of the Test Station for Wind Turbines at Risø National Laboratory are examples of projects financed in this way. Based on the experience gained from these projects the Energy Research Programme (EFP) has financed wind-energy-related research projects since 1980. Initially, the research programme had two main areas. One was research carried out by power utilities and the Danish Energy Agency focusing on large-scale wind turbines. The other focused on small-scale wind turbines, and financed the research performed at the Test Station for Small Wind Turbines, as the test station at Risø National Laboratory was called for the first few years. The two areas of research were merged in 1989. The Development Programme for Renewable Energy (the UVE programme) was established in 1982 under the Danish Technology Board (Danish Industry and Trade Agency). In 1990 the programme was transferred to the Danish Energy Agency.

The Danish Energy Agency operates test stations for different renewable energy technologies. One is the Test Station for Wind Turbines, established at Risø National Laboratory in 1978. The activities comprised:

- Information activities
- Ad hoc assistance to the Danish Energy Agency
- International cooperation with other test stations for wind turbines
- Secretariat for the Danish certification and type-approval scheme
- Spot-check of type approved turbines
- Inspections following major breakdowns of turbines
- International standardisation
- Development of test methods for wind turbines
- Development of test methods for blades
Participation in the IEA annex of the Round robin test of wind turbines

In addition to these programmes other R&D programmes and projects have been financed by the Danish Government. Examples of these are given below.

The programme New Energy Technologies (Nye Energiteknologier) was established in 1980 with the aim of stimulating ongoing commercial manufacture of new energy technologies. Funds were devoted to industrial development projects and, in a few cases, used as capital in new companies. Between 1980 and 1990 the Danish wind turbine industry received approximately EUR 6 million from this programme.

Between 1982 and 1989, the programme Individual Energy Projects (Energiøkonomiske enkeltprojekter) supported a number of demonstration wind farms, such as Masnedø (3.8 MW), Lynæs (0.9 MW), Oddesund Nord (1.1 MW), Ebeltoft (0.1 MW) and Tønder (0.7 MW for training purposes). Funding amounted to EUR 3 million between 1982 and 1985, and EUR 0.04 million between 1986 and 1989.

Denmark has also funded and participated in a number of international projects on RD&D. For instance, Denmark has participated in the international IEA R&D programme Wind since its establishment. Danish universities, research centres, power utilities and manufacturing companies also participate in the European Union’s RTD programmes (No quantitative data are available.) Active Danish participation in international standardisation through the IEC and CEN/CENELEC has high priority in the Danish Energy Agency’s plan of action for wind energy R&D, and R&D efforts supporting international standardisation are encouraged.

4.1.2 Investment subsidies from the national budget

Investment subsidies were introduced in Denmark already in 1979. Investment subsidies were initially 30% of the investment cost. However, the investment subsidy per turbine was reduced over the years, to 25% in 1983, 15% in 1984 and 10% in 1989. In 1990 the subsidy was removed completely. In total, 2567 turbines were subsidised by EUR 57 million, see Figure 4.2. The goal of the programme was to reduce the investment cost in order to increase the market penetration of wind turbines. The effect of the programme has not been evaluated.
Figure 4.1 RD&D funding in Denmark. The total amount includes resources provided for the Test Station at Risø National Laboratory. For the UVE programme the total cost for 1982-1990 has been divided equally between the years. Prices are expressed in 2000 year prices.

Figure 4.2 Investment subsidies in Denmark. Prices are expressed in 2000 year prices.
4.1.3 Price subsidies from the national budget

A price subsidy was introduced in 1979, parallel to the investment subsidies. The price subsidy started at 0.08 DKK/kWh (nominal, corresponding to 0.010 EUR/kWh) in 1980 and developed over time in accordance with Figure 4.3. Moreover, the price subsidy was complemented with a reduction in value added tax, see Figure 4.3. The tax reduction stabilised at 0.17 DKK/kWh in 1991 (nominal, corresponding to 0.021 EUR/kWh). Wind turbine owners also received 0.10 (nominal, corresponding to 0.013 EUR/kWh) /kWh as a refund for the CO₂ tax from 1992. The total price subsidy of wind generated electricity was 0.27 DKK/kWh in 2000 (nominal), corresponding to EUR 0.0036. The goal of the programme was to reduce the price of the electricity generated. The total funding for investment and price subsidies has been estimated to be EUR 806 million, see Figure 4.4.²⁹

4.1.4 Price support from other sources

Feed in tariffs have been applied in Denmark since 1979. Utility companies have been obliged to buy all the power produced by wind turbines, at a price equivalent to 85% of the consumer price of electricity in the distribution area in question. The feed-in tariffs are presented in Figure 4.5. On average, this feed-in tariff was approx. 0.32 DKK per kWh in 2000 (nominal), corresponding to EUR 0.0043. The cost to society of applying the feed-in tariff system is not known and no estimates are available.

4.1.5 Other forms of support

I addition to the already mentioned activities wind power has been supported by, for example, targets for wind energy deployment, land planning legislation, shared grid connection costs, utility involvement, etc.

Targets for the deployment of wind energy have been applied in Denmark. In 1996 the Danish Government set a national target to reduce CO₂ emissions by 20%, based on the 1988 level, by 2005. In the longer term, Denmark aims to reduce its CO₂ emissions to

²⁹ Tax credits are also used in Denmark. Different forms of ownership have different tax arrangements. The formation of a cooperative is a traditional way of owning a wind farm in Denmark. Each member can own up to 30 shares (corresponding to 30 MWh per year) and pays 60% tax on gross income above a certain lower limit. For personally owned turbines (e.g. owned by a farmer) a marginal tax of approx. 59% is paid on net income (after deducting interest on loans, operation/maintenance costs and depreciation).
half the 1990 level by 2030. Renewable energy sources and wind energy will play an important role in achieving these reduction targets.

Figure 4.3 Price subsidy in Denmark.

Figure 4.4. Investment and price subsidies in Denmark. Prices are expressed in 2000 year prices.
For quite a number of years land planning issues have been an integral part of the Danish development of wind power. Land planning issues can contribute one of the major barriers for the deployment of wind power. Land planning establishes a framework for siting wind turbines, and balances the interest of wind energy against other interests, including how existing urban features and landscapes can best be protected. Land planning in Denmark is carried out at three levels: local and municipal planning in municipalities, regional planning in counties and national planning coordinated by the Ministry of Environment.

Grid connection cost. According to a statutory order, the cost of grid connection for wind turbines is to be divided between the wind turbine owner and the power utility. The wind turbine owner must bear the cost of low-voltage transformer and connection to the nearest connection point on the 10/20 kV distribution grid, while utilities carry the cost of reinforcement of the 10/20 kV distribution grid when necessary.

Utility involvement. When the first wind power programme was initiated in the 1970s, Danish power utilities participated in the utility-scale research programme. In 1985 an agreement was negotiated between the Government and the Danish electricity utilities, committing the utilities to install 100 MW of wind turbines over a five-year period. This agreement was fully implemented by the end of 1992. A second 100 MW agreement between the Danish Government and the utilities entered into in 1990 was finally implemented in 1996. According to an executive order by the Government, a third utility phase of an additional 200 MW must be installed by 2000. These three phases

Figure 4.5. Feed in tariffs in Denmark, 1983 - 2000. Feed in tariffs are calculated as a weighted average of power price equivalent to 85% of the consumer price of electricity in the distribution area in question. As weights the amount of wind-produced power sold in each of the distribution regions is used.
have primarily focused on land-based wind turbines, but two offshore 5 MW
demonstration wind farms have also resulted from the agreements between the
Government and the utilities. In 1997 the Ministry for Energy and Environment entered
into an agreement with the Danish utilities to develop an additional 750 MW of offshore
wind power by the year 2008.

Sources of data for Denmark: (The Danish Ministry of Energy and Environment, 1991, 1995,
1999); (the European Commission, 1997, 2000); (BTM, 2001, 2002); (Morthorst, 2000);
(Fenhann, 1997).

4.2 Wind energy policy measures in Germany

Federal wind power policies in Germany took off soon after the oil crisis of 1973. They
fall clearly into two periods, representing two quite different approaches. The first
period (1975-1984) was characterised by R&D support focused on advanced turbine
concepts, which produced valuable results in fundamental wind energy research, but
initially had no influence on the commercial development of wind power. The second
period (1985-present) has been characterised by a very successful combination of a (1) a
favourable market policy for electricity produced by wind turbines, (2) favourable
loans, (3) subsidies to investors, and (4) a monitoring programme. (The wind power
policies are illustrated by a roadmap in Appendix 4).

4.2.1 RD&D subsidies from the national budget

Federal support for RD&D started in 1975 as a follow-up to a private charitable
donation in 1972 for the construction of a small turbine on the island of Sylt. The
federal government offered in 1974 to finance a testing programme for this turbine. At
the same time, a literature study of larger turbine concepts was commissioned. With
such modest activities, the RD&D budget started with EUR 0.13 million in 1975.

RD&D activities took off more substantially with the 1977 budget of EUR 3.3 million,
increasing 10-fold to EUR 33 million in 1981. Funding then fell rapidly to EUR 11
million in 1983 and remained at that level or below for the remainder of the 1980s. The
total RD&D funding from 1977 to 1989 amounted to EUR 177 million, see Figure 4.6.
A large part of this funding was given to companies that were sceptical about wind
energy, but were forced by the government to engage in wind power research. The
government bore nearly all the costs, with only token financial contributions from the
private sector. The most important example of this was the Growian project, a 3 MW
turbine, which received nearly 40% of all RD&D subsidies from 1977 to 1989. In
addition to this project, another 40% was used to test a small number of advanced
concepts that were quite expensive in terms of RD&D cost but never gained any commercial significance. In the late 1980s, a certain weariness seemed to develop in on the private side.

![Figure 4.6. Federal RD&D funding in Germany from 1975-2000. Prices are expressed in 2000 year prices.](image)

Since 1989, RD&D activities have been modest. They have focused mostly on generic activities, such as a monitoring programme for a large number of turbines, research into the problems of grid connection, research on early recognition of turbine failure, or demonstrations of the use of wind power for sea water desalination. Some money has also been given to specific turbine development projects in the MW range, but this type of support for a specific turbine concept has been quite modest compared with the 1980s. The successful development in the 1990s of proprietary technologies by German companies, such as Enercon, was based on both company funding and dedicated federal RD&D support.
4.2.2 Subsidies from the national budget

Wind energy subsidies were introduced in Germany in 1989 through the "100 MW Wind" programme that later became the "250 MW Wind" programme.\textsuperscript{30} Until it closed for new applications in 1996, it provided investment or operation subsidies for some 1,500 turbines, i.e. about 1/3 of the turbines installed in 1996. In the first years, investment subsidies were dominant, but since 1994 nearly all the funding was provided in the form of operation subsidies. This transformation was almost complete by 1994, when accounted for more than 95% of the programme expenditure. Subsidies were given first as 0.08 DEM per kWh (nominal, corresponding to 0.04 EUR/kWh), and then reduced in 1991 to 0.06 DEM per kWh (nominal, corresponding to 0.003 EUR/kWh). The subsidies are given for 10 years, but are terminated before this time if the accumulated amount paid exceeds a certain amount (defined relative to project costs). The advantages of subsidies per kWh over investment subsidies are that they reward production rather than costs. The last subsidies were awarded in 1996, but due to the 10-year duration of the subsidies (calculated from the start of production, not from the time of the award) payment will continue until 2006.

Projects were selected for subsidies on the basis of a complex set of criteria, based on the desire to promote technological innovation, geographical proliferation of turbines, and spread among different types of owners. All subsidised operators were obliged to join a monitoring programme. A total of some EUR 66 million was provided in the form of investment subsidies under the 100/250MW programme, see Figure 4.7\textsuperscript{31}. Regarding price subsidies, the total funding for the period 1989-2000 was EUR 131 million, see Figure 4.8. For 2001-2006, an additional expense of some EUR 18 million is expected.

Additional investment subsidies of EUR 2.5 million have been provided more recently (1995-97) through the "100 million DEM" renewable energy programme. Germany also provides investment subsidies for projects abroad, through the ELDORADO programme, which supports wind power investments in southern climates, if they are made in cooperation with German turbine manufacturers, see Figure 4.7.

\textsuperscript{30} The “100/250 MW Programme” was a demonstration programme funded by the RD&D budget. The programme was focused on price subsidies but also allowed investment subsidies.

\textsuperscript{31} The "250 MW" Programme” included 3 Danish manufacturers among the top 7 manufacturers delivering turbines to subsidised projects (Li et al., 1997).
**Figure 4.7** Federal investment subsidies. Figures include investment subsidies awarded through the 100/250MW programme. Prices are expressed in 2000 year prices.

**Figure 4.8** Price subsidies from the federal budget. Figures include price subsidies awards through the 100/250MW programmes. Prices are expressed in 2000 year prices.
4.2.3 Soft loans from the state bank

Investors in German wind power often take advantage of soft loans available from DtA, the federal government’s bank for entrepreneurs and small to medium sized enterprises (SMEs). Loans are either made from the bank’s own funds or from ERP funds (ERP = European Recovery Programme = Marshall Plan). These loans typically have an interest rate 1% below the market rate, and are often given for a period of 10-15 years. In optimal circumstances, such loans can cover up to 75% of the total investment cost. The loans are not pure state loans, as they must be arranged by the investors’ own bank, which must also cover the credit risks. It is estimated that some 80-90% of German wind power projects make use of such loans (Hemmelskamp, 1998), see Figure 4.9. The value of the subsidy cannot be determined in an exact way, but is here estimated to be 4.7%, in accordance with Nitsch et al. (2000), who based this estimate on 10 years maturity and an interest rate advantage of 1%, i.e. conservative assumptions.

4.2.4 Price support from other sources

The most important subsidy to German wind power was provided in 1990, in the form of the "electricity feed-in law". Utilities were required to pay wind power producers 90% of the average retail price of electricity. Similar rules were applied to other renewable energy sources. The exact level of subsidy is difficult to define. Nitsch et al. (2000) set the alternative costs of the utilities at 0.10 DEM (nominal) per kWh, corresponding to EUR 0.005 per kWh, probably with long-term marginal costs in mind, including investment costs. BMWi (2002a) set the alternative costs as low as 0.025 DEM (nominal) per kWh, considering only marginal fuel costs, corresponding to EUR 0.05 per kWh. In the first case, the total subsidy made by the utilities from 1991-2000 amounts to EUR 995 million, see Figure 4.10. In the second case, they are EUR 2,094 million. Both are much larger than any subsidies provided by the federal budget.

The electricity feed-in law created a secure market with high and stable prices for electricity generated by wind power. In this way, wind power was transformed into a low-risk investment with the promise of good economic returns for investors. No other government policy has been as important in the expansion of wind power in Germany. The implementation of the electricity feed-in law entailed a move from federal based subsidies to private subsidies (electric utilities), as is evident from Figure 4.11.
Figure 4.9. Subsidy value of soft loans. Prices are expressed in 2000 year prices

Note: Credit volumes for 1998-2000 are estimated on a business-as-usual basis, i.e. as a fixed percentage of total investments.

Figure 4.10 Price subsidies provided by utilities. Prices are expressed in 2000 year prices
4.2.5 Other forms of support

Germany is a federal republic, in which the states ("Länder") often have the same or stronger powers than the federation. It also has a strong tradition of citizens’ involvement and bottom-up policy making in the matters concerning environmental. In consequence, the separate states have often acted earlier and demonstrated more clear-cut and decisive policies than the federation, even in regard to global problems such as climate change. This is also the case with wind power issues. In the period 1991-97, for which data are available for each state, the total wind power subsidies provided by the states were in fact higher than those provided by the federal government, namely EUR 218 million at state level, and EUR 148 million at federal level. Both state and local levels of government may be important in areas that do not explicitly involve subsidies, such as planning, building permits, procurement of green electricity, direct participation in projects, and information to the public.

The policies of the European Union affect wind power development in Germany mainly through their implementation at the member state level, i.e. through federal policies. This is true for EU decisions concerning the Kyoto Agreement and the electricity market. In some cases, however, EU policies or institutions have exerted more direct
influence on wind power development in Germany. For instance, the RD&D programmes of the European Union have directly subsidised a large number of projects with German participation. Litigation at the European Court of Justice concerning the German electricity feed-in-law led to some nervousness among investors in German wind power projects.

Several policies, that do not involve monetary subsidies have an effect on the investment costs of wind power. Important examples are the regulations governing grid connection, the procedure for obtaining building permits, and the tax regulations governing depreciation.

Sources of data for Germany: (BMWi, 2002a, 2002b); (Ecotec Research and Consulting & Aphrodite Mourelatou, 2001); (Hemmelskamp, 1998); (Heymann, 1995); (Li et al., 1995, 1997); (Nitsch et al., 2000); (Reichert et al., 1999).

4.3 Wind energy policy measures in Spain

Spanish wind power policies were introduced in the late 1970s. They fall clearly into two periods, before and after 1994. Before 1994, support for wind power mainly took the form of RD&D subsidies for specific projects, paid for out of public funds or by ENDESA. After 1994 mandatory premium prices became increasingly dominant as the principal form of support. Thus, the burden of subsidies was transferred, to a large extent, from the national budget to the electricity consumers.

Both periods appear to have been rather successful. This can be seen most easily for the second period, during wind power capacity has nearly doubled every year. Within only 6 years, the mandatory price policy brought Spain to a leading international position as the second largest wind power producer in the world, surpassed only by Germany. The first period was, however, successful in laying the foundations for this rapid expansion. Modest financing from the national budget provided the domestic wind power industry with an opportunity for development and consolidation. Experience was also gained by developers, banks and public agencies. Wind power became known to the general public. Without such preconditions, the rapid expansion during the second period would not have been possible.

4.3.1 RD&D subsidies from the national budget

National support for RD&D started in 1978 with government subsidies for a 100 kW turbine at Tarifa. Subsequently, a number of other projects involving small and medium-sized turbines received RD&D subsidies from 1981 to 1986. This created the
first basis for a national industry. Two renewable energy plans sought to increase the funds available by combining money from the national budget with money from the European Commission, the regions and the electric utilities. The first renewable energy plan changed the emphasis from single turbine projects to small wind farms, and the second sought to replace the previous technology-push strategy with a demand-pull strategy, by providing subsidies on the basis of market parameters, such as productivity, quality and price.

In 1990, as a result of these efforts, Spain was ranked fourth among the European countries in terms of installed wind power capacity. The national industry had successfully passed the 100 kW mark with competitive designs and had built 4 wind parks. During this process, two manufacturers had grown to sustainable levels of competence and experience, namely Made and Ecotècnia. Both were using the pragmatic strategy of combining technology transfer from the USA and Denmark with internal technology development. Thus, the development of the Spanish industry was not solely dependent on domestic RD&D efforts, but received input from abroad, while at the same time providing an additional market for foreign technology development.

Up until the mid-1990s, practically all wind power projects received some kind of financial support from the Spanish Government, in the guise of RD&D support. During the 1990s, however, such support became less important as price support took over as the main instrument for the promotion of wind power. Although the absolute amount of financial support for RD&D in the 1990s was only slightly smaller than that in the 1980s, its importance has much diminished.

Antoni Martinez, who has worked at Ecotècnia since 1983 and is now its CEO, emphasizes the importance of RD&D subsidies in the 1980s (McGovern, 2001). It was only possible to develop the company by convincing the administration and society at large of the need to support wind power. No turbines were commercially viable in Spain before 1992, but as money was not easily available, the company had to emphasize simplicity and a practical approach. "Right from the beginning, in order to survive, we had to get the technology right every time in order to generate financing". In his opinion, this lack of money in the early days is the reason for the strong market position of Ecotècnia today. This seems to indicate a different relation between RD&D subsidies and business development than those in countries like Germany and Sweden, where generous funding in the 1980s appears to have led to advanced projects, but where the results in terms of business development were often more meagre.
The data illustrated in Figure 4.12 are from the IEA R&D database and have not been checked against domestic sources. The IEA data relate to R&D, while the programmes referred to here also have a significant demonstration aspect. It is therefore not known to what extent these programmes are accounted for in the IEA data, as the dividing line between development and demonstration is not well defined. The IEA data should include only subsidies by the national governments, and not subsidies by the EU, which may have been significantly larger. Other sources cite much higher numbers that cannot easily be reconciled with the IEA database. For instance, IEA (1997) states that "the funding level for wind energy R&D is basically the budget of the wind energy department of CIEMAT, which for 1996 was around ESP 300 million (nominal), whereas the IEA R&D database gives a figure of 125 million (nominal) for the same year (corresponding to EUR 1.9 million and EUR 0.8 million, respectively). It is possible that EU funding can explain this difference. Private or public utility funding might also contribute to the IEA figures, but under-reporting to the IEA database is also a possibility. So it is far from clear that Figure 4.12 gives the correct picture of Spanish R&D funding."
4.3.2 Investment subsidies from the national budget

Investment subsidies from the national budget appear to have constituted a significant source of wind power funding. No coherent accounts (concerning time and scope) have been found of such subsidies, and the scope of the present project does not hallow detailed investigation of this issue.

Nabe (1998) mentions public spending for wind power projects of EUR 19 million within the PAEE programme (Plan de Ahorro y Eficiencia Energética). This is equivalent to a subsidy level of around 25% for the wind power projects covered by the PAEE programme, which may well be practically all projects during this period. Apparently this covers the period 1991-1994, where the IEA R&D database only accounts for EUR 5 million. The relationship between this R&D spending and the PAEE figures is not known.

Varela (1999) explains the 1998 regulations governing national investment subsidies awarded to wind parks with special characteristics (such as access conditions or grid connection costs), large prototypes and special applications (such as desalination), or small turbines combined with photovoltaic electricity generation. There is no indication, however, of the budget allocated to these investment subsidies, or how broadly they were given.

The general picture thus appears to be that national investment subsidies have been gradually reduced in scope and level. From a situation in the early 1990s with an average 25% subsidy for a large proportion of ongoing wind power projects, the value fell to an average of 10% in the middle of the decade, and by the end of the decade subsidies were only awarded under special conditions. But this can be regarded only as a hypothesis.

An “educated guess” based on the above hypothesis would give the development of investment subsidies as indicated in Figure 4.13. This development is based on the assumption that investment subsidies were equally important (in terms of percentage of total investment cost) before 1991 as in the period 1991-94, and that budget for this purpose has not increased since 1997. The purpose of this guesswork is simply to give some idea of the likely extent of the investment subsidy data that is missing.

32 The figures in this section are nominal amounts.
4.3.3 Price support from other sources

Since the middle of the 1990s, the most important subsidy to Spanish wind power has been the premium price paid by electric utilities. As capacity has increased exponentially, this subsidy has dwarfed all other subsidies. State-owned utilities appear to have been paying premium prices for wind power, on a voluntary basis, even before this became mandatory, perhaps from the very beginning of Spanish wind power.

Premium prices were legally established basis in 1994. All electric utilities were required by law to pay a guaranteed premium price for wind power over a five-year period. This premium price was determined, in principle, according to long-term avoided cost considerations (Saiz de Bustamante & Gil Sordo, 1997). This resulted in wind power prices in 1996 of ESP 3.90 (nominal) above the average cost of electricity (corresponding to 0.024 EUR) (Nabe, 1998).

A new policy was introduced in 1998, the result of which was that wind power producers now had two alternatives: to receive a premium wind power price per kWh generated, amounting to 88.5% of the retail price to consumers, or to receive the average market price for electricity plus a wind power bonus. The bonus for 2000 was 4.79 ESP/kWh, corresponding to EUR 0.029 per kWh. The premium wind power price and the wind power bonus are adjusted every year by the ministry responsible, according to market prices. There are several sources of uncertainty in the estimates of price support shown in Figure 4.14, and these are discussed below.

- Data regarding financial support per kWh were available only for the years 1996, 1999 and 2000. As the policy was stable from 1994 to 1998, the figure from 1996 was assumed to be representative for this period and was extended to other years, after adjustment for inflation.

- The policy before 1994 was not investigated. Available sources indicate that good prices were paid for wind power by utilities (mostly state owned) before this was required by law. Such “voluntary subsidies” were simply assumed to be of the same order as the subsidies that were mandatory from 1994 due to a lack of information to the contrary.

- Available figures concerning wind power production are surprisingly divergent. The high and low estimates shown in Figure 4.14 are based on the information found. The low estimate was based on statistics from the grid operator Red Electrica de España (REE), which are available only for 1995-2000 (REE, 1996 & 2001). The high estimate was based on capacity data from IEA publications (IEA, 1999) and capacity factor data (i.e. the relation between electricity production and capacity).
from the same organisation (IEA, 1997 & 2000).\textsuperscript{33} We did not have sufficient resources to investigate the reason for this divergence in the data in the present project. One possible explanation may be, however, that the REE data only cover part of the wind power capacity and production, although there is no statement to this effect in the publications by REE. Another possibility is significant over-reporting of capacity and/or capacity factors to the IEA.

- The capacity factor data only cover 1994-1996, but have been extrapolated to cover the whole period shown in Figure 4.14. A stable capacity factor was assumed after 1996. For the years prior to 1994, a yearly improvement of ½ percentage point in the capacity factor was assumed. Data concerning capacity factors are also strikingly different depending on the source. IEA data indicate that a level of 28-29\% was reached in 1995-96. In the high estimate in Figure 4.14 it was assumed that this level has prevailed since then. REE data indicate much lower capacity factors. A comparison of production and capacity data from REE (published in one table) results in capacity factors of around 20\%, varying slightly from year to year. The difference between the two curves in Figure 4.14 is due solely to one source of uncertainty, namely the divergent estimates concerning the amount of wind power produced. The other sources of uncertainty have not been quantified.

\subsection*{4.3.4 Other forms of support}

The European Commission has been a major source of subsidies for wind power RD&D in Spain, and perhaps more important than the national government budget. For instance, Ciemat, now the main public research centre in the field of wind energy, started its wind power activities with a 1.2 MW turbine erected in 1989, funded mainly by the EU. In addition to the general RD&D programmes, which are also used by other countries studied in this project, Spain has had access to generous regional development funds for wind power projects that contribute to local employment and infrastructure. Of the 17 regions in Spain, 10 are eligible for funds from the ERDF (European Regional Development Fund).

\textsuperscript{33} The production was estimated from the average capacity during the year, calculated by interpolation between the initial and final figures for each year, assuming an exponential development during the years. This average capacity was then multiplied by the capacity factor.
Figure 4.13 Proposed development of investment subsidies in Spanish wind power. Prices are expressed in 2000 year prices.

Figure 4.14 Low and high estimates of price support in Spanish wind power. Prices are expressed in 2000 year prices.
At the national level, the state-owned electric utility Endesa has also been a major vehicle for government policy in support of wind power, but the money it has devoted to RD&D does not appear in the available statistics. Particularly in the early 1980s Endesa’s internally funded RD&D efforts was an important parallel activity to the activities funded by the national budget. Ecotécnica, now no. 4 in the Spanish market, depended mostly on national budget subsidies for its early growth. But MADE, now no. 2 in the Spanish market, grew from Endesa’s internal RD&D funding in the early 1980s. Regional authorities have also provided significant subsidies for wind power projects.

We have been unable to find data concerning the magnitude of the subsidies provided by these alternative sources, but their total is probably greater than the funds provided by the national budget. Thus, the description given in this chapter of subsidies on RD&D in Spain is incomplete. This incompleteness is particularly important in the period 1980-95, before price support became the main instrument for promotion of wind power.

Several kinds of policy measures, that do not involve monetary subsidies, are important with regard to the investment cost of wind power. Examples are the regulations governing grid-connection, the procedures for obtaining building permits, and the tax rules governing depreciation.

Sources of data for Spain (IEA, 1997-2000, 2002); (Lecuona Neumann, 2002); (McGovern, 2001); (Nabe, 1998); (REE, 1996, 2001); (Saiz de Bustamante and Sordo, 1997); (Varela, 1999)

4.4 Wind energy policy measures in Sweden

Swedish wind power policies came into force in the mid-1970s. The policy measures have been limited to RD&D and investment subsidies and, to a limited extent only, price subsidies. These programmes were not connected or coordinated in any way. RD&D measures were focused on the development of large turbines, while investment subsidies were used to finance investments in commercialised (Danish) wind turbines.

4.4.1 RD&D subsidies from the national budget

Two major RD&D programmes have been pursued in Sweden during the past 20-30 years: The Wind power Programme ("Vindkraftsprogrammet" part of "Energiföknings-programmet") and that financed by Energy Engineering Foundation ("Energiteknikfonden"). These programmes have focused on research, development and
demonstration of large wind turbines, and a number of demonstration turbines have been developed. Efforts have also been directed towards the development of concepts such as two-bladed turbines, soft yaw, and windformer etc. Since 1998, part of the RD&D funding has been used for socio-technical research.

RD&D activities have been ongoing since 1975. In the period from 1975 until 2000 funding by the Swedish Government was EUR 127 million, see Figure 4.15. Figures concerning funding of wind RD&D by the Swedish utilities are not available. The RD&D activities have not effected cost reduction of the wind turbines installed in Sweden, as these have been medium-sized wind turbines, to a large extent, developed in Denmark.

![Figure 4.15 RD&D funding in Sweden. Prices are expressed in 2000 year prices.](image)

**4.4.2 Investment subsidies from the national budget**

Investment subsidies were first introduced during the period of 1991-1996. In 1991 investment subsidies were 25% of the investment cost. However, in 1993 this was increased to 35% of the investment cost. A minimum size of 60 kW and quality approval were required to obtain a subsidy. The funding for the programme was EUR 41 million, see Figure 4.16. The programme resulted in the installation of medium-sized turbines with a total capacity of 100 MW.
In 1998 a second investment subsidy programme was introduced. This programme, which ran until the end of 2002, provided a 15% subsidy of the investment cost during its first four years. In 2002 the subsidy was reduced to 10%. Only turbines of a capacity greater than 200 kW were eligible. The funding of the programme was originally EUR 32 million. In 2000 another EUR 10 million was added. The goal of the second programme was to increase the market penetration of turbines and to increase the amount of wind-generated electricity by 0.5 TWh over five years, 1998-2002. There has been a high demand for the subsides offered by the government and the market penetration of medium-sized turbines has increased. By the end of 2000 a total capacity of 280 MW had been installed in Sweden.

4.4.3 Price subsidies from the national budget

From 1994 an “environmental bonus” was introduced with the aim or reducing the price of electricity generated by wind turbines. This environmental bonus corresponded to the size of general electricity tax applied to households. In 1994 the environmental bonus was SEK 0.088 per kWh (nominal) and in 2000 SEK 0.162 per kWh (nominal) (corresponding to 0.010 and EUR 0.019 per kWh, respectively). The bonus was paid by the electricity distributors to the owners of wind turbines. The total funding by the environmental bonus until 2000 was EUR 27 Million, see Figure 4.17. In 2000 a temporary additional subsidy of SEK 0.09 per kWh was introduced, corresponding to EUR 0.011 per kWh. The goal was to further reduce cost of wind-generated electricity and to secure the economy for small-scale electricity producers.

4.4.4 Other policies employed to reduce investment costs

A technology procurement programme was run in 1995-1996. The aim of this programme was to improve further development of wind turbine technology, to improve the environmental conditions for wind power, and to reduce production costs. The outcome of the programme was a reduction of the cost of generated electricity and a reduction of noise. The funding for the programme was EUR 3 millions. The program resulted in the delivery of 15 turbines from Bonus Energy A/S.

Figure 4.16 Investment subsidies in Sweden. Prices are expressed in 2000 year prices.

Figure 4.17 Price subsidies in Sweden. Prices are expressed in 2000 year prices.
5. Analysis of the effect of energy policy on the development of the experience curve

Policy measures can affect the development of the experience curves by promoting technology development and by supporting market expansion. Policy measures that improve technology development will make wind technology more reliable, improve wind capture and reduce the cost of wind turbines and wind-generated electricity. Such measures are often referred to as “technology push” measures, see Table 5.1. Policy measures that support market expansion, or create new markets, provide learning opportunities in production and use, which in turn may reduce the cost of wind turbines and wind generated electricity. Measures focused on market expansion are often referred to as demand “pull measures”, see Table 5.1.

In this chapter we will analyse how different policy measures have affected the ride down the experience curve, in terms of installed capacity and cost reduction of wind turbines and wind generated electricity. Since experience curves provide an aggregated picture of development, we will improve the analysis by describing the effect in terms of different sources of cost reductions, as described in Chapter 3. We will also consider the possibility of policy programmes that limit cost reduction and thus jeopardise market development.

Table 5.1. Policy instruments used to promote wind turbine technology and installation.

<table>
<thead>
<tr>
<th>Demand pull instruments</th>
<th>Technology push instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incentives</td>
<td>Incentives</td>
</tr>
<tr>
<td>• Investment and price subsidies</td>
<td>• RD&amp;D programmes</td>
</tr>
<tr>
<td>• Taxation</td>
<td>• Dedicated research centres</td>
</tr>
<tr>
<td>• Soft loans</td>
<td>• Test stations for wind turbines</td>
</tr>
<tr>
<td>• Re-powering</td>
<td>• International cooperation</td>
</tr>
<tr>
<td>• Foreign-aid programmes</td>
<td></td>
</tr>
</tbody>
</table>

Other forms of regulation
- Resource assessment
- Local ownership
- Agreements with utilities
- Regulation of grid connection
- Feed-in law
- Information programmes
- Legislation

Other forms of regulation
- Certification
- Standardisation

We will analyse how policy measures applied in Denmark, Germany, Spain and Sweden have affected the development of experience curves. We will do this by

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34 The study is limited to those countries for which it has been possible to develop experiences curves.
analysing (1) how different measures have affected cost reduction due to technology development and the effect these had on the development of experience curves, and (2) how measures have affected cost reduction due to market expansion and their effect on the development of experience curves.

In the analysis we will use experience curves based on a production perspective:

1. Experience curves for wind turbines produced by different manufacturers
2. Experience curves for the specific production cost of electricity (at a reference site) for wind turbines made by different manufacturers
3. Experience curves for the levelised production cost of electricity (at a reference site) for wind turbines made by different manufacturers

and those based on a market perspective:

4. Experience curves for wind turbines (turbine cost) installed in different countries
5. Experience curves for wind turbines (total installation cost) installed in different countries

5.1 Denmark

Denmark has applied several policy measures to promote the development of wind power, see Chapter 4. Programmes have included both technology push and market pull measures. Major policy programmes include:

- RD&D programmes, 1975 and onwards
- Investment subsidies, 1979-1990
- Price subsidies, 1979 and onwards
- Feed-in-tariffs, 1979 and onwards

The programmes have affected the number of units installed (see Figure 5.1) the cost of wind turbines (see Figure 5.2) and the specific production cost of electricity (see Figure 5.3).
Figure 5.1 Number of wind turbines produced by Danish manufacturers (and installed in Denmark), and investments in Denmark. The plateau in price subsidies is due to a decrease in wind speed and the production of less electricity in 1996 and 1999. Prices are expressed in 2000 year prices.

Figure 5.2 Price of wind turbines produced by Danish manufacturers, and investments in Denmark. The plateau in price subsidies is due to a decrease in wind speed and the production of less electricity in 1996 and 1999. Prices are expressed in 2000 year prices.
Figure 5.3 “Specific production cost of electricity” by wind turbines produced by Danish manufacturers and investments in Denmark. The plateau in price subsidies is due to a decrease in wind speed and the production of less electricity in 1996 and 1999. Prices are expressed in 2000 year prices.

The cost reductions described by these different types of experience curves show progress ratios of 83%-97% depending on system boundaries (Figure 2.3) and whether they are based on an industrial or market perspective, see Table 5.2.

Table 5.2. Selected experience curves for Denmark

<table>
<thead>
<tr>
<th>Experience curve (EC)</th>
<th>Progress ratio (%)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. EC for wind turbines produced by Danish manufacturers</td>
<td>92</td>
<td>0.84</td>
</tr>
<tr>
<td>II. EC for specific production cost of electricity for wind turbines in I</td>
<td>86*</td>
<td>0.97</td>
</tr>
<tr>
<td>III. EC for levelised production cost of electricity for wind turbines in I</td>
<td>83**</td>
<td>0.97</td>
</tr>
<tr>
<td>IV. EC for wind turbines installed in Denmark (turbine price)</td>
<td>91</td>
<td>0.94</td>
</tr>
<tr>
<td>V. EC for wind turbines installed in Denmark (installation price)</td>
<td>90</td>
<td>0.92</td>
</tr>
</tbody>
</table>

* The specific production cost of electricity was calculated by dividing the average wind turbine list price by the number of full load hours. The number of full load hours is, in turn, determined by dividing the average production in roughness class 1 by the average turbine size.
** The levelised production cost of electricity (see Trade and Hunter (1994)) is based on the specific production cost of electricity for wind turbine produced in Denmark at roughness class 1, the cost reduction in the installation of wind turbines in Denmark, a lifetime of 20 years, an interest rate of 6%, and a model for O&M costs based on surveys of actual O&M costs (see Redlinger, et al., 2002).
5.1.1 Technology push measures

The Danish Government has sponsored several RD&D programmes since the mid-1970s. The two main programmes are the Energy Research Programme (EFP) and the Renewable Energy Development Programme (UVE) (see Chapter 4). The focus of the programmes is on both large-scale and small-scale wind turbines. However, the two programmes were merged in 1989 and turbines have since been scaled up over time. The Danish Government has also supported a test station for wind turbines. As part of the work of test station a certification programme was introduced in 1978. This certification programme improved the reliability of the wind turbine technology developed. The total amount invested through these programmes up to 2000 was EUR 100 million. The research programmes mentioned above have also been combined with other RD&D programmes (see Chapter 4). Moreover, private RD&D investments have been important in the development of wind power. No figures are available, however, regarding private RD&D investments.

Cost reductions due to technology push measures

The development of wind turbines in Denmark, supported by RD&D measures and the certification programme, led to the Danish concept, as described in Chapter 3. In the mid-1970s several wind turbine concepts were tested and produced by small companies entering the wind energy industry, and already in 1981 the whole Danish wind turbine industry was developing its technology within a certain paradigm: the upwind, three-bladed, stall-regulated, grid-connected, and horizontal axle concept. This concept has been adhered to ever since, with only incremental changes being made. These incremental changes have formed the basis for the experience curves presented in this report. Experience curves show the succeeding cost reductions as a result of incremental changes.

These incremental improvements can be divided into three different types of innovation processes: innovation within one turbine size, innovation on a specific platform, and the introduction of a new platform, as described in Chapter 3. The three processes succeed each other as newer larger turbines are introduced onto the market. Although the innovation process is different in these three categories, it is incremental in all three categories. The different types of innovation processes leading to different magnitudes of cost reduction cannot be observed individually in the aggregated cost reduction demonstrated by experience curves.

The reduction in cost of wind turbines, demonstrated by the experience curve describing cost of wind turbines production (experience curves of category I, see table 5.2), is quite modest. To analyse the sources of cost reduction further, it is necessary to analyse the
individual components of a wind turbine. However, we have not been able to find data on which to base experience curves for individual components. We will thus discuss the sources of cost reduction for different components.

The development of Danish wind turbines, in the early 1980s, was based on the assembly of a number of standard components such as gearboxes, generators, hydraulic motors for yaw systems, standard bearings for the main shaft and yaw rim etc. Only blades and control systems were especially tailored for the wind turbine industry. Because of the relatively small volume in the wind turbine industry, no vendor was prepared to tailor special components (e.g. bearings). As the total market volume increased specialised suppliers to the wind industry evolved. Large international corporations such ABB, VALMET and FAG have come to focus much more on adopting components for wind turbines. In recent years, international corporations have also pursued dedicated R&D on these components.

Moreover, the development of improved wind turbines has included improved wind capture (efficiency, availability) and decreased load on turbines. This development has contributed to improved cost reductions of wind-generated electricity. The reduction in specific production cost of electricity, illustrated in experience curves of category II and III (see Table 5.2) are more progressive. These experience curves include the cost reduction due to improved wind capture of the turbines. An experience curve for the cost of wind-generated electricity would probably illustrate cost reductions larger than those illustrated by experience curves for specific and levelised production cost of electricity. However, it was not possible to develop such experience curves.35

In all, RD&D measures have certainly affected the development of experience curves and the observed reduction in cost. However, the technical changes and the cost reductions are incremental and the effect is distributed over the years. Moreover, the experience curves illustrates the aggregated cost reduction due to several RD&D measures and several sources of cost reduction. It was not possible to study the different sources of cost reduction separately.

5.1.2 Market pull measures

The wind turbines market in Denmark has been significantly affected by several market-pull measures such as investment subsidies, price subsidies, programmes for the replacement of small and old turbines, feed-in tariffs, etc. An investment subsidy of 30% was introduced in Denmark already in 1979 (this was later reduced and removed in

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35 Only experience curves for tariff prices have been developed. However, these do not illustrate cost reductions due to market-based learning but regulated prices.
A price subsidy was also introduced in 1979, parallel with the investment subsidies, which developed over time (see Chapter 4). Moreover, the price subsidy was complemented with a reduction in the value added tax, and wind turbine owners also received a refund for the CO₂ tax from 1992. Governmental investment and price subsidies from 1979 to 2000 have amounted to EUR 806 million (in terms of 2000 prices).

Denmark has also applied feed-in tariffs (or power purchase agreements). This means that utility companies have been obliged to purchase all the power produced by wind turbines, at a price equivalent to 85% of the consumer price of electricity in the given distribution area. The “cost” of the feed-in tariff has not been borne by the government but by the utilities. No estimate of the total cost of the feed-in tariffs is available.

**Cost reductions due to market pull measures**

Market pull incentives have also affected the development of the experience curves and the observed cost reductions in Denmark. The experience curves illustrate a need for market development for further cost reductions, and the market development in Denmark has been significant. Measures have supported market expansion by lowering the investment cost of wind turbines and later by lowering the production cost and securing a high price for the wind-generated electricity. This has reduced the risk associated with generating power from wind. Moreover, the increase in the market has, in turn, led to the further development of new turbines.

The expansion of the market has supported learning processes in both the production and use of wind power. The learning process of production, i.e. the development of wind turbines is discussed above. The learning process in use has resulted in reductions in the cost of installed wind turbines, including cost reduction of the foundations, electrical installation, grid connection etc., illustrated by experience curves in category IV and V in Table 5.2. Regarding the additional costs a significant decrease can be observed. The proportion of additional costs, as a percentage of the total cost has decreased during the past 20 years. In 1989 almost 29% of the total investment cost was related to costs other than that of the turbine itself. By 1996 this had declined to approximately 20%, a level that has been maintained over the past five years.

Learning in the use of wind turbines has also resulted in decreased maintenance cost. Experience curves including cost reduction of O&M together with cost reduction of equipment, installation, and specific production cost of electricity (excluding, however, cost reduction due to sitting) show progress ratios grater than those for wind turbines only, see experience curve III. The increase in the use of wind turbines has resulted in reducing the risks, as described above. As banks have gained experience in financing wind power projects they have felt able to offer a lower (relative) discount rate. The
same is true for insurance – as experience is gained the financial risks are better understood and insurance has become cheaper. Experience curves for wind-generated electricity would probably illustrate greater cost reductions than those illustrated by the experience curve above. However, such experience curves have not been able to develop.

5.1.3 Other measures that have affected cost reduction

Several sources of cost reduction affect the experience curves. We have discussed the influence of investments in RD&D and subsidies. Other measures applied in Denmark have also affected the cost reductions illustrated in the experience curves. Such measures include national targets, utility agreements, legislation regarding the connection of wind turbines to the grid, resource assessment, permitting procedures, information programmes, and land planning issues as an integral part of the Danish development of wind power. Such measures may not have any direct pull or push effects on the experience curve, but they are necessary for the development of wind power. Failure or deficiencies in planning or legislation may well limit the development of the experience curve.

5.2 Germany

Germany has applied several instruments to develop wind power since the early 1970s (see Chapter 4). Policy measures have been directed towards both technology push and market pull. This report focuses on policy measures developed by the German federal Government, and the following major wind energy programmes:

- RD&D programmes, 1975 and onwards
- Subsidies, 1989-1996 (“100/250 MW Wind”)
- Feed-in tariffs, 1991 and onwards

These programmes have affected the number of units installed (Figure 5.4), the cost of wind turbines (Figure 5.5) and the specific production cost of electricity (Figure 5.6). The cost reductions described by different types of experience curves show progress ratios of 88%-94%, depending on system boundaries (Figure 2.3) and whether they are based on an industrial or market perspective, see Table 5.3.
Figure 5.4 Number of wind turbines produced by German manufacturers and wind turbines installed in Germany, and investments in Germany. Prices are expressed in 2000 year prices.

Figure 5.5 Price of wind turbines produced by German manufacturers, and investments in Germany. Prices are expressed in 2000 year prices.
Figure 5.6 “Specific production cost of electricity” by wind turbines produced by German manufacturers and investments in Germany. Prices are expressed in 2000 year prices.

Table 5.3. Selected experience curves for Germany

<table>
<thead>
<tr>
<th>Experience curve (EC)</th>
<th>Progress ratio (%)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. EC for wind turbines produced by German manufacturers</td>
<td>94</td>
<td>0.74</td>
</tr>
<tr>
<td>II. EC for specific production cost of electricity for wind turbines in I</td>
<td>88*</td>
<td>0.87</td>
</tr>
<tr>
<td>IV. EC of wind turbines installed in Germany (turbine price)</td>
<td>94</td>
<td>0.88</td>
</tr>
</tbody>
</table>

* The specific production cost of electricity was calculated by dividing the average wind turbine list price by the number of full load hours. The number of full load hours is, in turn, determined by dividing the average production in roughness class 1 by the average turbine size.

5.2.1 Technology push measures

The German Government has sponsored several RD&D programmes since the mid-1970s. During 1977 to 1989 the focus of the programmes was on large-scale turbines, e.g. the Growian and other turbines above 1 MW rated power. The historic background behind the development of large turbines was the ideal of a centralized power supply structure. Proposed manufacturers came from the vehicle, machinery, aviation and space industries. The customers were expected to be utilities with technological know-how and financial resources, but in fact with only little interest in such technology.
From the mid 1980s federal funding resources were given to domestic turbine manufacturers (Enercon, Husumer Schiffswerft, Tacke and others) to develop small and medium-sized turbines. This policy continued almost until today. Enercon was especially successfully in obtaining federal RD&D resources to develop its gearless wind turbines in the range from 500 kW (1990) to 1,500 kW (1993) and 4,500 kW (1998). Other manufacturers, e.g. Tacke Windtechnik (later Enron Wind, now General Electric Wind) also obtained support for turbine development.

Additional RD&D funding was devoted to issues such as grid integration, certification, control, wind analysis, energy balance etc. The total RD&D funding for the period 1977-1989 amounted to EUR 177 million. However, these RD&D measures did not lead to any substantial commercial development. Since 1989, RD&D activities have been more modest; EUR 50 million, has been devoted mostly to generic activities, such as a monitoring programme for a large number of turbines, research into the problems of grid connection, research for early recognition of turbine failure, and the demonstration of the combination of wind power with sea water desalination. Some money has also been given to specific turbine development projects in the MW range, but this type of support for specific turbine concepts is quite modest compared with that in the 1980s.

**Cost reductions due to technology push measures**

As for Denmark, limited reductions in the cost of wind turbines are illustrated by the experience curves for wind turbines produced by German manufacturers (experience curve I, Table 5.3). Although the development of wind turbines produced by German manufacturer is not exactly the same as that of the development of the Danish produced wind turbines, similarities do exist.

Early governmental RD&D in Germany was focused on the development of large wind turbines but did not result in the commercial production of turbines, and thus no cost reductions. However, early RD&D certainly led to the gaining of experience and know-how in wind power. This, in turn, supported the development of German manufactured medium sized wind turbines in the mid 1980s, a few years later than the development of the “Danish concept”. Two main turbine concepts were funded: 1) the variable speed turbine (Enercon), 2) the “Danish” concept (HSW, Tacke). Federal funding was given to domestic turbine manufacturers to develop small and medium-sized turbines. Furthermore, testing of other concepts with various numbers of blades, rotor position, power control systems etc. has also been funded. Continuous, incremental development and scaling up of wind turbines can be observed from the mid 1980s until up today.

The funding of the development of prototypes was the foundation for very successful series of turbines on the market. This, in turn, resulted in reductions in the cost of
turbines. The concept has been developed, and today the proportion of variable-speed plants is considerably higher. Also, double fed, asynchronous machines, originally developed for the “Growian”, are now used in some German manufactured wind turbines (as well as in Danish manufactured turbines). Early RD&D, which was focused on large wind turbines, may have contributed to experience that have been useful in recent years when developing turbines in the MW size range.

5.2.2 Market pull measures

Domestic turbines at moderate prices have been available on the market for private investors since the late 80s. The development of these turbines (and others) allowed wind power to enter the next stage; the testing and monitoring programme 100/250 MW Wind. The 250 MW Wind programme provided price subsidies rather than investment subsidies, although the funding could be used as an investment subsidy in some cases. A total of some EUR 66 million was provided as investment subsidies within this programme.

Price subsidies from the 250 MW Wind programme were normally awarded for 10 years, but are terminated earlier if accumulated amount exceeds a certain limit defined relative to the cost of the turbine. The last subsidies were awarded in 1996, but due to the 10-year duration of the subsidies (calculated from the start of production, not from the time of the award) expenses will continue until about 2008. During the period 1989-2000 the total amount awarded was EUR 131 million. For 2001-2006, additional expenses of some EUR 18 million are expected.

Wind turbine investors have also been able to take advantage of soft loans that have an interest rate 1% below the market rate, and which often are granted for 10-15 years. The possibility of financing projects with special loans (ERP, DTA) with favourable conditions was, and still is, an important factor making wind energy commercially viable.

The most important German wind power subsidy legislation was adopted in 1991, in the form of the "Stromeinspeisungsgesetz” (Electricity Feed Law, EFL). This law allowed the breakthrough of wind energy through important measures such as the feed-in tariff and grid access. Utilities were required to pay wind power producers 90% of the average retail price of electricity. The exact level of the subsidy is difficult to define. Estimates of the total subsidy provided by the utilities from 1991 to 2000 vary from EUR 995 million to EUR 2,094 million, see Chapter 3. In April 2000 the EFL was changed into the “Erneuerbare Energien Gesetz” (Renewable Energy Law). This was an improvement of the EFL with legal options to adjust energy tariffs for renewable energy
sources. These measures initiated and significantly reinforced the wind energy boom in Germany.

**Cost reductions due to market pull measures**
The market pull measures introduced in Germany have created a secure market with high and stable prices for electricity generated from wind power. The market pull measures have affected market development and the development of the experience curve for wind turbines installed in Germany (see experience curve IV in Table 5.3 which also includes wind turbines produced by Danish manufacturers). The cost reduction illustrated in this curve is approximately the same as that for wind turbines installed in Denmark. As for Denmark, market pull measures have decreased the risks for investors and stimulated further wind turbine development etc. In all, market pull measures have aided learning processes in both the production and use of wind power, as in Denmark. It was not possible to develop experience curves for wind-generated electricity for Germany.\(^{36}\)

**Other measures that have effected cost reduction**
Several kinds of governmental policies that do not involve monetary subsidies have been important in the development of the German experience curves. Examples are the regulations governing grid connection, the procedures for obtaining building permits, and the tax regulations governing depreciation.

### 5.3 Spain

Spain has applied several policy instruments to develop wind power, see Chapter 4. Their programmes have been directed towards both technology push and market pull measures. Wind power has been supported by the national government, regional governments, the European Commission, the state-owned electricity company Endesa, and electricity consumers. This section focuses on the following national government programmes and the major governmental policy measures:

- RD&D programmes, late 1970s and onwards
- Investment subsides, early 1990s and onwards
- Premium electricity price, mid-1990s and onwards

Governmental programmes have affected the number of units installed (Figure 5.7) and the cost of wind turbines installed (Figure 5.8).

\(^{36}\) Only experience curves for tariff prices can been developed. However, these do not illustrate any cost reductions due to market based learning but rather regulatory prices.
Figure 5.7 Number of wind turbines installed in Spain, and investments in Spain. Prices are expressed in 2000 year prices.

Figure 5.8 Total installation cost of wind turbines installed in Spain, and investments in Spain. Prices are expressed in 2000 year prices.
The cost reduction can also be described by different types of experience curves, see Chapter 2 and Table 5.4.

Table 5.4. Experience curve for wind turbines installed Spain.

<table>
<thead>
<tr>
<th>Experience curve (EC)</th>
<th>Progress ratio (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V. EC of wind turbines installed in Spain</td>
<td>90%</td>
<td>0.92</td>
</tr>
</tbody>
</table>

5.3.1 Technology push measures and cost reductions

Wind power policies gained momentum in the late 1970s with national support for RD&D. Subsequently, a number of projects involving small and medium-sized turbines received RD&D funding. Since 1986, and with the development of the Renewable Energy Plan, national RD&D has received funding from the European Commission, the regions and the electricity utilities. Moreover, the emphasis has been changed from single-turbine projects to small wind farms. Up until 2000 national RD&D funding was EUR 58 million. No data are available for additional investments.

The experience curve for wind turbines produced in Spain and installed in Spain indicates cost reductions of the same magnitude as for the Danish produced and installed wind turbines (see experience curve for category IV). However, no in-depth study was performed in this project to describe the cost reduction of wind turbines produced in Spain. In general, Made and Ecotècnia have both adopted the practical strategy of combining technology transfer from the USA and Denmark with internal technology development. Thus, the development of the Spanish industry has not solely been dependent on domestic RD&D efforts, but has made use of inputs from abroad. The reduction in cost of installed wind turbines, illustrated by the experience curve in category IV, can be an effect of national as well as international RD&D investments.

5.3.2 Market pull measures and cost reductions

In the early 1990s investment subsidies were introduced in Spain. National investment subsidies have gradually been reduced in scope and percentage. From a situation in the early 1990s with an average of a 25% subsidy for a large proportion of wind power projects, the percentage was reduced to an average of 10% in the mid 1990s, and was restricted to special circumstances by the end of the decade (see Chapter 4).
Since the middle of the 1990s, the most important subsidy to Spanish wind power has been the premium price paid by the electricity utilities. Premium prices were enforced on a legal basis in 1994. All electricity utilities were obliged to pay a mandated guaranteed premium price for wind power over a five-year period. This premium price was determined in principle according to long-term avoided cost considerations (Saiz de Bustamante & Gil Sordo, 1997). A new policy was adopted in 1998. Wind power producers now had two alternatives: to obtain a premium wind power price per kWh, amounting to 88.5% of the retail price to consumers, the average market price for electricity plus a wind power bonus. The premium wind power price and the wind power bonus are adjusted every year by the ministry responsible, based on market prices.

The market pull measures have certainly aided the rapid increase in the number of turbines installed in Spain. This, in turn, has provided the basis for the development of Spanish wind turbines. The experience curve for wind turbines installed in Spain, based on installation costs, includes not only learning in the production of wind turbines but also reductions in the cost of foundations, electrical installation, grid connection, roads etc.

5.3.3 Other policy measures that have effected cost reduction

Policies other than those involving monetary subsidies, have also played a role in the investment costs for wind power. The regulations covering grid connection, procedures for obtaining building permits, and tax regulations governing depreciation are important examples.

5.4 Sweden

Sweden has also applied various measures aimed at wind power (see Chapter 4). Programmes have been directed towards both technology push and market pull. This chapter focuses on the major governmental programmes:

- RD&D programmes, 1975 and onwards
- Price subsidy, 1994 and onwards

These programmes have affected the number of units installed (Figure 5.9) and to some degree also the cost of the wind turbines installed (Figure 5.10).
Figure 5.9 Number of wind turbines installed in Sweden, and investments in Sweden. Prices are expressed in 2000 year prices.

Figure 5.10 Total installation cost of wind turbines installed in Sweden, and investments in Sweden. Prices are expressed in 2000 year prices.
The cost reduction can also be described by different types of experience curves, see Chapter 2 Table 5.5.

Table 5.5 Experience curves for wind turbines installed in Sweden.

<table>
<thead>
<tr>
<th>Experience curve (EC)</th>
<th>Progress ratio (%)</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V. EC of wind turbines installed in Spain (installation price)</td>
<td>90</td>
<td>0.92</td>
</tr>
</tbody>
</table>

5.4.1 Technology push measures

Sweden has funded wind power development since 1975 by RD&D investments. The RD&D programmes have been focused on larger wind turbines (MW size), and a number of demonstration turbines have been developed. Effort have been directed towards the development of concepts such as two-bladed turbines, soft yaw, wind former etc. These investments have not led to the large-scale production of wind turbines, and have not effected the cost of wind turbines installed in Sweden (which have largely been wind turbines developed in Denmark). Up until 2000 funding by the Swedish government amounted to EUR 127 million. Figures regarding funding by Swedish utilities for wind RD&D are not available.

5.4.2 Market pull measures and cost reductions

Investment subsidies have been employed in two periods: 1991-1996 and 1998-2002 (see Chapter 4). Subsidies were initially 25% of the investment cost and were increased in 1993 to 35% of the investment cost. The second programme provided a 15% subsidy of the investment cost during the first four years, and a subsidy of 10% in 2002. The total funding of these two programmes was amounted to EUR 61 million. In 1994 an environmental bonus was introduced. The environmental bonus corresponds to the general electricity tax for households, and is paid by the distributors to wind turbine owners.

The increase in the number of wind turbines installed in Sweden is a result of Swedish market pull measures. These wind turbines are almost all produced by Danish manufacturers. The reduction in cost of wind turbines installed in Sweden, as illustrated in the experience curve, may only to a very limited degree be due to Swedish market pull measures. These market pull measures may, however, have contributed to learning in the use of wind turbines and cost reductions in siting, wind capture etc. It was not
possible to develop an experience curve for the cost of wind-generated electricity in Sweden due to a lack of appropriate data.

5.5 The cost reduction illustrated by the experience curve

The policy measures applied in Denmark, Germany, Spain and Sweden have aided the ride down the experience curve and led to an increase in the wind turbine capacity installed and a reduction in cost of wind power. Investments in different measures differ between countries, see Table 5.6.

Table 5.6. Investment in wind power. Additional policies not included may be taxation, national targets, planning, grid connection, regional incentives etc. (N.A. = data not available)

<table>
<thead>
<tr>
<th></th>
<th>Denmark</th>
<th>Germany</th>
<th>Spain</th>
<th>Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governmental RD&amp;D</td>
<td>100*</td>
<td>227</td>
<td>59</td>
<td>128</td>
</tr>
<tr>
<td>-RD&amp;D before 1990</td>
<td>47</td>
<td>177</td>
<td>32</td>
<td>100</td>
</tr>
<tr>
<td>- RD&amp;D 1990-2000</td>
<td>53</td>
<td>50</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>EU RD&amp;D</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Private R&amp;D</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Investment subsidies</td>
<td>57</td>
<td>69**</td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>Price subsidies</td>
<td>749</td>
<td>131</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>“Feed -in law”</td>
<td>N.A.</td>
<td>997</td>
<td>318</td>
<td>-</td>
</tr>
</tbody>
</table>

*Combined with testing and certification  
**Excluding soft loans from state bank  
Exchange rates from the Swedish National Bank (2002): 1EUR= DEM 1.96; DKK 7.45; ESP166.4; SEK 8.45.

RD&D measures have formed the basis for technology development in all the countries included in this study. Initial RD&D was pursued in both small and large turbines, however, on time development came to focus on small turbines; first in Denmark and then also in Germany and Spain. These small turbines were then scaled up, and technology development can be characterised as incremental. This, in turn, resulted in succeeding cost reductions which were observed in the experience curves. Early RD&D investments in large turbines, which although not resulting in commercial wind turbines, provided useful experience and know-how, and seem to have been contributed to the development of large wind turbines of the end of the 1990s in Germany.

Furthermore, demand pull incentives have led to market expansion and provided opportunities for the incremental cost reductions in wind turbines described above. Market measures, which started as investment subsidies, developed into price subsidies and privately funded feed-in tariffs in Denmark in 1983, in Germany in 1990 and in Spain in 1994. As a result of these measures a large number of wind turbines have been
installed in Denmark, Germany and Spain (see Table 5.6). (Wind turbines have also been installed in Sweden but in smaller numbers). However, market incentives do not cause cost reductions per se, but provide opportunities for cost reduction in both production and use. This, in turn, means that the measures not only affect the cost of turbines, as described above, but also the reduction in cost of installation, O&M etc. The cost reductions illustrated by the experience curves also show greater cost reductions for larger systems, i.e. systems including not only cost of wind turbines (cf. experience curve in category I) but also improved wind capture and lower O&M costs (cf. experience curve in category III and V).

In all, the results show that the aggregated reduction in cost of wind turbines is rather moderate. However, the reduction in cost of specific and levelised production cost of electricity is greater. The experience curve for the cost of generating electricity would probably illustrate even larger cost reductions. However, we cannot see the direct effect of individual policy measures in the curves. The cost reduction observed in the experience curves is the result of several programmes and combinations of different measures. Moreover, these reductions in cost are in the same range for all countries studied. This means, that we can not even see any differences in cost reductions due to combinations of measures implemented in different countries.

5.6 The limiting effect on the ride down the experience curve

As described above, various measures have affected the development of experience curves and led to cost reductions. However, such measures may also limit the development of experience curves and cost. Too few incentives for product development and learning processes may limit wind power development. The use of incorrectly designed measures may also limit cost reduction. In this section we will theoretically discuss the possibility of the limiting effects of the measures studied.

A measure that is incorrectly designed could jeopardise the development of the experience curve. Technology development must result in a reliable product; this may not be the case if market development is too rapid. This could result from high unrestricted subsidies, as was the case in the development of wind power in California in the late 1970s and early 1980s (see Box 5.1).

Another example of is the incorrect use of targeted measures such as RD&D. Targeted measures are intended to improve the development of the experience curve, however, such measures could also jeopardise development as too narrowly targeted RD&D could lead to lock-in effects. As in the wind sector, RD&D directed towards large wind turbines can lead to delays, or even stagnation, of wind turbine development and the development of experience and experience curves. This was the case in Sweden.
Some measures may also affect the development of the price of electricity in relation to cost development, i.e. the price may not decrease at the same rate as the cost decrease. However, is has often been denied that this is the case for wind turbines and wind-generated electricity; this due to hard competition in the wind power industry. The development of new wind turbines has been rapid and the mobility of workers (nationally and internationally) between manufacturers has not made it possible for any particular manufacturer to be favoured by the measures implemented. However, the price of the wind turbines probably includes some margin for further development expenses.

The use of measures that guarantee a high price of wind-generated electricity could, theoretically, also limit the development of the experience curve and cost reduction. For example, measures that guarantee a high price level for wind-generated electricity may reduce the incentive for the wind turbines manufacturer to reduce the price. Moreover, measures that guarantee a high electricity price may also lead to limited learning in the use and siting of wind turbines. Turbines may very well be sited in areas with poor wind resources. (On the other hand, this increases learning in the use of turbines in low-wind areas). High electricity price may lead to a limitation in the development of the experience curve. However, we can not see this in our data. Moreover, such measures are easily changed in order to follow cost reductions due to increased experience.
6. National and international learning systems with regard to wind power

The findings presented in Chapters 2, show that the cost reductions illustrated by the experience curves for different countries differ very little. As a result of this we would like to elaborate on the terms national and international learning systems. Moreover, we will study the cost reductions and the experience curves for different countries in one and the same graph.

6.1 National and international learning systems

We state that learning systems can be considered to be national or international. In a national learning system the learning process is limited to national production and use of a product, i.e. national learning in the production and use of a product is the only source of learning. International learning, on the other hand, is based on learning on an international arena. Learning, for example, be considered to be international when manufacturers are inspired by manufacturers and employees from other countries (i.e. know-how) that travel from one country to another. Moreover, learning can be considered to be international when “the use of a product” exceeds its use in the country producing the product, and the “learning system associated with use” is larger than that in the country of the manufacturer.

As described earlier, initially RD&D programmes were applied to develop wind power. These programmes were to a large extent national, and affected the learning process of individual manufacturers and the overall learning associated with wind turbines produced in a certain country. This has led to different paths of wind turbine developments in different countries. Early development in the 1970s and 1980s in Germany and Sweden was characterized by the development of large wind turbines, whereas development in Denmark was focused on small turbines. The successful development of wind turbines in Denmark led to the “Danish concept” of wind turbines, the upwind, three-bladed, stall-regulated, grid-connected, and horizontal axle concept. In the 1990s the learning process associated with producing wind turbines developed from being national to international. In countries, such as Denmark and Germany, the learning system associated with producing wind turbines developed from being national to international through the development of multinational companies. In some countries, such as Spain, the early development of nationally produced wind turbines was, to a
large extent, inspired by the experience gained from the production of wind turbines in other countries.

Moreover, deployment programmes were introduced to complement RD&D programmes. These programmes affected the learning associated with the production and use of turbines installed in a country. In the first place, national deployment programmes and an increase in the use of wind turbines affect the national learning associated with generating electricity by wind turbines. This includes, for example, learning associated with installation, siting, planning etc. (as described by the experience curves regarding the electricity generated). Secondly, national deployment programmes affect the learning associated with producing wind turbines. This learning process can be national or international, as described below.

- In countries with national manufacturers that only have a national market (e.g. Spain and Spanish manufacturers) the learning associated with producing wind turbines depend on the learning associated with turbines installed in that country.

- In countries with no domestic manufacturers or manufacturers not producing commercial wind turbines (e.g. Sweden) there is no national learning process associated with producing wind turbines and the cost reduction of turbines installed represent the learning process of producing wind turbines in other countries.

- In countries which export turbines (such as Denmark and Germany), the national learning associated with installed turbines only represents part of the actual learning regarding wind turbines produced. The learning associated with producing the wind turbines installed in that country may, however, constitute a very important part of the actual learning associated with wind turbines produced.

6.2 Project results: national and international learning systems

We will now analyse national and international learning systems by comparing the cost development in different countries. We will consider the cost/price development of wind turbines over time, as well as the experience curves of different manufacturers and different countries. In Figures 6.1 and 6.2 we present the price development of wind turbines produced or sold by manufacturers in Denmark and Germany. In Figures 6.3 and 6.4 the cost development of wind turbines installed in Denmark, Spain and Sweden.
including turbine cost and cost of foundation, etc is shown. (All costs/prices are relative to those in 2000)

The curves indicate that an international learning system for wind turbines has been established and still is progressing. The very similar progress ratios for wind turbines in Denmark (92%) and Germany (94%) indicate this. Furthermore, the average list prices of wind turbines in Denmark and Germany have converged during the past two decades. However, the market situation and market structure in the two countries are different and may temporarily have developed differently over recent years.

Also, the average project costs for wind turbine projects in Denmark, Spain and Sweden seem to be converging. This also indicates that an international learning system for wind turbine technology is emerging. However, local or regional learning may still be dominant in relation to civil works and other costs related to the installation of the turbines.

The experience curve for wind turbines installed also indicates an international learning system. The experience curves for wind turbines installed in Denmark and Spain show almost the same progress ratio, 90% and 91% respectively. The progress ratio for wind turbines installed in Sweden, on the other hand, is higher (96%). This may be due to the data used for the Swedish experience curve which are limited to a few years (1994-2000) and are sensitive to all minor changes in price.\(^\text{37}\)

These indications of an international learning system are supported by other empirical observations. Today, the leading wind turbine manufacturing companies operate internationally and have manufacturing capability in several countries. Other wind turbine companies in Spain and India were originally started as joint ventures between local engineering firms and international leading wind turbine manufacturers. Twenty years ago vendors in the wind turbine market may have been locally or regionally focused. (European wind turbine manufacturers may still use different vendors for their operations in America, Europe and India.) But over the years learning has taken place between vendors due to international wind turbine manufacturers’ general and increasingly more advanced specifications.

International R&D has also helped the establishment of an international learning system. The EU’s framework programmes have facilitated the creation of a European field of research on wind energy. Through the International Energy Agency national governments in America, Asia and Europe have been able to coordinate their governmental wind energy R&D and implement policies for more than 25 years.

\(^{37}\) If data for the first year are excluded from the Swedish experience curve the progress ratio is 89%.
Figure 6.1. Price of wind turbines produced by Danish and German manufacturers as a function of time.

Figure 6.2. Experience curves of wind turbines produced by Danish and German manufacturers as a function of total number of wind turbines produced in each country.
Figure 6.3. Total cost of installation of wind turbines installed in Denmark, Spain and Sweden.

Figure 6.4. Experience curves for wind turbines installed in Denmark, Spain and Sweden, based on total installation cost, as a function of total number of wind turbines installed in each country.
7. Cost efficiency evaluated by experience curves

Experience curves have come to be used to calculate investments to reduce the cost of renewable energy technologies (see, for example, Williams and Terzian, 1993; Neij, 1997; OECD/IEA, 2000). These investments, also referred to as the “learning investments”, illustrate the investments required to “buy down” the cost of new technologies to a certain level, see Figure 7.1. These “learning investments” can be used as a strategic decision support of industries and government. Moreover, governmental investments are often used to initiate such “buy-down” effects and to stimulate investments by commercial market actors. For wind power, several governmental measures have been used (see Chapter 4). These measures, taken together, reduce the risks and facilitate investments by commercial actors.

![Figure 7.1. Learning investments. C1 represents the cost of the first unit produced; Cn represents the cost of the last unit produced. In this case the experience curve is extrapolated the value of Cn must be assumed.](image-url)
Experience curves have also been used in ex post evaluation to calculate the cost efficiency of policy measures (OECD/IEA, 2000). The cost efficiency is then calculated by comparing the calculated cost, using the experience curve, with the actual governmental subsidies investments. In other words, funds used from government budgets in relation to funds mobilized by commercial market actors. The ratio between these gives the cost effectiveness:

\[
\text{Cost efficiency} = \frac{\text{Learning investments}}{\text{Government subsidies}}
\]

In this chapter we will calculate the cost efficiency of the measures applied to reduce the cost of wind power in Denmark, Germany, Spain and Sweden. This will be achieved using experience curves and calculations of learning investments. The results illustrate the use of experience curves for such calculations, rather than the actual cost efficiency of the measures implemented.

### 7.1 Calculation of cost efficiency of wind power measures

We start by calculating the learning investments and see that the experience curve can be used to calculate different kinds of learning investments; the kind of learning investment will depend on the experience curve used. If the experience curve for the cost of wind turbines is used, as in Figure 7.1, the calculated learning investments represent the amount of funding that must be invested in turbines. Such investments include investments by commercial actors and government subsidies. If the experience curve for the cost of wind-generated electricity is used the calculated investments represent investments required in wind-generated electricity. Such investments include the cost of buying electricity for commercial actors (including investments in wind turbines) and government production subsidies (and indirectly, investment subsidies). In this study it has not been possible to calculate the learning investments based on the experience curve for the cost of wind-generated electricity, since such experience curves could not be developed.

We then identify the cost of measures implemented to subsidies wind turbines and the cost of wind-generated electricity. The direct effect of “buying down” the cost of wind turbines will be considered through investment subsidies, and the direct effect of “buying down” the cost of wind generated electricity will be taken into account through price subsidies. These subsidies will cover part of the learning investments calculated. The calculated cost efficiency will tell us to what extent private funding has been part of the total “buy-down” cost.
We now calculate the cost efficiency of investment subsidies for reducing the cost of wind turbines in Denmark, Germany, Spain and Sweden. (We have not been able to calculate the cost efficiency based on the cost of wind-generated electricity, since such experience curves could not be developed). We use the experience curve that describes the cost of installed wind turbines in each country to calculate the learning investments. The following results were obtained:

- For Denmark the learning investments (1981-2000) were found to be € 68 million, based on turbine price only, and € 83 million based on total installation price of wind turbines. The cost efficiency was calculated to 1.2 and 1.5, respectively.
- For Germany the learning investments (1983-2000) was found to be € 196 million, based on turbine price only, and the cost efficiency 2.8.
- For Spain the learning investments (1984-2000) were € 161 million, based on the total installation cost of wind turbines, and the cost efficiency 1.1.
- For Sweden the learning investments (1994-2000) were € 7 million, based on the total installation cost of wind turbines, and the cost efficiency is less than one.

These results show that the calculated cost efficiency depends on the following factors.

1. The cost/price considered. In the calculations price of wind turbines only could be used (as for Denmark and Germany) or the total installation cost of wind turbines (as for Denmark, Spain and Sweden). Considering the total installation cost of wind turbines gives a larger learning investment and higher cost efficiency.

2. The price of the first wind turbines developed. The calculated learning investments depend greatly on the price of wind turbines in the early years. A high initial price, as in the cases of Germany and Spain, will result in a relatively high learning cost, which, in turn, will favour high cost efficiency. However, the initial price can be associated with large uncertainties due to the non-standardised product.

3. The number of turbines installed. The more turbines installed in a country, the greater the calculated learning cost. However, investment subsidies have been limited in time and combined with other subsidies. In Germany, for example, the number of turbines installed is high and investment subsidies constitute only a small fraction of the policy measures employed. This results in a high cost efficiency.
(4) The subsidies considered. We only considered investment subsidies that directly affect the “buy-down” process. However, additional governmental investments affect the motivation of actors to make investments. First, RD&D programmes, certification programmes and other government investments affect the development of reliable wind turbines. Second, production subsidies, indirectly, affect investments in wind turbines. Third, additional investments by commercial actors also affect the willingness of others to invest in wind turbines. Such investments include RD&D expenditure by commercial actors and transaction costs.

(5) The data available on which the experience curve is based. If early data regarding the development of an experience curve are not available, the calculated learning investments will be low as will the calculated cost efficiency. This was the case for Sweden, where data were not available before 1994.

The results indicate that the calculations are very sensitive to the data available and the kind of experience curve used. Although we have access to very good data in this project they are not sufficient for cost efficiency calculations. Moreover, the results indicate that cost efficiency calculations should rather be based on a system-wide approach using the experience curve for wind-generated electricity and total subsidies. However, such learning curves could not be developed for wind power in Europe. Moreover, subsidies can be characterised as a complex combination, and the evaluation of individual measures will be difficult. To this we can add the difficulties arising from the existence of international learning systems. In all, we are of the opinion that experience curves not are appropriate for cost efficiency evaluation of wind power measures.
8. Synthesis and conclusion

The aim of this study was to examine the experience curves as a tool for the analysis and assessment of energy policy measures. In this concluding chapter we will synthesize the findings presented in Chapters 1-7. We will do this by describing the advantages and disadvantages and the potential and limitations of experience curves as a tool for energy technology policy assessment.

The use of experience curves for the analysis and assessment of energy policy measures is based on further development of the experience curve concept. This development includes several aspects, as described in Chapter 1, and extends the concept to include non-standardised products, produced globally, nationally, or by an individual company. Moreover, the experience curve is extrapolated and used to analyse future cost trends of different energy technologies and energy carriers, and integrated into complex energy modelling of future energy scenarios. The development of the experience curve concept for the analysis and assessment of energy policy measures raises several questions. We will highlight the issues that are important regarding the findings on advantages and disadvantages and the potential and limitations of experience curves as a tool for energy technology policy analysis and assessment.

1. The most suitable kind of experience curve
2. The analysis of policy measures using experience curves
3. Disaggregating the experience curve
4. The learning process; an international, national or regional process
5. The analysis of cost efficiency using experience curves
6. Assessment of policy measures for wind power vs. those for other renewable energy sources
7. Experience curves as a tool for strategic decisions

The synthesis will be based on our findings regarding wind power; however, generic conclusions will be presented considering energy policy measures for the introduction and commercialisation of renewable energy sources. Our objective was to improve our understanding of how and if experience curves can be used as a generic tool for the analysis and assessment of energy policy programmes.
8.1. The most suitable kind of experience curve

Many experience curves can be developed; in this report we have developed more than 60 experience curves for wind power only. Therefore, the use of experience curves for energy policy analysis requires an in-depth understanding of the technology and a methodological understanding of which types of experience curves that can be developed, how they can be used, which data are needed, and the statistical methods available for developing experience curves.

Furthermore, different types of experience curves can be developed. In Chapter 2, Figure 2.3 we illustrate the different system approaches that can be used, describing different parts of the wind power system such as components, wind turbines, installed wind turbines, wind-generated electricity etc. Moreover, we illustrate two different experience perspectives, the production perspective and the market perspective; the production perspective includes, for example, wind turbines produced by different manufacturers, the specific production cost of electricity by turbines produced by different manufacturers, while the market perspective includes wind turbines installed in different countries, electricity generation by wind turbines installed in different countries etc.

When analysing the development of wind power we have developed several experience curves with production perspectives and market perspectives with the focus on wind-generated electricity and wind turbines (produced and installed). When analysing wind policy programmes an experience curve based on the actual cost of wind-generated electricity (cost/kWh) is preferable. However, such a curve is very difficult to develop for wind power, since the required data are usually not publicly available. Using the actual price of wind-generated electricity is not relevant, since these prices are set by tariffs. Therefore, the analysis of experience curves in this report has been based on the ex works cost of wind turbines, the specific production cost of electricity (where development of the cost of wind turbines is adjust with the development of efficiency) and the levelised production cost of electricity (which is the best available presentation of the actual cost of electricity).

The development of experience curves requires reliable data, which are difficult to obtain. The best data are those based on several sources, including the manufacturer, sub-contractors, consultants, government etc. The data used in this study are based on price-list data and data reported to authorities. An enormous amount of data has been collected, including price data for more than 17,000 wind turbines. Strictly speaking, these data are insufficient and will not describe the true cost development of wind power. In reality, however, the data should be considered very good, and are the best data available for cost (price) development analysis for independent research.
The results of this study show several experience curves that can be used to describe the reduction in cost of wind power. The progress ratio of these experience curves is in the range of 83-117%, see Table 8.1. The range depends on the system chosen, the perspective selected, the manufacturers involved, the time-frame used, the sizes of turbines included and the variation within the data. Based on these results we can see that the cost reductions are greater if we base our experience curve on a larger system, including not only the cost of wind turbines, but also the improvement in turbine efficiency (ability to capture the wind), other installation costs, and O&M costs. Using experience curves for wind turbines only when analysing cost reductions of wind power, will therefore require complementary analysis of the cost reduction due to parameters not included in the experience curve (e.g. installation cost, O&M cost, siting, etc.). The method used to develop the experience curves in this project is based on average prices in cost per kW by year. If other methods are used slightly different results may be obtained (see Chapter 2).

Although the progress ratios of the experience curves found in this study vary between 83 and 117%, we are able to draw certain conclusions. Firstly, for Danish and German manufacturers, which account for an overwhelming percentage of the world’s turbines (produced and installed), the progress ratios based on ex works costs of wind turbines and the cumulative production of turbine capacity (in MW) are 92% for turbines produced by Danish manufacturers and 94% for turbines produced by German manufacturers. The difference is estimated to be within the uncertainty of the data. Secondly, our study indicates that almost the same progress ratios are found when the calculations are based on the total project costs for installed turbines. That is, the ex works cost of wind turbines plus additional costs for foundations, roads, installation, etc. Thirdly, if the development of wind turbine efficiency is included in the analysis the progress ratios are improved significantly. This is expressed as the specific production cost of electricity, which includes the price reduction for wind turbines (cost/kW) as well as additional improvements in wind capture at a reference site (kWh/kW). In this case the progress ratios were determined to be 86% for turbines produced by Danish manufacturers and 88% for turbines produced by German manufacturers. Again, the percentage is, for all practical purposes the same. Fourthly, our study indicates that a progress ratio based on the cost of electricity is even lower. As mentioned, we were not able to find data for the exact cost of the electricity generated, but in the Danish case we

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38 A progress ratio less than 100% indicates a cost reduction, as described in Chapter 1. A progress ratio greater than 100% indicates that the total cost cannot be reduced by product standardisation, process specialisation, scale effects, labour rationalisation, etc., as fast as costs are added through design changes and product performance improvements. Experience curves with increasing progress ratios have been identified in this project for individual wind turbine manufacturers.
were able to estimate a levelised production cost of electricity (defined in Table 8.1). In this case, the progress ratio was 83%.

### Table 8.1 Experience curves and calculated progress ratios. The results are based on experience curves for wind power in Denmark, Germany, Spain and Sweden. It was not possible to find data with which to develop (relevant) experience curves for wind power in other European countries (for the UK and the Netherlands see Appendix 3). (N.A. = data not available.)

<table>
<thead>
<tr>
<th>Experience curve</th>
<th>Progress ratio (%)</th>
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<tr>
<td><strong>Production perspective</strong></td>
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<tr>
<td>Experience curves for different wind turbine (WT) manufacturers</td>
<td>89-117</td>
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<td>Experience curves for WT produced according to country</td>
<td>92-94</td>
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<tr>
<td>Experience curves for WT produced according to country during different periods</td>
<td>88-101</td>
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<tr>
<td>Experience curves for WT produced according to country and turbine size</td>
<td>98-102</td>
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<td>Experience curves for specific production cost of electricity according to country*</td>
<td>86-88</td>
</tr>
<tr>
<td>Experience curves for levelised production cost of electricity according to country**</td>
<td>83</td>
</tr>
<tr>
<td><strong>Market perspective</strong></td>
<td></td>
</tr>
<tr>
<td>Experience curves for WT installed in different countries</td>
<td>90-96</td>
</tr>
<tr>
<td>Experience curves for WT installed in different countries during different periods</td>
<td>85-101</td>
</tr>
<tr>
<td>Experience curves for electricity tariffs</td>
<td>98</td>
</tr>
<tr>
<td>Experience curves for the cost of wind-generated electricity</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

* The specific production cost of electricity was calculated by dividing the average wind turbine list price by the number of full load hours. The number of full load hours is, in turn, determined by dividing the average production in roughness class 1 by the average turbine size.

**The levelised production cost of electricity is based on the specific production cost of electricity for wind turbine produced in Denmark (at roughness class 1), the cost reduction in the installation of wind turbines in Denmark, a lifetime of 20 years, an interest rate of 6%, and a model for O&M costs based on surveys of actual O&M costs (see Redlinger et al., 2002).

### 8.2 The analysis of policy measures using experience curves

Experience curves have come to be used for the analysis of policy measures. This raises questions, such as:

- Can experience curves be used to analyse the impact of different policy measures?
- Can experience curves be used to analyse how, through individual measures and combinations of measures, and in what proportion money should be best spent?
In order to analyse these issues, we have analysed wind energy policies in Denmark, Germany, Spain and Sweden in relation to the development of experience curves. The measures implemented in these countries differ in the type of measures applied, money spent, time frame applied, etc. The measures analysed affected technology development and the number of turbines installed. This, in turn, has affected the reduction in cost of wind turbines and the electricity generated.

The analysis shows that the experience curves do not indicate the effect of individual policy measures, and we cannot see any distinct trend in the cost reduction due to the use of individual measures. The curves rather describe the aggregated cost reductions in response to the combination of measures employed. Therefore, experience curves for wind power cannot be used to analyse the effect of an individual measure, such as RD&D measures only, investment subsidies only, etc. However, experience curves could be used to indicate the success or failure of a combination of measures, in terms of installed capacity, electricity generated, reduction in cost of wind turbines, and reduction in cost of wind-generated electricity.

The results of this project further show how the combination of measures in Denmark, Germany and Spain resulted in a huge number of turbines, both produced and installed, and a related trend in reduction in the cost of wind turbines, the specific production cost of electricity, and the levelised production cost of electricity. We also observed a less efficient combination of measures in Sweden, which only resulted in a limited number of turbines being installed, which furthermore, were produced in other countries. The programmes applied in Denmark, Germany and Spain are all based on the same combination of measures: governmental research, development and demonstration programmes, governmental investment and price subsidies, which created and supported stable — but competitive — market conditions for wind turbines and wind-generated electricity. Initially, in 1970s and early 1980s, measures primarily consisted of RD&D programmes sometimes, but not always, directed towards the needs of this awakening industry. Publicly funded RD&D in some countries helped companies to design better machines and deploy prototypes and demonstration plants. During the years, publicly funded research also made it possible for industry to scale up commercial wind turbines. RD&D was first supported by investment subsidies and then by price subsidies. Later, private funding, in terms of private R&D and premium prices, increased. In Figure 8.1 we illustrate the combination of major measures applied in

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39 Policy programmes have only been analysed for those countries for which it has been possible to develop experience curves of wind power.

40 Experience curves may be used to analyse the affects and cost reduction resulting from individual measures directed towards a limited technology system, e.g. RD&D for blade construction. In this project we did not analyse this further.
Denmark, Germany and Spain: we also extrapolate the policy measures in the direction we consider probable.

Based on the results of our study, we can make no statements concerning any other combinations of measures. In general, it is difficult to say how funds are best used. The experience curves, in general, however, illustrate the need for experience in the production and use of turbines and the potential need for market pull measures. This indicates that RD&D measures alone will not always be sufficient for the commercialisation of new products. Based on this study, for example, we could see that the large amount of money spent on RD&D in Germany and Sweden (in comparison to the amount spent in Denmark) might not have been necessary for the development of wind power. In general, the combination of measures and the best way to use funding will depend on the product and the innovation system in question. Such an analysis will require methods and tools in addition to experience curves.

Figure 8.1. Schematic figure showing governmental policy instruments applied (as % of the total funding) for wind power development in Denmark, Germany and Spain. It is important to note, that the curves do not indicate the real figures for funding but only the percentage of the total. For this reason, initial finding may very well be much smaller than later funding. The figures have been extrapolated in the direction we consider probable and private RD&D has been introduced.
8.3 Disaggregating the experience curve

The experience curves used in this study describe how the cost per unit is reduced as a function of experience by designing, producing and using the products. However, experience curves give an aggregated picture of the total cost, including labour, capital, administrative, research and marketing costs, etc. and the cost reduction described is related to production changes, product changes, and changes in input prices. Furthermore, it is important to point out that experience per se does not lead to cost reductions, but rather provides opportunities for cost reductions.

To understand the causes of cost reduction underlying the experience curve requires an understanding of the innovation system in question (Chapter 3). If we, furthermore, want to quantify each source of cost reduction additional detailed data are required. Such an analysis could involve the investigation of cost reduction due to product development, process development, fall in input prices, etc. In this study we have considered such different sources of cost reduction. However, it was difficult to find relevant data. The data required are usually not provided by manufacturers, operators etc. as they are perceived as vital for the company’s future competitiveness.

We have analysed some sources of reduction in cost of wind power technology, such as those due to scaling-up of wind turbines provided by list prices, and those due to innovations. No data were available with which to study reduction in cost of individual components, that due to process development, or that due to changes in input prices, despite the fact that the partners in the project have very good contact with the wind power industry.

In all, an experience curve constitutes an aggregated tool describing cost reduction. Using experience curves as a tool for the analysis of cost reduction for new technologies, and for the assessment of policy measures intended to bring about such cost reductions, will require additional analysis of different sources of cost reduction. Experience curves represent the aggregated result of a number of sources of cost reduction. However, sometimes aggregated data may be the best available.

8.4 The learning process; an international, national or regional process

As discussed in Chapter 6, experience curves may be the result of a national or an international learning system. We will elaborate further on this topic and analyse the differences in the experience curves developed for different countries. For the countries we have studied, we suggest the existence of an international learning system rather
than a national one for wind power. The experience curves indicate that an international learning system for wind turbines has been established and is still progressing. The almost identical progress ratio for ex works costs of wind turbines in Denmark (92%) and Germany (94%) provide evidence of this. Furthermore, the average list prices for wind turbines in Denmark and Germany have converged during the past 20 years. Also, the average cost of wind turbine projects in Denmark, Spain and Sweden seem to be converging. This also indicates that an international learning system for wind turbine technology has emerged. The existence of an international learning system is supported by other empirical observations (see Chapter 6).

8.5 The analysis of cost efficiency using experience curves

Experience curves have come to be used to calculate the cost efficiency of policy measures, as described in Chapter 7. The experience curve is then used to calculate learning investments, i.e. investments in wind turbines or wind energy, needed to ride down the experience curve. These investments are then compared with government investments, such as investment subsidies or price subsidies, applied to initiate market development.

The results of this study indicate that calculations of cost efficiency are very sensitive to the data available and the experience curve used. Although we have access to very good data in this project they are not sufficiently good for cost efficiency calculations. Moreover, the results indicate that cost efficiency calculations should be based on a system-wide approach using the experience curve for wind-generated electricity and total subsidy investments. However, such learning curves could not be developed for wind power. Moreover, the subsidy investments used can be characterised as a complex combination, and the evaluation of individual measures will be difficult. To this we can add the difficulties arising from the existence of international learning systems. In all, we are of the opinion that experience curves not are appropriate for cost efficiency evaluations of wind power policy measures.

8.6 Assessment of policy measures for wind power vs. those for other renewable energy sources

In this study the analysis of assessment was based on wind power. This energy system is, in many ways, well suited for analysis using experience curves. Wind power is, to large extent, technology based, the technology concept is well defined, the development of innovations has been incremental, the technology is easily integrated into the energy supply system, etc. Other energy systems are less technology based and will, to a larger
extent, include additional components such as fuel cycles etc., and include complex connections between technologies and to infrastructure. For the analysis of other energy systems experience curves may therefore be less relevant. In addition, wind power is a developed technology to which policy measures have been applied for some time. The analysis and assessment of policy measures thus make sense. For other technologies with less experience of production and use and little experience of policy measures are experience curves less relevant, especially for policy analysis and assessment. The construction of experience curves requires long-term experience. Gaining experience is a long-term process which represents the combined effect of a large number of parameters, which may undergo fluctuations over short periods. Only after many doublings of experience can the underlying pattern or trend be distinguished.

Using experience curves for the analysis and assessment of wind power policy programmes make sense, as described above. The use of experience curves for the analysis and assessment of other energy policy measures depends on the technology of the systems involved, the developmental stage of the technology, the innovation system in question, etc.

8.7 Experience curves as a tool for strategic decisions

Experience curves can be used either for historical evaluations (“ex post”) of energy policy measures or as decision support for new energy RD&D programmes. Experience curves for ex-post evaluations were presented in Sections 8.1-8.6, and although we conclude that the method has some limitations it could provide a complement to other assessment tools (see also Chapter 1).

The use of experience curves for strategic decision support is based on extrapolation. Even for very new, emerging technologies, where only limited data are available, we can develop a “draft” experience curve which could be extrapolated. We then base the experience curve on a few data points and the progress ratio from an experience curve for another relevant technology with similar characteristics. The extrapolation of the experience curve will indicate the size of investments required to achieve competitiveness of the product. Too high investments may indicate the need for supplementary RD&D programmes to cut the initial cost of the product. Thus, experience curves may prove helpful in discussion on strategic decisions and the relevance of RD&D measures in influencing radical innovations versus market-based policy measures.

However, the use of experience curves for prognosis may be questioned. Experience curves provide a tool for trend analysis and they, together with, similar trend analysis
tools, are suitable under conditions of low uncertainty, for series of incremental innovations, short time ranges and/or a high level of aggregation. Such tools cannot be used under circumstances characterised by high uncertainty, shifts in technology or market situation and long time ranges. In such cases, judgmental methodologies such as interviewing experts, expert panels, Delphi-surveys, development of scenarios, etc should be used.

On the other hand, one could argue that the logic of the experience curve is central to the foresight dialogue, i.e. the idea that the society will have to invest in a particular technology in order to overcome initial cost barriers and to bring costs down. We are of the opinion that the empirically based experience curves could be used in a qualitative way to confirm the need of initial investments by society. The analysis of extrapolation of experience curves must be considered very vague, but technology foresight is a fairly intuitive art. For the best result we recommend the combination of experience curve with other methodologies.

8.8 Conclusions

Based on the synthesis of this report we here present our conclusions regarding the advantages and disadvantages, the potential and limitations of experience curves as a tool for energy policy assessment. We will describe the potential of the use of an extended experience curve methodology as a generic tool for the assessment of energy policy, specifically programmes for the introduction and commercialisation of renewable energy sources.

8.8.1 Advantages and potential of experience curves as a tool for the assessment of energy policy

I. Experience curves describe how cost decline with cumulative production and use; the curve emphasises the need of experience to realise cost reductions. It clearly illustrates that RD&D programmes cannot stand alone. Such technology push measures need to be combined with market pull measures or other strategies to create commercialisation of the technology and allow that industry to gain experience from production and use of the product. The experience of the industry and other actors provides important input in the prioritisation of government RD&D programmes. (However, it must be pointed out that governments often have legitimate interests different from and more long-term than those of industry.)
II. Experience curves can be used as an aid in strategic decisions. Strategies and policy measures of relevance for new emerging energy technologies can be discussed based on an experience curve. “Draft experience curves” can be developed and compared for different types of technologies in their early stage of development and commercialisation. These curves could support the discussion of strategies and the relevance of RD&D measures to effect radical innovations versus market-based policy measures.

III. Experience curves can be used to analyse the effect of combined policy measures in terms of installed units and cost reductions. Using wind power as a model, we found that experience curves do not indicate the effect of an individual measure, but describe the aggregated cost reduction resulting from the combination of measures used. The results of this project show how the combination of measures in Denmark, Germany and Spain resulted in a huge number of wind turbines being produced and installed, and a related trend in the reduction in cost of wind turbines, specific and levelised production cost of electricity. We observed that the larger the systems included the experience curve, the greater the cost reductions.

IV. Experience curves can be used to investigate the existence of national and international learning systems. In the study of wind power we found almost identical progress ratios for wind turbines produced in Denmark and Germany. Furthermore, the average list prices for wind turbines in Denmark and Germany have converged during the last two decades. Also, the average cost of wind turbine projects in Denmark, Spain and Sweden seem to be converging.

V. Experience curves can assist several actors, such as financial analysts, industry, researchers and policy makers, in analysing and assessing strategies and policy measures.

8.8.2 Disadvantages and limitations of experience curves as a tool for the assessment of energy policy

VI. The success of this study was dependent upon being able to develop relevant experience curves based on good data. With this in mind the authors behind this study were often surprised by the uncertainty in the data in resent experience curve literature. Constructing reliable experience curves required a high degree of “data discipline”. Experience curves cannot be better than the raw data from which they are constructed. Only experience curve studies that provide evidence
of their validity, reliability and relevance should be taken into account in policy making.

VII. Constructing reliable experience curves requires a basic understanding of the technology in question. Misinterpretation is possible when analysing time tracks of data. Policy makers interested in the use of experience curves should consult specialists from science or industry before drawing any conclusions from experience curve analysis.

VIII. Experience curves constitute an aggregated tool that must be combined with other methods of analysis of sources of cost reduction. An important lesson learnt from this project is, that even with the vast amount of data made available for this project, we were only able to draw conclusions on an aggregated level. For a more detailed analysis, detailed technological, economical and market data are required. However, these are in the possession of private companies and are not made available for reasons of competition. A full analysis in the case of wind power would include data from wind turbines equivalent to over 20,000 MW of power installed throughout the world.

IX. Experience curves do not show the effects of individual policy measures, but rather the combined effect of several measures. The analysis of individual measures requires additional tools for analysis. For this reason, experience curves can not be used to decide in what proportion of funding should be given to different types of measures.

X. Experience curves can not be used to analyse the cost efficiency of policy measures unless the experience curves are relevant. This situation is complicated by the fact that experience curves cannot differentiate between individual measures and difficulties arising due to the existence of international learning systems. In all, we believe that experience curves are not appropriate for cost efficiency evaluations of wind power policy measures.

The limitations on the use of the experience curves arise from data availability and we maintain that only studies that provide validity, reliability and relevance should be taken into account in policy making. Due to their limitations complementary methods should also be considered.

Experience curves should be considered as a generic tool for energy technology analysis. In the case of wind power, the use of experience curve is highly relevant. However, for some energy technology systems, which include complex combinations of technologies and connections to infrastructure, experience curves will be less relevant.
Moreover, the analysis and assessment of policy measures require that policy measures have been applied for a considerable time.
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Appendix 1: Experience curves for wind power

Selected experience curves developed within the project

A. Production perspective

<table>
<thead>
<tr>
<th>Category</th>
<th>Experience curves for wind turbines (WT) produced by different manufacturers</th>
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<tbody>
<tr>
<td></td>
<td>Country</td>
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<td>Denmark</td>
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<tr>
<td></td>
<td>Germany</td>
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</tr>
</tbody>
</table>
## A. Production perspective

### Category II
**Experience curves for the specific production cost of electricity in each country***

<table>
<thead>
<tr>
<th>Country</th>
<th>Company</th>
<th>Number of units</th>
<th>Years</th>
<th>Sizes (kW)</th>
<th>Progress ratio (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>All**</td>
<td>n.a.</td>
<td>1981-2000</td>
<td>Selected*</td>
<td>86</td>
<td>0.97</td>
</tr>
<tr>
<td>Denmark</td>
<td>All**</td>
<td>n.a.</td>
<td>1981-2000</td>
<td>Selected*, ≥55</td>
<td>87</td>
<td>0.97</td>
</tr>
<tr>
<td>Germany</td>
<td>Selected</td>
<td>2963</td>
<td>1991-2000</td>
<td>≥30</td>
<td>88</td>
<td>0.87</td>
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</tbody>
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### Category III
**Experience curve for the levelised production cost of electricity in each country****

<table>
<thead>
<tr>
<th>Country</th>
<th>Company</th>
<th>Number of units</th>
<th>Years</th>
<th>Sizes (kW)</th>
<th>Progress ratio (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>-</td>
<td>n.a.</td>
<td>1981-2000</td>
<td>Selected*</td>
<td>83</td>
<td>0.97</td>
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</tbody>
</table>

## B. Market perspective

### Category IV
**Experience curves for wind turbines installed in each country (turbine cost only)**

<table>
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<tr>
<th>Country</th>
<th>Number of units</th>
<th>Years</th>
<th>Sizes (kW)</th>
<th>Progress ratio (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>3570</td>
<td>1981-2000</td>
<td>Selected*</td>
<td>91</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>3225</td>
<td>1981-2000</td>
<td>Selected*, ≥55</td>
<td>91</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>2621</td>
<td>1990-2000</td>
<td>Selected*, ≥55</td>
<td>88</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>1872</td>
<td>1995-2000</td>
<td>Selected*, ≥55</td>
<td>95</td>
<td>0.74</td>
</tr>
<tr>
<td>Germany</td>
<td>9228</td>
<td>1987-2000</td>
<td>All</td>
<td>94</td>
<td>0.88</td>
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<tr>
<td></td>
<td>8966</td>
<td>1987-2000</td>
<td>≥55kW</td>
<td>96</td>
<td>0.80</td>
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<tr>
<td></td>
<td>8862</td>
<td>1990-2000</td>
<td>≥55kW</td>
<td>94</td>
<td>0.82</td>
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<tr>
<td></td>
<td>6788</td>
<td>1995-2000</td>
<td>≥55kW</td>
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<td>0.05</td>
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### Category V
**Experience curves for wind turbines installed in each country (total cost of installation)**

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<th>Country</th>
<th>Number of units</th>
<th>Years</th>
<th>Sizes (kW)</th>
<th>Progress ratio (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>3570</td>
<td>1981-2000</td>
<td>Selected*</td>
<td>90</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>3225</td>
<td>1981-2000</td>
<td>Selected*, ≥55</td>
<td>90</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>2621</td>
<td>1990-2000</td>
<td>Selected*, ≥55</td>
<td>85</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>1872</td>
<td>1995-2000</td>
<td>Selected*, ≥55</td>
<td>94</td>
<td>0.86</td>
</tr>
<tr>
<td>Spain</td>
<td>4050</td>
<td>1984-2000</td>
<td>All</td>
<td>91</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>4022</td>
<td>1984-2000</td>
<td>≥55kW</td>
<td>93</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>4010</td>
<td>1990-2000</td>
<td>≥55kW</td>
<td>92</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>3558</td>
<td>1995-2000</td>
<td>≥55kW</td>
<td>93</td>
<td>0.92</td>
</tr>
<tr>
<td>Sweden</td>
<td>413</td>
<td>1994-2000</td>
<td>All</td>
<td>96</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>413</td>
<td>1994-2000</td>
<td>≥55kW</td>
<td>96</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>394</td>
<td>1995-2000</td>
<td>≥55kW</td>
<td>88</td>
<td>0.54</td>
</tr>
<tr>
<td>Category VI</td>
<td>Experience curves for cost of wind-generated electricity in each country</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>- 1991-2000 All 98 0.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>- 1983-2000 All 98 0.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Comments:**

* The experience curves are based on data for selected turbines for which data could be verified. In total more than 27000 wind turbines (or 9810 MW) have been produced by Danish manufacturers in the period 1976 to 2000, of which 6427 (or 2221 MW) were installed in Denmark. Almost 60 makes and manufacturers have manufactured 289 types and variations of turbines alone for the Danish market. It is without the frame and scope of this project to include technical and cost data for all variations in the analyses. Therefore, we have excluded data from 1) machines from smaller manufacturers, 2), machines only sold in small numbers and 3) machines with unavailable or uncertain sets of data. The turbines included cover the most common types of turbines (21 different types) that amounts to 3570 turbines and approximately 56 % of the turbines installed in Denmark. Expressed in terms of manufacturer the study cover 81% of all turbines installed in Denmark. The final data are representative of the wind turbines produced and/or installed in Denmark.

**Cumulative production (sales world wide) is based on total sales from members of the Danish Wind Turbine Manufacturers Association. As only installed capacity in MW can be determined from the reports we have assumed that the average size of all turbines from these manufacturers corresponds to the average size of turbines installed in Denmark. From this the Danish wind turbine manufacturer’s accumulated number of installed turbines can be determined. The final data are representative of the wind turbines produced and/or installed in Denmark.

*** The specific production cost of electricity was calculated by dividing the average wind turbine list price by the number of full load hours. The number of full load hours is, in turn, determined by dividing the average production in roughness class 1 by the average turbine size.

****The levelised production cost of electricity (see Trade and Hunter (1994)) is based on the specific production cost of electricity for wind turbine produced in Denmark (at roughness class 1), the cost reduction in the installation of wind turbines in Denmark, a lifetime of 20 years, an interest rate of 6%, and a model for reduction of O&M costs based on surveys of actual O&M costs (see Redlinger, et al., 2002). Total investment cost is determined as Ex Works costs plus Other Costs. Estimation of “other costs” is based on comprehensive questionnaire surveys carried out in other projects (Redlinger, et al., 2002, p76)
Appendix 2: Data for the experience curves presented in Chapter 2

Category I: Experience curves for wind turbines produced by Danish and German manufacturers

Figure 2.4. Experience curve for wind turbines produced by Danish manufacturers: 1981-2000 (PR=92%, $r^2=0.84$).

<table>
<thead>
<tr>
<th>Year</th>
<th>x-axis (MW)</th>
<th>x-axis (DKK/kW)</th>
<th>y-axis (€/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>10</td>
<td>10909</td>
<td>1464</td>
</tr>
<tr>
<td>1982</td>
<td>15</td>
<td>11075</td>
<td>1487</td>
</tr>
<tr>
<td>1983</td>
<td>40</td>
<td>11451</td>
<td>1537</td>
</tr>
<tr>
<td>1984</td>
<td>156</td>
<td>10811</td>
<td>1451</td>
</tr>
<tr>
<td>1985</td>
<td>399</td>
<td>10199</td>
<td>1369</td>
</tr>
<tr>
<td>1986</td>
<td>611</td>
<td>9576</td>
<td>1285</td>
</tr>
<tr>
<td>1987</td>
<td>699</td>
<td>8485</td>
<td>1139</td>
</tr>
<tr>
<td>1988</td>
<td>801</td>
<td>7722</td>
<td>1037</td>
</tr>
<tr>
<td>1989</td>
<td>937</td>
<td>7614</td>
<td>1022</td>
</tr>
<tr>
<td>1990</td>
<td>1099</td>
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<td>1064</td>
</tr>
<tr>
<td>1991</td>
<td>1265</td>
<td>8152</td>
<td>1094</td>
</tr>
<tr>
<td>1992</td>
<td>1431</td>
<td>7456</td>
<td>1001</td>
</tr>
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<td>1993</td>
<td>1641</td>
<td>7033</td>
<td>944</td>
</tr>
<tr>
<td>1994</td>
<td>2027</td>
<td>6644</td>
<td>892</td>
</tr>
<tr>
<td>1995</td>
<td>2601</td>
<td>6100</td>
<td>819</td>
</tr>
<tr>
<td>1996</td>
<td>3327</td>
<td>5946</td>
<td>798</td>
</tr>
<tr>
<td>1997</td>
<td>4295</td>
<td>6041</td>
<td>811</td>
</tr>
<tr>
<td>1998</td>
<td>5511</td>
<td>5958</td>
<td>800</td>
</tr>
<tr>
<td>1999</td>
<td>7710</td>
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<td>765</td>
</tr>
<tr>
<td>2000</td>
<td>9810</td>
<td>5563</td>
<td>747</td>
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</table>

Figure 2.5. Experience curve for wind turbines produced by German manufacturers: 1987-2000 (PR=94%, $r^2=0.74$).

<table>
<thead>
<tr>
<th>Year</th>
<th>x-axis (MW)</th>
<th>x-axis (DEM/kWh)</th>
<th>y-axis (€/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>1.25</td>
<td>3142</td>
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<td>1988</td>
<td>4.4</td>
<td>2549</td>
<td>1301</td>
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<td>1989</td>
<td>10.7</td>
<td>2888</td>
<td>1473</td>
</tr>
<tr>
<td>1990</td>
<td>32.7</td>
<td>2542</td>
<td>1297</td>
</tr>
<tr>
<td>1991</td>
<td>52.9</td>
<td>2854</td>
<td>1456</td>
</tr>
<tr>
<td>1992</td>
<td>82</td>
<td>2949</td>
<td>1505</td>
</tr>
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<td>1993</td>
<td>126.9</td>
<td>2500</td>
<td>1276</td>
</tr>
<tr>
<td>1994</td>
<td>277.9</td>
<td>2102</td>
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<td>577</td>
<td>1987</td>
<td>1014</td>
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<td>1996</td>
<td>849</td>
<td>1752</td>
<td>894</td>
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<td>1997</td>
<td>1132.6</td>
<td>1835</td>
<td>936</td>
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<td>1925</td>
<td>982</td>
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<tr>
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<td>2388.9</td>
<td>1958</td>
<td>999</td>
</tr>
<tr>
<td>2000</td>
<td>3324.2</td>
<td>1996</td>
<td>1018</td>
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</table>
Category II: Experience curves for the specific production cost of electricity by wind turbines produced by Danish and German manufacturers

Figure 2.6 Experience curve for specific production cost of electricity from wind turbines produced by Danish manufacturers 1981-2000 (PR=86%, $r^2 = 0.97$).

<table>
<thead>
<tr>
<th>Year</th>
<th>x-axis (MW)</th>
<th>y-axis (DKK/kWh)</th>
<th>y-axis (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>10</td>
<td>6.3</td>
<td>0.85</td>
</tr>
<tr>
<td>1982</td>
<td>15</td>
<td>5.9</td>
<td>0.79</td>
</tr>
<tr>
<td>1983</td>
<td>40</td>
<td>6.3</td>
<td>0.84</td>
</tr>
<tr>
<td>1984</td>
<td>156</td>
<td>6.3</td>
<td>0.85</td>
</tr>
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<td>1985</td>
<td>399</td>
<td>5.2</td>
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<td>3.4</td>
<td>0.45</td>
</tr>
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<td>937</td>
<td>3.3</td>
<td>0.45</td>
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<td>3.3</td>
<td>0.45</td>
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<td>0.45</td>
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<td>0.41</td>
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<td>3.1</td>
<td>0.41</td>
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<td>2.5</td>
<td>0.33</td>
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<td>1998</td>
<td>5511</td>
<td>2.3</td>
<td>0.31</td>
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<tr>
<td>1999</td>
<td>7710</td>
<td>2.3</td>
<td>0.30</td>
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<td>2000</td>
<td>9810</td>
<td>2.2</td>
<td>0.29</td>
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</table>

Figure 2.7 Experience curve for specific production cost of electricity from wind turbines produced by German manufacturers 1991-2000 (PR=88%, $r^2 = 0.87$).

<table>
<thead>
<tr>
<th>Year</th>
<th>x-axis (MW)</th>
<th>y-axis (DEM/kWh)</th>
<th>y-axis (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>102.6</td>
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<td>1.59</td>
<td>0.81</td>
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<tr>
<td>1993</td>
<td>315.8</td>
<td>1.32</td>
<td>0.67</td>
</tr>
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<td>1994</td>
<td>610.1</td>
<td>1.18</td>
<td>0.60</td>
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<td>1127.7</td>
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<td>0.55</td>
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</tr>
<tr>
<td>2000</td>
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<td>0.44</td>
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</table>
Category III: Experience curves for the levelised production cost of electricity by wind turbines produced by Danish and German manufacturers

Figure 2.8 Experience curve for levelised production cost for wind turbines made by Danish manufacturers, 1981-2000 (PR=83%, $r^2 = 0.97$).

<table>
<thead>
<tr>
<th>Year</th>
<th>x-axis (MW)</th>
<th>x-axis (DKK/kWh)</th>
<th>y-axis (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>10</td>
<td>1.00</td>
<td>0.13</td>
</tr>
<tr>
<td>1982</td>
<td>15</td>
<td>0.94</td>
<td>0.13</td>
</tr>
<tr>
<td>1983</td>
<td>19</td>
<td>0.99</td>
<td>0.13</td>
</tr>
<tr>
<td>1984</td>
<td>26</td>
<td>0.99</td>
<td>0.13</td>
</tr>
<tr>
<td>1985</td>
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<td>1986</td>
<td>80</td>
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</tr>
<tr>
<td>1987</td>
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<td>1989</td>
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<td>0.07</td>
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<td>1994</td>
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<td>1995</td>
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<td>1997</td>
<td>1155</td>
<td>0.32</td>
<td>0.04</td>
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<tr>
<td>1998</td>
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<td>0.04</td>
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Category IV: Experience curves for wind turbines installed in Denmark and Germany (turbine cost only)

Figure 2.9 Experience curve for wind turbines installed in Denmark, 1987-2000 (PR=91%; $r^2=0.94$).

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Figure 2.10 Experience curve for wind turbines installed in Germany, 1987-2000 (PR=94%; $r^2=0.88$).

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Category IV: Experience curves for wind turbines installed in Denmark and Germany (total installation cost)

Figure 2.11 Experience curve for the total installation cost for wind turbines installed in Denmark, 1981-2000 (PR=90%, $r^2=0.92$).

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Figure 2.12 Experience curve for the total installation cost for wind turbines installed in Spain, 1984-2000 (PR=91%, $R^2=0.85$)

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Figure 2.13 Experience curve for total installation cost for wind turbines installed in Sweden, 1994-2000 (PR=96%, $r^2=0.32$).

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Appendix 3: Experience curve – the Netherlands and the UK

Experience curves for wind power in the Netherlands

The search for good data for the development of experience curves for the Netherlands resulted without success. The best available data was from the IEA report “R&D Wind Annual Report 1999” (IEA, 1999) which present data for wind turbines installed in the Netherlands. However, the data could not be verified, the source of data is unknown, it is unclear whether the data includes turbine cost only or total cost of installed, it is unclear how the annual prices per kW has been calculated etc. Moreover, it is not clear if the prices have been corrected by inflation or not. In all, the data is uncertain and not appropriate for the development of experience curves. If using this uncertain data for the development of an experience curve anyway, assuming that the data published are not corrected for inflation (nominal data), and using a deflator for recalculating the data, the progress ratio of this experience curve will be 94% ($r^2=0.40$). This result, however, is in the same range as presented in the report for experience curves for wind turbines in other European countries. However, if the data published are already corrected for inflation – this would result in an experience curve with a progress ratio of only 99%.

Experience curve for total installation prize of wind turbines installed in the Netherlands year 1989 – 1999; $PR=94\%, R^2=0.40$
Experience curves for wind power in the UK

As for the Netherlands, the search for qualified data for the development of experience curves for wind power for the UK resulted without success. Moreover, best available data for wind power in the UK is also from the IEA report “R&D Wind Annual Report 1999” (IEA, 1999). This data for the UK could not be verified or described in more detail. The data represent wind energy schemes awarded UK Renewable orders, i.e. average price per kWh for contracted capacity by NFFO, SRO and NI-NFFO. However, we do not know the actual average price of the realised plants.

If plotting the operating capacity (contracted by NFFO, SRO and NI-NFFO) against average price per kWh, for contracts from 1990 to 1999, as an experience curve, assuming the data are nominal prices, the progress ratio of this curve will be 74%, see figure below. However, the price data in the IEA report gives the average prices for the contracts and not for the project realised. Moreover, much of the price reduction between 1991 and 1994 can be attributed to the change of regulatory design (e.g. longer remuneration terms, change from strike to bid price, longer allowance for commissioning) (Langniss 2003). Therefore, it could be of interest to develop an experience curve excluding the first two schemes from 1990. However, this experience curve will result in a progress ratio of 99%. Moreover, it is questionable to use average price of kWh as a benchmark for installed capacity, see Chapter 2. In all, the development of experience curves for the UK will require additional data. For more information on price development of English wind power, see (Langniss 2003).

Experience curve for cost of electricity in the UK year 1990 – 1999

Note: An experience curves for wind power in the UK has also been published by Ibenholt (2002). However, we have not been able to reconstruct this experience curve.
## Appendix 4. Roadmap of German wind energy RD&D, policy and other measures

Abbreviations: st: stall turbine; pt: pitch turbine; const: constant rotor speed; var: variable rotor speed; ng: gearless turbine; g: turbine with gear

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