Experience curves in the wind energy sector

Use, Analysis and Recommendations

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Preface

This paper was written within the frame of a two-month project, which is part of the final year of the Masters of Science course at the Department of Science, Technology and Society. The primary objective was to compare and analyze the use of experience curves in the wind energy sector on the basis of literature study. Due to time constraints, the author specifically did not analyze the use of experience curve for other (energy) sectors, e.g. for PV-cells or fuel cells.

During the analysis of the literature, a number of discrepancies and problems related to the use of experience curves were observed. Some of these issues were not described in the reviewed literature. On basis of these issues, a number of recommendations are given on how to construct an experience curve and how it may be used in order to forecast the development of the wind energy sector.
It is stressed that further research is needed to strengthen these recommendations. Comments and suggestions are encouraged.

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Executive summary

Background and objective

The wind energy sector is one of the fastest-growing energy sectors in the world. Both prices of wind turbines and cost of wind-generated electricity have dropped significantly over the last twenty years. However, electricity from wind is not yet fully able to compete with fossil fuel based electricity. In order to be able to forecast the development of the cost of both the cost of wind turbines and the cost of electricity, use is made of so-called experience curves. Basically this concept analyses how much costs have dropped with every doubling of the cumulative production. On the basis of recorded data on cumulative production of a certain product and accompanying g drop in costs per product, a historic experience curve can be constructed. Historic experience curves are used in literature for a number of models and scenarios to predict the future development of wind power (e.g. [EWEA, 1999a], [Ybema et al., 1999], [Neij 1999]). The outcome of these models and scenarios are strongly influenced by the so-called progress ratio, which determines the drop in cost with every doubling of cumulative production. Also, experience curves are often based on highly aggregated data, and may include large uncertainties. In addition, data may be difficult to obtain in many countries. Therefore experience curves are often based on the data from a single country. Also it is questionable to what extent learning curves derived from data in one country can be used for a global model. In summary, it is unclear what the possible uncertainties are, and thus how accurate current predictions based on experience curves are.
The objective of this paper is first to analyze and discuss how experience curves are currently used in studies on wind energy. Based on this overview it is formulated what lessons can be learned to use experience curves for future predictions.

The experience curve theory

An experience curve can be expressed as:

$$C(Cum) = a * Cum^{b} \qquad (1)$$
$$\log (C(Cum)) = \log a + b \log Cum \qquad (2)$$
$$PR = 2^{b} \qquad (3)$$

C	Cost per unit	a	learning cost at Cum=1
Cum	Cumulative (unit) production	b	learning index (constant)
PR	Progress ratio		

The progress ratio is a parameter that expresses the rate at which costs decline each time the cumulative production doubles. For example, a progress ratio of 0.8 (= 80%) equals a 20% cost decrease for each doubling of the cumulative capacity.
Every experience curve can be placed within a ‘learning system’ in which inputs and outputs influencing the experience curves are described.

Current use of experience curves in the wind energy sector

In literature, a number of studies were found describing the historic development of the costs of wind turbines and wind-generated electricity. Several types of experience curves are used in literature. A number is assigned to each type found in literature:

I The costs per kW vs. the cumulative number of kW installed/produced
II The costs per kWh vs. the cumulative number of kWh produced
III The costs per kWh vs. the cumulative number of kW installed/produced
IV The costs per kWh vs. the cumulative number of wind turbine units installed/produced

When comparing the studies, a number of differences are noted. The majority of the studies use the type-I experience curves. The variation in progress ratios is considerable, varying from 85-92%. Four other experience curves were found which analyze the costs per kWh. Also it is noted that a number of studies were performed for the Danish market, while less studies are available for other countries with an own wind turbine manufacturing industry (e.g. the US or Germany). Also, it is remarkable that all studies in Denmark describe the number of turbines produced or sold, while studies for the US or Germany describe wind turbines installed.

In addition, a number of forecasting studies based on experience curve were analyzed. Almost all studies forecasted the global development of wind energy. Studies cannot simply be compared with each other, as some use current annual growth trends of installed wind turbine capacity for their forecast, while other studies use normative objectives, e.g. that 10% of the worlds electricity demand is satisfied by wind energy. Yet it is interesting to compare the minimum and maximum values that different authors find under these different circumstances, as shown in Table 1:

Table 1 Comparison of different forecasts for the global development of the wind energy sector

	Min	Max
Progress ratio (for type I experience curves) (%)	84	97
Cumulative global capacity (GW) in 2020	110	1209
Cumulative doublings until 2020	3.8	8.2
Investment costs in 2020 (US$ / MW, 1997)	380	795
kWh costs in 2020 (US$¢ / kWh, 1997)	2.4	3.7

As can be seen from Table 1, both assumptions on progress ratios and the maximum global capacity vary strongly, causing the predictions for investment costs and cost of electricity to diverge considerably.

Discussion, conclusion and recommendations

While comparing studies in literature, a number of different approaches and shortcomings were found and are discussed in chapter 4. For example, in many studies it is unclear what exactly is plotted in an experience curve, e.g. how exactly the costs per unit were determined. Also data quality and the degree of correlation in an experience curves are often neglected. Also, advantages and disadvantages of using experience curves of types I, II and III are discussed. For type II, obtaining accurate data may be difficult. While type III may not be sound in regard to the experience curve theory, it may yet be useful to forecast future decline in electricity costs.
Analyzing the speed of technology development may also be limited due to country-based differences. In a country which imports a large proportion of its wind turbines, the observed progress ratios may not be representative for the actual learning rate. Preferably, experience curves should based on the amount manufactured or sold by the wind turbine industry. Furthermore, strong market distortions may severely influence the obtained progress ratio, as is shown for the 'Californian wind rush'. Depending on whether or not data from 1982-1985

is included in an experience curve, the resulting progress ratio may vary between 82.2% and 89.7%. Preferably data from a time period with serious market distortions should not be used for an experience curve.
Another issue is a forecast for a single region. As wind energy has become a global market, the total global amount of capacity that will be installed is relevant for determining the decline in wind power costs. There is little point in only considering the added capacity within a small region for forecasting cost reductions.

Finally using existing historical experience curves based on onshore wind turbines for offshore wind turbines is only possible within limits. The costs of offshore installation of wind turbines only depend for approximately 25% on the actual turbine cost. Additional experience curves analyzing e.g. the cost reductions for offshore foundations may be helpful to forecast the future developments of offshore wind energy.

From the discussion it is concluded that in order to forecast the global development of wind energy, preferably a global experience curve should be devised. By obtaining data from the major wind turbine manufacturers, about 84% of the world’s production can be assessed.

Furthermore, a set of five steps are formulated on how to set up a (global) forecast, and how to assess the uncertainty involved in such a forecast. These steps basically consist of analyzing the quality of the available data, analyzing the correlation of the obtained experience curve, making estimates for future growth of production, checking whether the chosen time frame can be analyzed with the available historical data, and finally devising a worst-case and best-case scenario. By doing so, the extent of uncertainties involved in such a forecast should be clarified.

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Chapter 1 Introduction

The amount of global wind power has increased rapidly over the last few years. At the end of 1999 the total installed capacity was approximately 13.4 GW, a rise of 36% compared to 1998. This is the largest worldwide addition to capacity in a single year [AWEA, 2000a]. These figures represent a large growth, but compared to the worldwide total electricity-generating capacity, the wind fraction is still very small (0.11% in 1997, [BTM 1998]).
There have been several trends during the last two decades that influenced this growth. The average rated capacity of new wind turbines has steadily increased in time from 30-50 kW in 1980, to 500-750 in kW in 1997. Today, the largest commercial available wind turbines have a rated capacity in the range between 1-1.5 MW for onshore turbines [Neij, 1999]. For future offshore-markets, manufacturers even prepare to develop wind turbines in the size of 1.5-2.5 MW [BTM, 1999]. Furthermore, better siting, improved reliability (lower O&M costs) and efficiency have increased the capacity factor of wind turbines significantly.
With this increasing experience in manufacturing, increasing production volumes, upscaling of wind turbine units and continuing R&D spending, prices per kWh have strongly dropped. For example, in Denmark prices dropped from 16.9 US$¢/kWh 1981 to 6.15 US$¢/kWh in 1995[1] [Madsen, 1999], and lie today within the 5,0-6,0 US$¢/kWh range. Similar, prices per kW have dropped in Denmark from 1770 US$/kW in 1982 to 850 US$/kW in 1997[2] [Neij, 1999]. Wind turbines placed at top sites are now competitive with traditional energy sectors such as nuclear or coal.

However, in the same time period, costs for electricity from nuclear or coal and gas-fired power plants have also dropped. For example, between 1991 en 1999 the installed costs of combined cycle gas turbines have dropped about a third and the price of coal delivered to American utilities fell by 40% from 1986-1996. In addition, the US Department of Energy reckons the cost of coal may fall another 24% until 2020 [Milborrow, 1999]. To assess the economic potential of wind energy, insight is needed on the future wind-generated electricity price. It is therefore of great interest for policy makers, wind turbine producers and owners and the electricity consumer just how much the cost of electricity can be expected to drop in the near-term and long-term future (given a certain increase in cumulative production) and to assess when wind power will be fully able to compete with fossil fuels.

In order to do so, trends from the past may be used to make predictions for the future. A widely used method is the experience-curve concept: basically this concept analyses how much costs have dropped with every doubling of the cumulative production. On the basis of recorded data on cumulative production of a certain product and concurring drop in costs per product, a historic experience curve can be constructed. Historic experience curves are used in literature for a number of models and scenarios to predict the future development of wind power (e.g. [EWEA, 1999a], [Ybema et al., 1999], [Neij 1999]). However, the outcome of these models and scenarios are strongly influenced by the chosen experience curve and especially by the so-called progress ratio, which determines the drop in cost with every doubling of cumulative production. Therefore it is important to choose a representative experience curve. Experience curves are often based on data, which may be highly aggregated, may include large uncertainties and may be difficult to obtain in many countries. Therefore experience curves are often based on the data from a single country. It is however questionable to what extent learning curves derived from data in one country can be used for a

[1] All costs converted to 1995 levels
[2] All costs converted to 1997 levels

global model, or if new developments in the wind industry (e.g. the increasing proportion of off-shore wind farms) have a significant impact on future developments which potentially cannot be predicted by using experience curves. In summary, it is unclear what the possible uncertainties are, and thus how strong and accurate current predictions based on experience curves are.

The objective of this paper is first to analyze and discuss how experience curves are currently used in studies on wind energy. Based on this overview it is formulated what lessons can be learned to use experience curves for future predictions.

In chapter 2 of this paper, the basic theory of experience curves and general limitations to the theory will be explained in detail. In chapter 3 an overview will be given of studies describing historic wind experience curves, studies describing scenarios which solely aim to forecast the development of wind energy, and models which include wind energy to forecast general development in the energy sector. On the basis on these studies, in chapter 4 a number of factors will be discussed which are important when constructing a historic experience curve. Also several issues will be discussed which limit the accuracy of future predictions. In addition, the issue whether offshore developments can or cannot be predicted using existing experience curves, will briefly be addressed. In chapter 5, recommendations for constructing and using experience curves for the wind energy sector are given. In addition, further conclusions and recommendations in regard to further research are given.

Chapter 2 The experience curve concept

2.1 Introduction

The performance and productivity of technologies typically increase substantially as individuals, enterprises and industries gain experience with them. The very first learning curve was described by Wright in 1936 who reported that unit labor costs in airframe manufacturing declined significantly with accumulated experience of the workers. This phenomenon is also called 'learning-by-doing'. Technological learning has since then been described for many different industries ranging from refined petroleum products and the unit costs of ships and power plants to the productivity of kibbutz farming [Argote & Epple, 1990].
However there is a significant difference between the learning curve concept and the experience curve concept. The learning concept only comprises the phenomenon of learning through accumulating experience. Unlike the learning concept, the *experience concept* does include other factors, the two most important being learning through research (R&D) and learning through large-scale production (economies-of-scale) and upscaling of individual products. Thus, an experience curve takes into account all parameters that influence the total costs of a product (i.e. for research, capital, administrative and marketing) and traces them through technological and product evaluation [Mackay & Probert, 1998]. The Boston Consultancy Group was the first to introduce the *experience curve concept* relating to the total costs and cumulative quantity [BCG, 1968]. So, while learning curves are historically used to monitor a single factory, experience curves analyze a complete market [IEA, 2000].

2.2 The experience curve formula

An experience curve can be expressed as:

$$C(Cum) = a * Cum^b \qquad (1)$$

$$\log (C(Cum)) = \log a + b \log Cum \qquad (2)$$

C Cost per unit
Cum Cumulative (unit) production
a learning cost at Cum=1
b learning index (constant)
Cum_0 Initial cumulative unit production (at t=0)
C_0 Initial specific cost (at t=0), equals $a*Cum_0^b$

Symbols and terms used for costs, cumulative production and the learning index vary widely in literature, for example the learning index is also called 'experience parameter' [IEA, 2000] or 'learning parameter' [Mackay & Probert, 1998]. The terminology given under formula (2) will be used throughout the rest of this paper. In case of a normal experience curve were costs decline with cumulative production, the value of the learning index is negative. When using the logarithmic version of equation (1) the learning index represents the negative slope of a straight line (see equation (2)). An example of an experience curve is given in Figure 2.1.[3]

[3] Note that when using historical data for constructing an experience curve (such as shown in figure 2.1), all costs should be based on the currency in a base-year and have to be corrected for inflation in other years. In other words, an experience curve must be constructed in real terms, not in nominal terms.

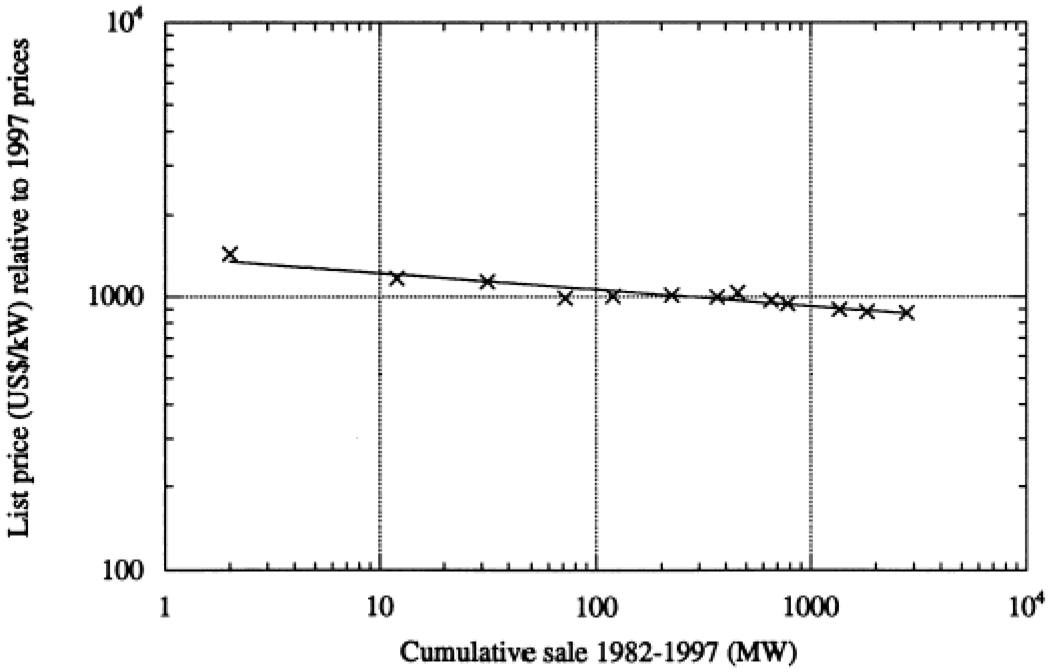


Figure 2.1 An experience curve for wind turbines produced by four major producers in Denmark. The progress ratio is 96%. Adopted from Neij [Neij, 1999].

From the learning index, the progress ratio and the learning rate can be calculated:

$$PR = 2^b \quad (3)$$
$$LR = 1 - 2^b \quad (4)$$

$$C_{min} = PR^n * SC_0 \quad (5)$$

PR Progress ratio
LR Learning rate
n The (assumed) maximum number of times the cumulative production will double
C_{min} The minimum price given for the maximum cumulative production

Both the progress ratio and the learning rate are parameters that express the rate at which costs decline each time the cumulative production doubles. For example, a learning index of -0.322 results in a progress ratio of 0.8 (= 80%) which in turn equals a learning rate of 0.2 (20%), and thus a 20% cost decrease for each doubling of the cumulative capacity. The advantage of using the learning rate rather than the progress ratio is that a 'higher' learning rate means a faster decrease of costs, while a 'higher' progress ratio means a slower decrease of costs and thus is somewhat misleading. Despite of this, the use of the progress ratio is far more widespread, and will be used preferably throughout this paper.

Note that formula (1) and (2) represent the basic experience curve model. There are many variations to these formulas which may be able to describe historical data more accurately [Badiru, 1992]. In this paper, only the basic form will be discussed.

2.3 The learning system model

It is important to understand that the concept of experience curves should not be considered a 'law' or that there are fundamental reasons why they should apply. It is rather a correlation phenomenon that has been observed on numerous occasions, including the production of equipment that transforms or uses energy [IEA, 2000]. However, in order to be able to discuss what should constitute an experience curve, a simple model of the experience phenomenon is required. Both learning and experience curves establish relations between the input and the output of a learning system. The basic model of a learning system can be considered a black box for which only input and output are observed. The input is measured in monetary terms, while the output is measured in physical terms, so that the measure is cost per unit, e.g. US$/kW [IEA, 2000].
Watanabe identified that elements inside the black box consists of public R&D policies, industry R&D, technology stock R&D, production, total costs and deployment policies which all interact with each other [Watanabe, 1999] (See Figure 2.2). He finds that for the production of PV-modules over 70% of cost reductions were directly due to an increase in the stock of technology knowledge, and in conclusion the quantitative analysis of learning in producing PV-modules supports the use in the experience curves of cumulative output as the variable against which performance should be measured [IEA, 2000]. In this paper the simple ‘black box’ model will be used. The individual components will not be further analyzed.

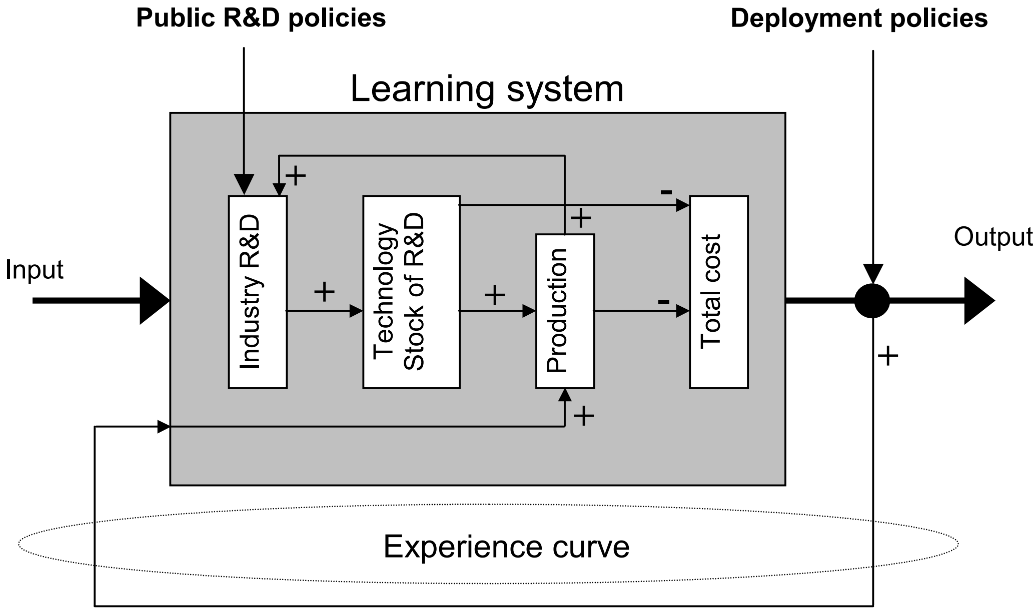


Figure 2.2 Influences on the learning system from public policy. The gray box represents the learning system. The input is measured in monetary terms, while the output is measured in physical terms, so that the measure is cost per unit (e.g. US$/kW). Factors influencing the total cost are from Watanabe [Watanabe, 1999]. From IEA [IEA, 2000].

Furthermore, the choice and exact definition of the ‘unit’ of product also depends on the borders chosen for the learning system. Examples for the choice of unit are e.g. 1 airplane of a certain type, or 1 tonne of a chemical compound. However, in case of for example a power plant, it may be more useful to define a unit as ‘MW peak capacity’, or as ‘kWh produced’. According to the experience curve formula and the learning system model, on the x-axis of the experience curve, the cumulative number of units produced (or sold, or installed etc.) should be plotted. In correspondence, on the y-axis the costs *per unit* should be plotted. This will be illustrated by the example of a power plant. It is in accordance with the theory to plot the costs per kW (peak capacity) against the cumulative number of capacity (in MW) produced. It is also possible not only to analyze the production of a power plant, but also to include the operation, i.e. the electricity generation. In this case the learning system is extended, and it would be valid to plot the costs per kWh against the cumulative produced electricity. However, it is e.g. not in accordance to the theory to plot the costs per kW against the cumulative number of power plants built, or the costs per kWh against the cumulative capacity (in MW) produced.

2.4 Limitations and uncertainties of the experience curve concept

2.4.1 Theoretical limitations and uncertainties

Experience curves can be used to extrapolate a trend from the past into the future. However, they cannot simply predict the future. One of the main points is that the experience curve concept does not indicate within what time frame the next doubling of the cumulative production may occur. Thus, it is necessary to use the experience curve concept in combination with another model or forecast that predicts the future growth of the cumulative production.

It is a point of discussion, whether the progress ratio will become less favorable in time, or whether it will never change.
According to some sources (e.g. [Mackay & Probert, 1998] and [Grübler, 1998]) the experience curve theory makes a difference between two (or more) phases. The first main phases is the 'R&D and technical demonstration phase', in which normally a high learning rate is observed. The second phase is the commercialization or diffusion phase, in which a lower learning rate is achieved as market saturation is achieved (see the experience curve of gas turbines in figure 2.3). Possibly a third phase may be introduced at the point when (total) market saturation is reached, and the learning rate may have dropped to zero (for example see [EWEA, 1999a], [Mackay & Probert, 1998]). If this was not the case, the cost of a unit would approach zero with a continuing increase in cumulative production. This is not realistic, as there will always be a minimum cost involved for labor and capital.
On the other hand, it can be argued that not only experience effects never cease to occur but that in addition the PR will not change over time / cumulative production. The cost of a unit will not approach zero as this would require exponentially increasing cumulative production, which will in reality come to a point where the market is saturated and no more or only marginal capacity addition is possible. For a well established technology the volume required to double cumulative sales may be very large, and thus the experience effect is hardly noticeable in stable markets [IEA, 2000]. However, even in the case of an established technology that has reached market saturation, units may have to be replaced. For example, when considering nuclear electricity plants and a lifetime of 30 years, all existing plants would be replaced within 30 years, thus contributing to a significant further cumulative "addition" of capacity. In any case, the experience curve concept does not predict when a phase transition and the accompanying decrease in learning rate will occur.

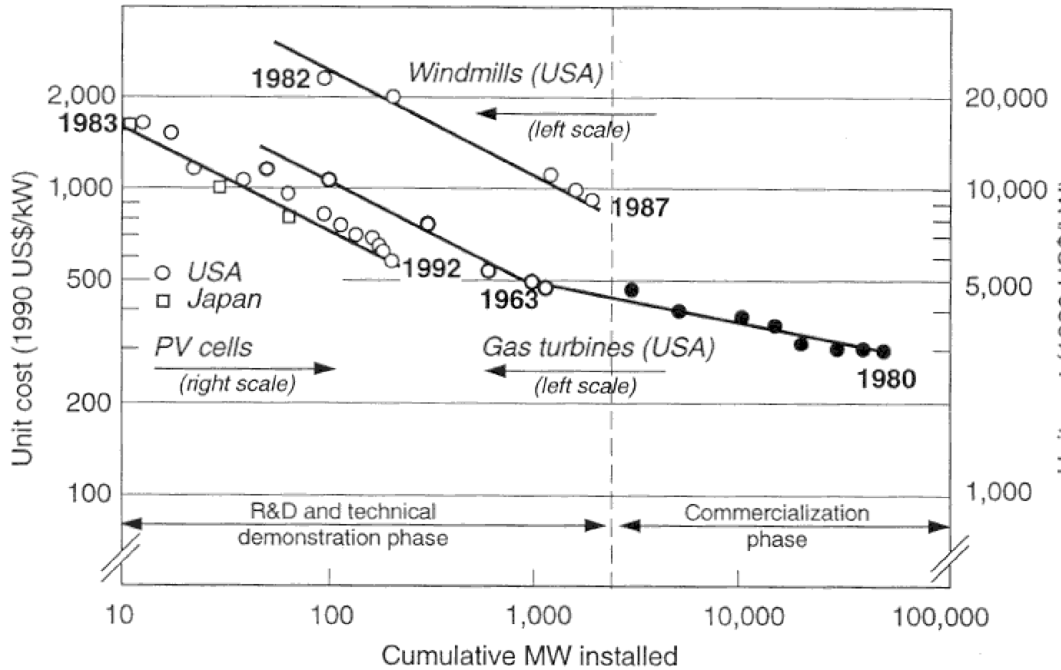


Figure 2.3 Technology learning curves: unit cost (US$ /kW) versus cumulative installed MW for PV cells (right scale), wind and gas turbines (left scale). Adopted from [IIASA-WEC, 1995]

There are also other reasons why a experience curve may show a “knee’, i.e. different learning rates.

Inside the learning system this may also occur when a technology structural change takes place, i.e. a shift in the technology paradigm leading to a new variant of the technology or a major change in the way the technology is produced [IEA, 2000]. This is mainly the case when a technology is still in the first stage and different technology variants of the same principle co-exist.

Also factors outside the learning system may cause a change in the learning rate. For making experience ideally curves, the actual production *costs* should be used. In reality however, these costs are often classified and only list *prices* are available. In a competitive market, the profit margin is normally constant and small compared towards the total price. However, in the case of introduction of a new technology, typically four different phases will occur: development, price umbrella, shakeout and stability (for more detailed information see [IEA, 2000], [BCG, 1968]). In each of these phases a different progress ratio is found (if based on the market price), and only in the last phase the profit margin is constant, and the progress ratio based on costs and prices are identical (See also Figure 2.4). Thus, great care should be applied when using prices instead of costs to construct an experience curve.

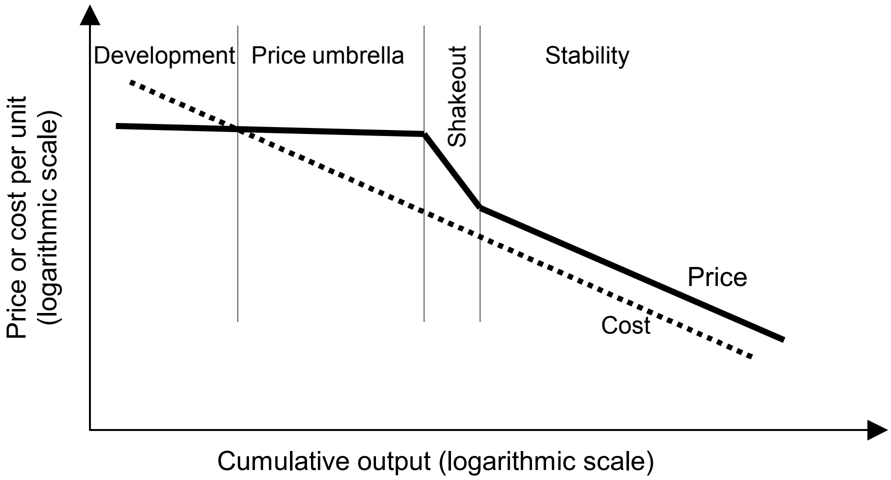


Figure 2.4 Price-cost relation for a new product. Published in [IEA, 2000], Adopted from [BCG, 1968].

Another noteworthy issue is the fact, that the learning index, and thus the progress ratio of the main product unit is most likely not the same as the learning index of a sub-operation in the manufacturing process of the main product (see for a discussion [Mackay & Probert]). The learning rate does only apply to the integrated product, and not for each of the sub-processes. For example, a wind turbine consists (amongst many other parts) of rotor blades and a gearbox. Both the efficiency of the wind capture of the rotor blades and the efficiency of the gearbox can increase by learning. However, this will not likely be at the same learning rate. Thus, when analyzing the efficiency of a total wind turbine system, the determined learning rate is most likely not identical to the learning rates of each sub-component.

2.4.2 Practical limitations

A large problem for devising experience curves is obtaining suitable and accurate data. This is especially difficult for the initial stages of production, when reliable data is scarce [Mackay & Probert, 1998]. But also when a technology has gone beyond the start-up phase, several issues can cause uncertainties:

- As mentioned above, manufacturers are often reluctant to reveal the costs of a unit and will only publish prices instead of costs. However, in the case of (semi-) mature products, many markets are cyclic or unstable, and prices are not significantly determined by learning effects, but by decreasing or increasing demand. Examples are parts of the bulk chemical industry.
- In some cases, only highly aggregated data is available. This may occur either if this data is considered confidential, or when simply no detailed databases exist.
- The variation in prices of different manufacturers may also contribute to data uncertainty. For example, there may be several manufacturers offering a 1 MW wind turbine. However costs may differ per manufacturer, thus causing a range in prices. Furthermore, when calculating an average price, it is possible to consider all list prices as equally important, or weigh list prices by actual production or sales.
- Finally, manufacturers may offer wind turbines of different capacity, e.g. 55 kW, 500 kW and 1 MW. It is possible to construct separate experience curves for each of the turbine sizes, but when aggregating this data, and calculating a price per kW, this may cause a larger range of values and a greater deviation in the average data (e.g. smaller turbines have generally higher costs per kW than large turbines).

These factors may contribute to a significant spread in costs for each data point in an experience curve. Due to this uncertainty, it may also be difficult to detect phase transitions.

2.5 Use of the experience curve in practice

Experience curves have been established for major and minor industry classes, such as the semiconductor industry, mass production of cars or airplanes, nuclear plants, but also for the efficiency increase of workers in a kibbutz [Argote & Epple, 1990]. In most industries, progress ratios vary between 70-90%. In a comparison of 22 field studies, it was found that 85% of all experience curves fall into this range [Dutton & Thomas, 1984].
Remarkably, there are also rare cases known of 'organizational forgetting' or 'negative learning', where prices rise (instead of decline) with increasing cumulative production. An often quoted example is the Lockheed L-1011 Tri-Star model which became more expensive with cumulative production due to ‘organizational forgetting’ [Argote & Epple, 1990]. Another reason for a rise in cost with cumulative production can be that costs cannot be reduced as fast as costs are added through design changes (e.g. use of significantly more expensive material) as was found at the beginning of the 20th century for the Ford car [Abernathy & Wayne, 1984].
Christiansson notes that there are basically three categories of technologies / products [Christiansson, 1995]. Each category has its own range of progress ratios:

- Big plants representing economies of scale due to upscaling of units (e.g. large electricity-generating nuclear or coal power plants). The typical progress ratio range is 80-90%.
- Modules representing economies of scale due to mass production of identical units (e.g. automobiles and semiconductors). The typical progress ratio range is 70-95%.
- Continuous operations are a combination of the first two categories, e.g. standardized commodities in large scale units such as bulk chemicals or plastics. The typical progress ratio range is 64-90%.

Finally, it should be mentioned, that learning curves and experience curves can be devised for different purposes. A manager of a factory will most likely want to use a learning curve or experience to forecasts how many units of his product may have to be produced before a certain price level is reached.
A scientist analyzing the technology development of a certain product may more be interested on how a specific development can be analyzed, if any special circumstances influenced the learning process for the specific technology, and how the results can be used as benchmarks in order to compare the development in other studies. In turn, a policy maker may mainly be interested when a technology as a whole may be able to compete with another technology, but may little care about the exact causes for technological learning.

Though there is some overlap between these interests, it may occur that experience curves are used in different ways. Whether or not this may also lead to different results, will be discussed in chapter 4.

Chapter 3 Current use of experience curves in the wind energy sector

3.1 Overview of historical experience curves for the wind energy sector

In literature, a number of different experience curves for the wind energy sector were found. In order to be able to describe and compare these different studies, it has to be pointed out that several types of experience curves are used in literature. On the x-axis, either costs per kW or the costs per kWh are plotted. On the x-axis, either the cumulative capacity produced or installed in a country can be plotted, or the cumulative number of kWh produced. In addition, in some studies the cumulative number of wind turbine units installed / produced is plotted on the x-axis. To facilitate the nomenclature in this document, a number is assigned to all types found in literature:

I The costs per kW vs. the cumulative number of kW installed/produced
II The costs per kWh vs. the cumulative number of kWh produced
III The costs per kWh vs. the cumulative number of kW installed/produced
IV The costs per kWh vs. the cumulative number of wind turbine units installed/produced

The advantages and disadvantages of each type will be discussed in chapter 4.

An overview of the studies found in literature is given in table 3.1. Using the study of Mackay and Probert, each column in the table is explained:
Mackay and Probert used a type-I experience curve, and found a progress ratio of 85.7%. They used data originating from 1981-1996 of wind turbines installed in the US. Their experience curve starts with a cumulative capacity of 20 MW, and ends with a cumulative capacity of 1750 MW. This equals an average annual increase in capacity of 34.7%. Thus, between 1981 and 1996, the capacity in the US has doubled about 6,5 times. Finally, the experience curve had a correlation coefficient of 0,945.

Below, a short description and special points of attention of each study is given.

Mackay and Probert study the development of the costs of wind turbines installed in the US is described from 1981-1996 [Mackay and Probert, 1998]. Compared to other studies using the type-I experience curve, a relatively low progress ratio of 85.7% is found. This may be explained due to the fact that the US has imported a large percentage of its wind turbines (see chapter 4.2.1).

In the studies of Neij [1997 & 1999], the author analyzes the costs of wind turbines produced in Denmark. An important finding is that cost reduction of wind turbines has mainly depended on the upscaling of wind turbines, as experience curves for different turbine sizes reveal progress ratios between 98-101%. Only when combining all turbine sizes and all producers, a maximum progress ratio of 92% is found.[4]
As mentioned in the chapter 2.5, several categories of technologies can be distinguished. Wind energy could theoretically benefit from both upscaling of a wind turbine (big plant category) and mass production of a wind turbine (module category). Neij finds that until

[4] Wind turbines have been built in increasing size and capacity (e.g. 55 kW, 500 kW, 750 kW and 1 MW). When constructing an experience curve for each single type, progress ratios between 98-101% are found. However, the cost per kW generally become cheaper with increasing capacity. Thus, when combining all experience curves, a progress ratio of 92% can be obtained.

1997, wind energy has mainly benefited from the upscaling of wind turbines, but little from mass production of a turbine of a certain size [Neij, 1997]. Thus, wind turbines so far fall under the ‘big plant’ category. However, in case a maximum capacity per turbine unit is reached in the future (e.g. due to the visual impact onshore), this may still shift to the ‘modular’ category.
Note that both for Germany and Denmark, progress ratios are found of 92% (by [Neij, 1997] and [Durstewitz & Hoppe-Kilpper, 1999]). These are the two leading wind turbine manufacturer countries – together they accounted for over 60% of the worldwide installed capacity in 1996 [EWEA, 1999b].

Table 3.1 Overview of historic experience curves for the wind energy sector

Author	PR	Time frame	Region	Cum MW [I, III] / TWh [II] installed [i] / produced [p]	Average annual growth rate	Cumulative doublings n	r^2
[Mackay & Probert, 1998]	85.7%[I]	1981-1996	US	20-1750 (±) [I, i]	34.7%	6.5	0.945
[Durstewitz & Hoppe-Kilpper, 1999]	92%[I]	1990-1998	Germany	60-2850 [I, i]	21.5%	5.6	0.949
[Neij, 1999]	92%[I]	1982-1997	Denmark	n.a.	n.a.	n.a.	n.a.
[Neij, 1999]	96%[a, I]	1982-1997	Denmark	2-3000 (±) [I, p]	63% (±)	10.6 (±)	n.a.
[Neij, 1997]	96%[a, I]	1982-1995	Denmark	2-1800 (±) [I, p]	69% (±)	9.8 (±)	0.83
[Seebregts et al., 1998]	87% / 90% [b, I]	n.a.	Denmark	n.a.	n.a.	n.a.	n.a.
[Lund, 1995]	85%[I]	n.a.	Denmark	n.a.	n.a.	n.a.	n.a.
[IEA, 2000] p.21 / EU Atlas project	82%[II]	1980-1995	EU	0.02 -20(±)[II]	59% (±)	6.6 (±)	n.a.
[IEA, 2000] p.43 / Kline / Gipe	68%[II]	1985-1994	US	2-30(±)[II]	35% (±)	3.9 (±)	n.a.
[Dannemand Andersen & Fuglsang, 1996]	80%[III]	1981-1995	Denmark	7-2500 [III, p]	52.2%	8.5	n.a.
[Neij, 1997]	91%[b, III]	1980-1991	Denmark	7-1280 [III, p]	68.3%	n.a.	n.a.

± Data was estimated from a figure as exact numbers were not given
n.a. Data not available
a Only four Danish producers; only >=55 kW turbines
b based on data from [Dannemand Andersen & Fuglsang, 1996]
i experience curve based on the number of MW capacity actually **i**nstalled in the region
p experience curve based on the number of MW capacity **p**roduced in a country (of which a large percentage may be exported to other countries)
I The costs per kW vs. the cumulative number of kW installed/produced
II The costs per kWh vs. the cumulative number of kWh produced
III The costs per kWh vs. the cumulative number of kW installed/produced

[Seebregts et al., 1998] carried out a brief study in order to verify the study presented by [Neij, 1997], as the authors were not certain whether Neij did use nominal instead of real prices (corrected for inflation). However, from the original article it appears that Neij did use real prices. The reason for the difference in progress ratio (87% vs. 92%) could not be explained. In order not to be over-optimistic, the authors proposed a progress ratio of 90%.

Another study considering wind turbines in Denmark was carried out by [Dannemand Andersen & Fuglsang, 1996]. In difference to the previous studies, the costs *per kWh* are

related to the cumulative produced capacity. During the period 1981-1995, the author calculates the progress ratio *per year*, and finds variations between 79.4-103.1 %, but as a rough average, a progress ratio is estimated of 80% for this type of experience curve in case of a “normal situation”, while in a situation as the California boom between 1982-1984, annual progress ratios between 90-103% are determined. However, [Neij, 1997] finds a progress ratio of 91% for the period of 1980-1991 based on the data of this study. The influence of market changes and the time frame chosen will be further discussed in chapter 4.2.
Dannemand Andersen and Fuglsang also quote a study of Lund [Lund, 1995]. Lund finds an ‘approximate’ progress ratio of 85% for produced Danish wind turbines (no time frame, or number of cumulative doublings is given).

Finally, in the document ‘experience curves for energy technology policy’ [IEA, 2000] a number of historical wind energy curves are discussed, including the two historical experience curves based on costs/kWh vs. cumulative TWh production. The difference in progress ratio between Europe and the US (68% vs. 82%) will also be discussed in chapter 4.

When comparing these studies, a number of differences can be seen. The majority of the studies uses the type-I experience curves, i.e. the cost per kW of a wind turbine are plotted against the cumulative capacity produced or installed in a region. The variation in progress ratios is considerable, varying from 85-92% (only taking into account experience curves that includes all turbine sizes).
Only two type II experience curves were found which analyze the costs per kWh. This is probably caused by the fact that in comparison to produced capacity, detailed data for electricity production is difficult to obtain.
Also it is clear that a number of studies were performed for the Danish market, while less studies are available for other countries with an own wind turbine manufacturing industry (e.g. the US or Germany). No studies were found for countries such as the Netherlands, Spain or India with a (to some extent) significant installed capacity. Also, it is remarkable that all studies in Denmark describe the number of turbines produced or sold, while studies for the US or Germany describe wind turbines installed.

3.2 Use of experience curves in scenarios to evaluate possible future developments

As stated in the introduction, experience curves are used in a number of scenarios that try to predict the future development of wind power. In this section, studies are described which solely aim to forecast the development of wind power, and do not consider other technologies of the energy sectors. These studies are compared in Table 3.2 and are shortly described below. Most studies use a time frame starting between 1995-1998 until 2020. For studies, which have a longer timeframe, the data given for 2020 was used in Table 3.2. In order to be able to compare all data on cost of electricity or capacity, all currencies were converted to 1997 US$ (See Appendix A for more details).

[Neij, 1999]
The two scenarios are based on the Current Policy Scenario and the Ecologically Driven Scenario from the World Energy Council’s (WEC) 'Energy for tomorrows world'. A progress ratio is assumed of 95% for a type-I experience curve, as this was also found for all major manufacturers of turbines with size above 150 kW from 1990-1997. The sensitivity is measured by varying the progress ratio to 97% and 93%. The costs of electricity are

calculated by assuming a discount rate of 6%, a lifetime of 25 years and a annual wind capture of 2500 kWh/kW (capacity factor = 0.285).

[Ybema et al., 1999]
The estimate for the installed capacity in 2020 is based on an annual growth rate of 13%. This growth rate is average between the current growth in installed capacity of 18.4% and the 7% growth predicted by the World Energy Outlook of the IEA (1998). The assumed progress ratio is based on [Seebregts et al, 1998]. As sensitivity analysis, both the installed capacity and the progress ratio are varied.

[Chapman & Wiese, 1998]
In this study, actually no progress ratio is mentioned. However, the authors propose a scenario in which 10.000 additional MW are installed in the US in several steps, each accompanied by a given drop in costs / kW. When applying the experience curve formula type I, this results in a progress ratio of 84%. It is noteworthy, that although this study only reaches until 2006, the maximum cost reduction reaches 630 US$/kW, a value reached only much later in other studies / scenarios.

Table 3.2 Scenario-based predictions using experience curves

	Assumed progress ratio	Assumed cum. GW installed Present	In 2020	Cum doubl. n	Costs in 2020 US$ / kW [a]	Costs in 2020 US$¢ / kWh [a]
[Neij, 1999], Time frame 1997/2020, Global scenarios, experience curves type I						
	93%	7.6	188	4.6	n.a.	3,1
Current policy scenario	95%	7.6	188	4.6	670	3,4
	97%	7.6	188	4.6	n.a.	3,7
Ecologically driven scenario	95%	7.6	483	6.0	630	3,2
[Ybema et al., 1999], Time frame 1997-2010 / 2020, Global scenarios, experience curves type I						
Low estimate	87%	7.68	110	3.8	567	n.a.
Best guess	90%	7.68	140	4.2	677	n.a.
High estimate	93%	7.68	170	4.5	795	n.a.
[Chapman & Wiese, 1998] Time frame 1996-2006, Scenario for the US, experience curve type I						
	84%	1.75	11.75 (in 2006)	2.7	630 (in 2006)	n.a.
[Dannemand Andersen & Fuglsang, 1996] Time frame 1995 / 2020, Global scenario, experience curves type III						
Normal Progress	85%	4	180	5.5	380	2.7 (±)
Conservative Progress	90%	4	180	5.5	n.a.	3.5 (±)
[EWEA, 1999a] Time frame 1998-2020 / 2040, Global scenario, experience curves type IV						
	85 / 88 / 90 / 95 / 100% changing over time	10.15	1209	8.2	512	2.4
[BTM, 1998], Time frame 1997-2025/2040, Global scenarios, experience curves type IV						
Recent trends	85 / 88 / 90% changing over time	7.64	750	6.6	n.a.	3.1
International agreements	85 / 88 / 90 / 95% changing over time	7.64	1300	7.4	n.a.	2.7

a All costs have been converted to 1997 US$. For details see Appendix A.
I The costs per kW vs. the cumulative number of kW installed/produced
II The costs per kWh vs. the cumulative number of kWh produced
III The costs per kWh vs. the cumulative number of kW installed/produced
IV The costs per kWh vs. the cumulative number of wind turbine units installed/produced

[Dannemand Andersen & Fuglsang, 1996]
The progress ratio's in this study are based on costs/ kWh per cumulative sold capacity. The authors find different progress ratios per year, varying from 79.4-103.1 %, but assume an average progress ratio of 80% (see section 3.1). The authors point out that using experience curves for forecasts can only provide rough indications for future developments. The maximum capacity installed until 2020 is based on the WEC scenario 'current policy trend' (see above). This scenario comprises only a small part of the study. The main scope of the report was not aimed at the use of experience curves, but was actually to analyze the technological potentials and sources of learning (or technological improvement) of each main cost component of wind energy. [Dannemand Andersen, 2000].

[EWEA, 1999a]
This study was partially based on the study of BTM ([BTM, 1998]). However, the scenario-assumptions for the total to be installed capacity are different from [BTM, 1998]. There are a number of remarkable assumptions made in this study. First of all, the progress ratio is based on cost/kWh vs. the cumulative number of wind turbine units (type IV). The increase in capacity is modeled by assuming average sizes, varying from 0.7 MW in 1999 to 1,5 MW in 2020 and 2.0 MW in 2040. Furthermore, this is the only study reviewed, which actually assumes that the progress ratio will become 100%, i.e. that no further cost reductions can be achieved with further cumulative production. Also, this study finds a possible cost of 2.4 US$¢ /kWh (based on 1997), the lowest cost of all scenarios. A more detailed discussion of the approach used in this scenario is given in Appendix B.

[BTM, 1998][5]
As in the EWEA study, the progress ratio is based on a type IV-experience curve. Differences to the previous study are the assumed annual capacity growth rate and the higher final costs per kWh.

These studies cannot simply be compared with each other, as some use current annual growth trends for their forecast (e.g. [Ybema et al., 1998]), while other studies use normative objectives, e.g. that 10% of the worlds electricity demand is satisfied by wind energy [EWEA, 1999a]. Still it is interesting to compare the minimum and maximum values that different authors find under these different circumstances:

Table 3.3 Comparison of different forecasts for the global development of the wind energy sector

	Min	Max
Progress ratio (for type I experience curves) (%)	84	97
Cumulative global capacity (GW) in 2020	110	1209
Cumulative doublings until 2020	3.8	8.2
Investment costs in 2020 (US$ / MW, 1997)	380	795
kWh costs in 2020 (US$¢ / kWh, 1997)	2.4	3.7

As can be seen from Table 3.3 both assumptions on progress ratios and the maximum global capacity vary strongly, causing the predictions for investment costs and cost of electricity to diverge considerably.

[5] Only the abstract of this report was available to the author, which makes the information given here possibly incomplete.

3.3 Use of experience curves in models which incorporate endogenous learning

In section 3.2 only scenarios where compared which solely analyzed possible developments in the wind energy sector. There are also a number of models that consider developments for a number of renewable and fossil-fuel based technologies, which also include wind. These models also make use of the principle of technological learning (also called endogenous learning). Examples are the European models MARKAL, ERIS and MESSAGE [ECN, 1999a] and the American model NEMS [Kydes, 1999].

Little information was available on these models except on the MARKAL model [Seebregts et al, 1998]. This model estimates the maximum capacity of wind power in 2050. Limitations are both the theoretical gross global wind potential, and a maximum annual growth rate (e.g. an annual growth rate of 100% for a technology is unprecedented in history, while growth rates between 20-30% have often been observed). For comparison, the average growth rate in installed capacity in wind energy from 1992-1997 was 27% per year [BTM, 1998].

The models ERIS, MESSAGE and MARKAL were compared by [Seebregts et al., 1999] (see table 4.3). Note the difference in n (the maximum assumed cumulative number of doublings) (5 vs. 13), the assumed progress ratio (85% vs. 90%) and the effect on the price level compared to 1990. Depending on these assumptions, the price level in 2050 compared to 1990 may vary over a factor 2 (19% vs. 44%).

Table 3.4 Model-based predictions, period 1990-2050, adopted from [Seebregts et al, 1999a]

	MARKAL Europe	MARKAL global	Reduced MESSAGE global	ERIS global
PR	90%	89%	85%	88%
n	6	9	5	13
PR^n	53%	35%	44%	19%

n = number of maximum doublings; PR^n = price level compared to 1990

As the variety in progress ratios in table 3.4 suggests, Seebregts et al. remark that the estimation of progress ratios is not a trivial task, and that great care must be applied before historical curves can be extrapolated into the future [Seebregts et al, 1999a].

It must be emphasized that these models do not specifically aim to forecast the development in the wind energy sector, but comprise a number of technologies next to wind, e.g. advanced coal, new nuclear, fuel cell and solar PV. The development of these different technologies is linked within the model, and may influence each other. Thus, the annual wind energy capacity addition also depends on the development of other technologies. This makes endogenous learning models significantly different from direct estimates for the added capacity.

Chapter 4 Limits and possibilities of the experience curve

This chapter is divided into three main parts. In the first part, a number of recommendations are given on how to construct experience curves based on historic data. These recommendations are based on the different approaches found in literature and their advantages and disadvantages. In the second part, limitations of historic experience curves for future predictions are described. In the third part, the issue whether offshore developments can or cannot be predicted using existing experience curves, will briefly be addressed

4.1 Recommendations for constructing a historic experience curve

4.1.1 Practical recommendations

When using and presenting experience curves based on historic data, one should take many aspects into account in order to provide maximum clarity and facilitate comparisons between different studies. It is stressed that the recommendations within this section are solely based on the problems encountered while comparing the historic experience curves in the wind energy sector in chapter 3.1. No claim for general validity is made.

First of all, it should be clear what exactly is plotted on each axis. This may sound trivial, but it can be a source of misunderstandings and make comparisons with other experience curves more difficult. For example on the **x-axis**, the cumulative capacity can be plotted out. However, there is a difference of capacity *produced* by different companies in a country (or several countries) and the amount of capacity that is *installed* in a country / region. In the case of cumulative produced electricity, it should be clear whether this is the amount of electricity that is produced by *all wind turbines* which operated within the chosen time frame or *only by the newly installed wind turbines* in each time interval. In addition, it should be mentioned whether the amount of electricity produced originates from statistics (e.g. from electricity companies), or if it is derived by multiplying the additional capacity with an estimated capacity factor. The latter may introduce an additional uncertainty [Dannemand, 2000]. In one case [EWEA, 1999a], it was found that the cumulative number of wind turbine units was plotted. This is not advisable, as it is only another form of using cumulative capacity, but introduces an additional source of uncertainty. See also Appendix B for more details. Finally, the time frame and geographic location from which the data originates should be mentioned.

For the **y-axis**, similar differences exist. In case of costs per installed capacity, there are three possibilities: the actual costs per kW for the wind turbine manufacturer, the list prices a manufacturer publishes, and the actual installation costs (the list price is approximately 75% of the total installation costs [Neij, 1999]). As stated in chapter 2, in an ideal case, the progress ratio is the same regardless whether costs or prices are used. In reality, however, it should be motivated if this is the case in the specific situation.
Furthermore it should be stated whether average or lowest available costs / prices are used. As explained in chapter 2.4, it is possible either to simply use the average price / kW of all list prices, or use average list prices weighed by the actual sales volume per turbine type. Finally, it is informative not only to give an average price for a cumulative volume, but also at the same time the range in which prices may vary. For example, Neij [Neij, 1999] gives an average price of approximately 850 US$/kW for wind turbines (for 1997, at approximately cumulative 3000 MW sold). For this point in the experience curve, the maximum range in

prices was 690-1200 US$/kW (-19% / + 41%)[6]. Thus, the maximum ranges and standard variation for every data point ideally should be given.
As described in chapter 2.3 the cost per unit on the y-axis will normally refer to the same unit on the x-axis (for example $/kW plotted against cumulative installed MW). However, this is not always the case, as will be shown in section 4.1.2.

Second, the accuracy of the entire experience curve should be made clear. In order to judge the accuracy of an experience curve, the correlation co-efficient and the number of doublings (n) of the cumulative capacity should be given: the correlation co-efficient (r^2) indicates how much the data points deviate from the ideal line. Indirectly it is a measure on how accurate and reliable the calculated PR is. Also the number of cumulative doublings of production is important. A correlation coefficient may be 0.99 or even closer to 1, but if the range of data is only within one or two doublings of cumulative production, or if the number of data points is only very limited, it is highly questionable in how far the obtained PR is representative for e.g. the next ten doublings.

Third, the currency base year in which all costs / prices are expressed is important when using and constructing an experience curve. Optionally, the annual inflation rates for the time period may be given. By doing so, historic experience curves can more easily be compared with other experience curves from other countries (with the same time frame, but possibly different inflation rates). In the case when a currency is converted to US$ (in order to facilitate international comparisons), it is important to investigate how the exchange rate between the two currencies has changed during the years.

For example, Neij [Neij, 1999] finds progress ratios vary between 92-98% depending on the chosen time frame, the number of suppliers and the chosen wind turbine size. Furthermore she remarks that the exchange rate varied between 5.5 to 6.6 DKK = 1 US$ (1992-1997) which makes it difficult to compare these number with e.g. American experience curves from the same time frame.

4.1.2 Choosing the type of experience curve

The points described above are rather 'practical' recommendations, related to the construction of the experience curve. Another, more fundamental choice that has to be made, is the type of experience curve, as described at the beginning of chapter 3. In the following section, a discussion will be given of advantages and disadvantages of type I, II and III experience curves.[7]

As described in chapter 2.5, devising an experience curve can be done for several reasons. Two main interests were found in literature: On the one hand experience curves are used to analyze the progress of a certain technology (technological learning), and compare this learning progress to the speed with which other technologies learn. In this case studies mainly focus on the development of the wind turbine itself. Research on for example the reduction in costs of the foundation of a wind turbine system or the electronic control system has not been found in literature. On the other hand, there is the interest to analyze the decline of wind energy costs as a whole in time, for example to determine the degree of competitiveness of

[6] This may partially depend whether all available wind turbine sizes or only wind turbines above a certain size are included.
[7] The reasons why experience curve type IV should not be used are discussed in Appendix B.

wind energy in relation to fossil fuel-based electricity. In this case, the costs per kWh are of greater interest than the costs per installed capacity.

When looking from the 'technological learning' viewpoint, the total learning system of ‘producing electricity from wind’ basically consists of the subsystems ‘producers of wind-turbines’ and ‘producers of electricity using wind turbines’. These two subsystems are connected together not only through an output-input relation, but also through informational feed-forward and feed-backward loops. In Figure 4.1 the learning system is given for the US.

From the viewpoint of analyzing and comparing technological learning, it is not useful to relate cumulative installed capacity (in kW) to the cost of electricity (in $/kWh), as this would be relating the performance of the total system to one of its subsystems [IEA, 2000]. Thus the results cannot be used to benchmark results obtained from experience curves, and to compare this technology with other (renewable) technologies. However, from the viewpoint of available accurate data, and forecasting when the costs per kWh will reach a competitive level, it may be useful to do just this [Dannemand Andersen, 2000].

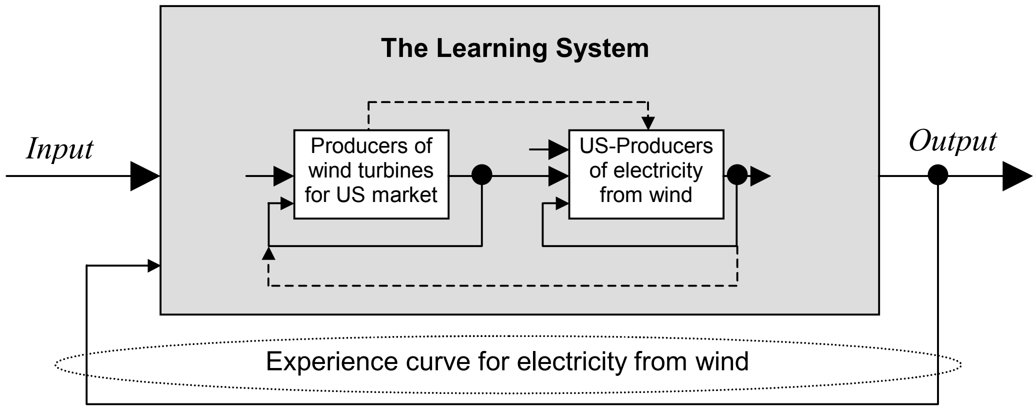


Figure 4.1 US Learning System for Production of Electricity from Wind. The system contains two subsystems, one producing wind turbines and one producing electricity from wind using wind turbines. Solid lines represent information feed-forward from one subsystem to another and information feed-backward within a (sub)system. Dashed lines represent information feed-forward or feed-backward between the two subsystems. Adopted from [IEA, 2000].

Learning rates of experience curve measuring the costs of electricity are in theory always higher than the corresponding learning rates of ‘costs of installed capacity’ experience curves. This is due to the fact that the decline costs of electricity are not solely influenced by the declining costs of the turbine (which are only the investment costs). They are also lowered by the possible increase in efficiency due to e.g. a better design of the rotor blades, which may enable the wind turbine to capture more wind energy at sub-optimal wind speeds. Also due to higher hub heights and better siting, the average wind speed has increased[8]. Both factors contribute to an increased wind capture and higher electricity production per swept area (kWh/m^2) [Neij, 1999]. In addition, improved materials and design may have decreased both annual O&M costs and the time a wind turbine is not operative due to a malfunction, and thus increase the capacity factor. Finally, also the average lifetime of a wind turbine may increase.

[8] This may not necessarily always be the case. In a country such as Denmark, all the best sites are already occupied. In the years from 1996-1999 the productivity of wind turbines has been declining, even when adjusted to a normalized wind year, while historically the productivity has improved by an average 5% per year. The recent decline is solely due to poorer siting [DWTMA, 2000]. This decline in productivity may result in a lower learning rate.

These are all significant learning effects affecting the cost of electricity that are not included in the type I experience curves. An obvious solution would be to use the type II experience curve. However, in reality it may be very difficult to obtain accurate data for cumulative electricity production. Electricity companies often aggregate the total number of kWh hours produced by wind turbines, and do not take into account the installation of new wind turbines during the year, thus making the available data rather unreliable [Dannemand Andersen, 2000].
Another possibility to estimate average electricity production is by taking the cumulative capacity and multiplying it by a (constant) capacity factor. However, in that case there is effectively no difference between type I and II, and the additional learning effects is not included. Even if a gradual increase in capacity factor were assumed, this would introduce a serious error. On the other hand, in most countries reliable data is available on the amount of cumulative capacity installed. Thus, using a type III experience curve may lead to more accurate results.

Still, for both type II and III the question remains how the costs per kWh are calculated. This can be done by using the installation costs of a wind turbine and estimated average wind speeds, O&M costs, life time and interest rate. In this case however, the additional experience benefits mentioned above are again basically disregarded. Another option is to survey the actual electricity production costs that are experienced every year by the operators of wind turbines. This method is rather laborious, as many operators have to be surveyed, and not all operators are always willing to reveal their costs [Dannemand Andersen, 2000].

The bottom line is that type I and II are sound in regard to the methodology. However, the type-I curve cannot ideally be used to forecast the development of decline in electricity costs. Type II might be able to do this, but may only be used within due to lack of accurate data. While type III may not be suitable to compare wind energy technology to other technology types, it may yet be helpful to forecast future cost per kWh developments (in case the exact amount of cumulative electricity produced is not known).

It can be questioned if the costs per kWh should be related to the performance of the total system to one of its subsystems. On the other hand, without any additional turbines, no additional electricity is produced[9]. In the end, it would seem that the quality of the data used is a major factor influencing the quality of the correlation found for any type of experience curve, disregarding whether the goal is to compare technologies, or to forecast future cost developments. Thus, it is the opinion of the author that in case a historic type-III experience curve can be devised with a high correlation, this curve can be used for future predictions.

Even more important, progress ratio's from one type of experience curve cannot be directly compared with another type of experience curve, even if on one axis of both graphs the same unit is used (e.g. type I and III). As explained above, the learning rate measuring the costs of electricity is in theory always higher than the corresponding learning rates of ‘costs of installed capacity’ experience curves. Therefore, there is little use in comparing a type-I curve with a type-II or type-III curve. Discussing a 'general learning rate for wind energy technology' is of little value if it is not specified to which experience curve type it applies.

[9] This is valid, unless existing turbines are moved to sites with higher wind speeds. However this seems not to be common practice.

4.2 Limitations of historic experience curves for future predictions

4.2.1 Limitations due to country-based differences

When comparing different historic experience curves in chapter 3.1, it is noteworthy that for both the type I and the type II experience curves, the US generally achieve higher learning rates (lower progress ratios) than European countries. However, it is possible that these country-based differences depend strongly on whether the wind turbines are produced in the same country or imported from elsewhere, as the following two cases will show.

First, a closer look is taken at the 'type I' experience curves. In the US apparently a lower PR is observed (85.7%) [Mackay & Probert, 1998] than in most Danish studies (85-92%). However, it is noted that in the Danish experience curves, all wind turbines *produced* are given, while in the US all capacity *installed* is given. There is a significant difference between learning curves based on turbines *produced* (as in the studies of Neij) and turbines *installed* (as in the study of Mackay & Probert) in a country, as the following hypothetical example will show.

It is assumed that the progress ratio in e.g. Denmark is 92%. At first, a large part of the in Denmark produced wind turbines are exported and installed in the US. For example before 1986, 60% of all wind turbines installed in the US came from European manufacturers, mainly Denmark ([EWEA, 1999b], [Neij 1999]). In this case it is assumed that in a first stage 60% of the Danish production is exported to the US. However, as a consequence of influences such as a market decline in the US or exchange rate fluctuations unfavorable for Danish exports, it is assumed that exports drop from 60% in stage 1 to 20-25% of the total Danish production in stage 4-5. However, the prices in Denmark and the US remain the same. Based on the last two columns of Table 4.1, an 'apparent progress ratio' of 88.2% (r^2=0.994) can be calculated for the US, while the actual Danish progress ratio remains 92%.

Table 4.1 Hypothetical example of calculating 'apparent' progress ratios

Stage	Denmark Additional produced capacity (MW)	Cumulative production (MW)	Price level (US$ / kW) at PR=92%	US Imported from Denmark (MW) / % of added Danish capacity	Cumulative capacity (MW)	Price level (US$ / kW)
1	-	1000	1000	600 (60%)	600	1000
2	1000	2000	920	500 (50%)	1100	920
3	2000	4000	846	500 (25%)	1600	846
4	4000	8000	779	800 (20%)	2400	779
5	8000	16000	716	1600 (20%)	3900	716

Of course this is only a very simplistic example. In reality the changes in exchange rate between the Danish Crone and the US$ and inflation rates in both countries also plays an important role, but are ignored in this case. Also the installation of wind turbines produced in the US is neglected[10].

[10] Due to constrains in time and available data, it would extend the frame of this paper to use real data for this example. It would be a very interesting exercise to analyze how these relationships really changed in the past.

The fact however remains, that about 90% of medium- and large-sized wind turbines installed in the US in 1994 were produced in Europe [Mackay & Probert, 1998] and also today the US still import approximately 55% of their annual added capacity[11], mainly from Denmark [AWEA, 2000b]. Thus, due to the fact that the US still import a large percentage of their wind turbines, it is questionable in how far experience curves based on wind turbines installed in the US actually indicate the speed of technology development.

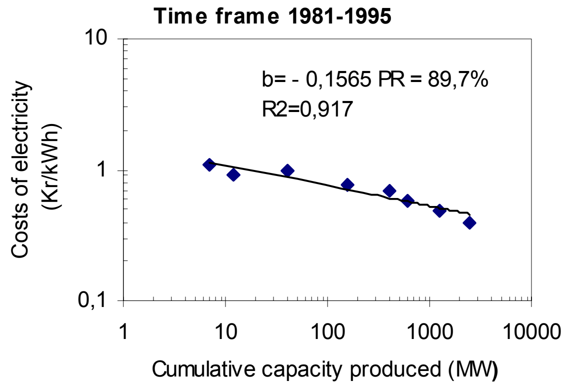
As a second case, the type-II experience curves are examined. In literature, only two type-II experience curves were found: one for Europe and one for the US. As in the previous case, they reveal a difference in progress ratio between Europe and the US (82% vs. 68%). Again the lower progress ratio can be explained by the fact that the US import a large part of their capacity from Europe. In the beginning, American wind turbines had a much lower capacity factor than the European ones, and could probably profit from the experience gained previously in Europe. However, at the end of both curves the capacity factor is about equal in both curves [IEA, 2000].

The conclusion from both cases is, that the PR calculated for countries such as the US may strongly depend on the export volume from other countries. It is therefore questionable if the American progress ratio can be maintained in the future, if for example imports strongly decrease.
In general, the question arises whether a learning curve based on national production or installation can be used for long-term predictions for the same country or even for a global forecast (which is the case in all studies presented in chapter 3.2).

4.2.2. Dependence on changes in the market

As pointed out in chapter 2, the progress ratio's can be influenced by a serious market distortion. In- or excluding this depends on the time frame chosen. An example is the study of [Dannemand Andersen & Fuglsang, 1996], which assumes a progress ratio of roughly 80% for a 'normal global market situation' (e.g. the time frame from 1986-1995) for a type III experience curve. For time period 1983-1985 (during 'California boom phenomenon'[12]) progress ratios between 90-103% are found.
Neij [Neij 1997] finds a progress ratio of 91% for the time frame 1980-1991 based on the data of Dannemand Andersen & Fuglsang.
To clarify the differences between these progress ratios, two calculations were performed based on the data given by Dannemand Andersen & Fuglsang. When calculating a progress ratio for the whole time period of 1981-1995, a progress ratio of 89.7% is obtained. When calculating the progress ratio for the period 1985-1995, (excluding the 'California boom phenomenon'), a progress ratio of 82.2% is obtained (see figure 4.2 and 4.3).

[11] These numbers exclude first generation California wind projects from the early 1980s that were repowered with new technology.
[12] From 1981-1985 more than 95% of the world's new wind turbines were installed in California. In addition to the federate tax incentive of 25% of wind turbine cost, California provided a 25% capital tax write-off which totaled half of a project's capital cost. Installations fell off after 1985 because the tax incentive was strongly reduced. The industry received large incentives in a short period of time such that installed capacity increased in a rapid rate. Technology developers were unable to improve designs and decrease costs fast enough to entice continued market growth at the same rate as with the subsidy. Adapted from [Cory et al, 1999].



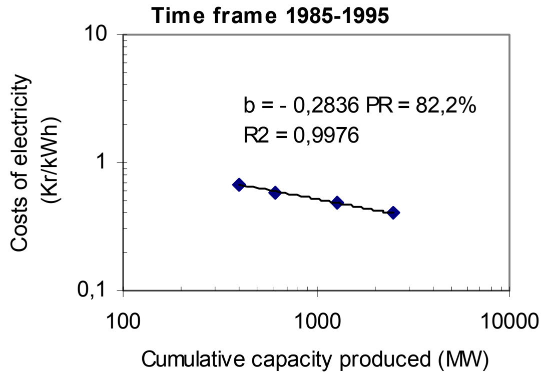


Figure 4.2 and Figure 4.3

Two experience curves based on sales by the Danish wind turbine industry (data from [Dannemand Andersen & Fuglsang, 1996]). All costs are based on 1995 Danish Kr. Figure 4.3 basically only consists of the last four data points from Figure 4.2. The number of cumulative doublings is 8.5 in Figure 4.2 and 2.7 in Figure 4.3

It is clear that in- or excluding the period between 1983-85 has a rather large impact on the resulting progress ratio. The question arises if and how these market fluctuations should be handled.
One can argue, that during the Californian wind rush the global wind turbine market clearly was not stable, and in fact there was no time and no incentive to lower costs. The market has been reasonably stable since 1986.
On the other hand, in the period of 1986-1995 only 2.7 cumulative doublings of the produced capacity against 8.5 doublings over the whole time frame of 1981-1995.
It is assumed that the Californian tax incentives worked similar as a price umbrella described in chapter 2. In this case, not a single company but a government influenced the cost per unit using a strong deployment policy. This seriously distorted market prices, and thus the author believes that in this case indeed the data from this time period should not be used for an experience curve. This is also recommended by Neij [Neij, 1999]. However, due to the limited number of cumulative doublings, this experience curve should not be used to make forecasts for a large number of cumulative doublings.

This is an example, how in reality changes in the market circumstances can influence the progress ratio, and that by choosing different time frames, progress ratios can significantly differ (which should of course not be the case in an ideal stable market).

4.2.3 Dependence on the assumed added capacity

When making a prediction for the future development of wind power, next to a progress ratio, another important assumption has to be made: the expected growth in capacity. As mentioned in chapter 2, the experience curve does not in any way indicate *when* or how often the next cumulative doubling of the capacity will occur. As was shown in chapter 3.2, assumptions on the global capacity increase vary widely, up to over a factor 10, depending on the chosen approach.

This brings up another difficulty when forecasting the expected drop in costs for a region that will be illustrated by the two MARKAL models compared in Table 3.3. Both models use very similar progress ratios (89% and 90% respectively). The global model forecasts a cumulative doubling of nine times until 2050, with an accompanying decrease in costs of 65%. In the

European model, in the same time frame a cumulative doubling of six times is assumed, with an accompanying decrease in costs of only 47%. However, in regard to the global model it is questionable whether this estimate is not too pessimistic.
In general, it would seem that in order to make prediction for a cost decline (both for a region or globally) the global installed capacity should be taken into account.

4.3 Limitations of using experience curves for offshore wind turbines

When discussing the global wind potential and the future share of wind power in the electricity sector, next to onshore wind turbines also the offshore potential should be included. Currently only a few pilot projects are in place, but expectations are that offshore wind farms may significantly contribute to the total of (worldwide) electricity production.
There is no doubt that offshore wind farms fall under the category ‘renewable wind-energy’ and should be included for forecasts predicting the future of wind energy. However, it is doubtful whether historical experience curves and learning rates based on onshore wind turbines can simply be used to forecast the development of offshore-wind turbines.
Again a difference will have to be made between type-I experience curves which describe the development of the investment costs, while type-II and type-III curves describe the development of the cost of wind-generated electricity. At this time, there is little known about offshore wind power costs, as only few pilot offshore wind farms currently exist in Denmark and The Netherlands. However, estimates exist on the future development:

- Offshore installation work is 5-10 times more expensive than on land, and reduction on installation and maintenance effort is essential in order to commercialize offshore wind electricity generation. [Kühn & Bierbooms, 1998]
- All studies expect that average offshore wind turbines will reach sizes far beyond the current maximum size of onshore wind turbines of 1 – 1.5 MW. Expectations vary between 3-5 MW [Kühn & Bierbooms, 1998], [de Noord, 1999].
- Investment costs of offshore wind-turbines vary significantly from onshore wind turbines. While for a onshore turbine the turbine purchase itself accounts for approximately 75%, this is estimated to be only 26% for an offshore wind turbine. Other major contributors are electrical infrastructure purchase (30%), foundation installation (26%) and foundation purchase (14%) [de Noord, 1999].

From these predictions, is seems clear that the existing experience curves cannot simply be applied. When using a type-I curve, only 25% instead of 75% of the total investment costs would be covered. Additional experience curves describing the decline in costs for foundations and electricity infrastructure would then also be required. But even for the 25%, it remains questionable whether the same learning rate applies. The wind turbine may have to fulfill different requirements than onshore-turbines. For example, offshore wind turbines may have to resist extreme wind speeds (e.g. during a major storm) than onshore (inland) turbines, while another demand may be that no major malfunctions may occur during the lifetime of the wind turbine. Furthermore, the average wind speed will be higher than on land, which may require different shapes and materials for the wind turbine blades.
For experience curves forecasting the cost of electricity, the factors mentioned before may also have a decisive influence on the costs per kWh. Depending on the speed with which for examples the foundation list prices and installation costs will decrease, the annuity and thus the costs per kWh may also decrease differently than those compared to onshore turbines.

In summary, existing experience curves can only partially be used to forecast investment cost developments for offshore wind turbines. Further development will show whether offshore wind turbines will have to be considered a separate technology or if they will remain similar to onshore turbines. In terms of electricity costs, even less can be said on costs reductions, as too many variables are unknown yet. Thus, it is the opinion of the author that existing experience curves and corresponding learning rates cannot simply be adopted from historic onshore experience curves.

Chapter 5 Recommendations for using experience curves for future predictions

In this chapter, recommendations are given on how experience curves may be used to predict future developments in the wind energy sector, and which limitations and precautions should be taken in order to deal with the inevitable uncertainty of predictions.

5.1 Global and regional forecasts

From the examples in paragraph 4.2.1, 4.2.2 and 4.2.3 it has been shown that using experience curves based on a single country may include many difficulties and uncertainties. In order to be able to determine learning rates, it is less relevant to analyze on a country-basis, but rather on a global industry / manufacturer basis.

When trying to forecast global wind energy development, it is therefore suggested to construct a global experience curve. Due to limited data availability this would probably be limited to a type I experience curve. This would mean that the learning system would no longer be limited to a geographical region.
A number of arguments justify this idea. For example in 1999, wind projects were known in over 50 countries on all seven continents. Also by assessing data from the thirteen biggest wind turbine manufacturers in the world, about 84% of the world's annual added capacity can be included. These manufacturers are situated in six countries: Denmark, Germany, the US, India, Japan and the Netherlands [EWEA, 1999b]. In conclusion it can be stated that there is a well-developed global market. In addition, the number of countries were wind turbines are installed is still increasing. Even if a single country would stimulate a similar development as the Californian wind rush, it would probably affect the global market less than twenty years ago, as the total added annual capacity does not so much depend on a single country. However, there is of course no guarantee that no market distortions may occur in the future. It is therefor a recommendation for further research whether a global experience curve should be based on data originating only after 1985, or also should include data from the 'California wind rush'. Also, changing exchange rates and different inflation rates in different countries may introduces a wider range in e.g. wind turbine prices, but these difficulties cannot be avoided.

When making forecasts for a region, this approach should be more differentiated. For example, the trend in western countries is clearly to install wind turbines with strongly increasing size. However, in developing countries, this may not be the case. For example rural electrification projects do generally not require large capacities but may require smaller wind turbines that can be more easily repaired in case of malfunction and may still satisfy the local electricity demand. In such a case, it is more useful to analyze which manufacturers have supplied wind turbines to the specific region, and use their experience curves.
Still the problem remains that outside the region considered also wind turbines will be installed which will influence the drop in costs.

5.2 Devising a forecast

As discussed above, there are a number of uncertainties involved when using experience curves in order to make prediction for the future. This uncertainty is unavoidable, but this is not necessarily a problem, if properly dealt with. The author suggests the following procedure to assess the uncertainty in a forecast:

1. As a first step, it is suggested to analyze the primary data used in the historical experience curve: for example how aggregated they are and what the standard deviation and maximum ranges for each data point are. Also, it should be checked if within the time frame of the historical experience curve any major market distortions occurred. If this is the case, possibly the data of the particular time frame should not be used for calculating a progress ratio.
2. From the historic experience curve, a 95% uncertainty interval for the learning index b should be calculated. By doing so, a minimum and maximum value for b and thus for the progress ratio is obtained. When using an experience curve with a high correlation-coefficient (R^2 close to 1.00) these intervals will be smaller than when using experience curves with a correlation of less quality (e.g. R^2 =0.90).
3. As a third step, estimates should be made for future growth of installed wind capacity. These may be based on scenarios (e.g. reaching policy goals of the EU) or by extrapolating current growth rates. Independent of how this is done, a worst-case and best case should be formulated in comparison with a best guess / reference case in order to account for the uncertainty in these estimates.
4. Next, take a look at the calculated maximum number of cumulative doublings (n). As a somewhat arbitrary rule of thumb, it is suggested that the calculated maximum number of cumulative doublings (n) should not be higher than the number of cumulative doublings in the historic experience curve. If this is the case, either reduce the time frame of the prediction, or remark this fact in a discussion.
5. Finally, the highest progress ratio (lowest learning rate) should be combined with the lowest estimated of additional capacity, and vice versa. By doing so, a worst-case and best-case estimate is calculated next to the ‘best guess’. (See also [Ybema et al, 1999] for a similar approach).

By following this procedure, a reasonable estimate is given on how the wind energy sector in a certain region may develop. By using the ranges determined in step 5, policy makers should be made aware of the extent of the uncertainties that are inevitably attached to a forecast. Again, it is emphasized that this procedure is solely based on the limitations that were found in chapter 4. They are open for discussion, and no claim for general validity is made. Further research is needed in order to support and strengthen these recommendations (e.g. the rule of thumb mentioned in step 4).

5.3 Further recommendations

A number of other recommendations can be made for further research:

- It seems that the experience curves for the Danish wind turbine manufacturer industry represent the best indication for the actual learning rate for ‘type-I’ experience curves, as they represent almost 50% of the global annual added capacity, and they analyze the amount of capacity produced (not installed). However, analysis of this industry by different authors reveals progress ratios between 85-92%. It would be interesting to investigate the reasons why these progress ratios vary strongly. In particular, the quality of data used in the different studies should carefully be analyzed.

- As already pointed out, it would also be interesting to investigate in how far the example sketched in section 4.2.1 for the US and Denmark does actually correspond to the real situation.

- Further research is recommended on the type-III experience curve, and whether relating costs of electricity to cumulative added capacity can be justified (either by extending the theoretical framework, or by a high correlation in practice).

- The different components for offshore wind turbine systems (the turbine, foundations and electricity infrastructure) may each contribute significantly to lowering the costs of electricity. Monitoring the cost development for these components and devising separate experience curves may be helpful to forecast the future of offshore wind energy.

- As described in Chapter 2, it is still a point of discussion whether or not a change in learning rate will occur due to a 'phase transition'. This issue still remains open to the author. Therefore, it was not discussed whether the learning rate found for e.g. the Danish wind turbine manufacturer industry *will* or *will not* decline in time. In case it is assumed that such a decrease in learning rate *does* occur, it would be interesting to analyze at which cumulative production level this would be likely to occur.

References

[Abernathy & Wayne, 1982]
W.J. Abernathy, K Wayne, *Limits of the learning curve*, in: Reading in the management of innovation. M.K. Tushman and W.L. Moore (eds.) Ballinger Publishing Company, 1982.

[Argote & Epple, 1990]
L. Argote, D. Epple, *Learning Curves in Manufacturing*, Science Vol. 247, pp. 920-924 February 1990.

[AWEA, 2000a]
American Wind Energy Association, *Global Wind Energy Market report 1999,* Available at: http://www.awea.org/faq/global99.html

[AWEA, 2000b]
Personal communication with R. Swisher, American Wind Energy Association, October 2000.

[Badiru, 1992]
A.B. Badiru, *Computational survey of univariate and multivariate learning curve models*, Engineering management, May 1992, Volume 39, Number 2, pp. 176-188.

[BCG, 1968]
Boston Consulting Group, *Perspectives on experience*, Boston Consulting Group Inc., 1968.

[BLS, 2000]
Bureau of Labor Statistics, Consumer Price Index Inflation Calculator. Available at: http://www.bls.gov

[BTM, 1998]
BTM Consult ApS, *Summary of 'global 10%',* October 1998. Available at: http://www.btm.dk/Articles/fed-global/fed-global.htm

[Chapman & Wiese, 1998]
J. Chapman, S. Wiese, *Expanding Wind Power: Can Americans afford it?*, Renewable Energy Policy Project Research Report Nr. 6, November 1998.

[Christiansson, 1995]
L. Christiansson, *Diffusion and Learning Curves of Renewable Energy Technologies,* WP-95-126, International Institute for Applied Systems Analysis, December 1995.

[Cory at al., 1999]
K.S. Cory, S. Bernow, W. Dougherty, S. Kartha, E. Williams, *Analysis of wind turbine cost reductions: the role of research and development and cumulative production,* Presented at: AWEA's Windpower '99 Conference, Burlington, VT, June 22, 1999.

[Dannemand Andersen, 1999]
P. Dannemand Andersen, *Global perspectives for wind power,* Presented at “Wind energy for the next Millenium”, the European Wind Energy Conference and Exhibition, March 1 – 5, Acropolis Convention Centre, Nice, France, 1999.

[Dannemand Andersen, 2000]
Personal communication with P. Dannemand Andersen, Head of Technology Scenarios Research Programme, System Analysis Department, Risø National Laboratory, October 2000.

[Dannemand Andersen & Fuglsang, 1996]
P. Dannemand Andersen, P. Fuglsang, *Vurdering af udviklingsforlob for vindkraftteknologien,* (Estimation of the future advances of wind power technology), Risø -R-829 (D), Forskningscenter Risø, Roskilde, Denmark, March 1996.

[DS, 1999]
Danmarks Statistics, *Main indicators*. Available at: http://www2.dst.dk/internet/k16/konjunktur/kon98_2.htm

[Durstewitz & Hoppe-Kilpper, 1999]
M. Durstewitz, M. Hoppe-Kilpper, *Wind Energy Experience Curve from the German "250 MW Wind"-Programme*, Proceedings IEA International Workshop on Experience Curves for Policy Making -the case of energy technologies. Stuttgart, Germany, 10-11 May 1999, Stuttgart, Germany. Available at: http://reisi.iset.uni-kassel.de/reisi/owa/www_page.show?p_name=134017&p_lang=eng

[Dutton & Thomas, 1984]
J.M. Dutton, A. Thomas, *Treating progress functions as a managerial opportunity* , Acad. Manage. Rev, Vol. 9, 235, 1984.

[DWTMA, 2000]
Danish wind turbine manufacturers association. *Danish Wind Energy in 1999: Danish Wind Turbine Manufacturing Sextuples in Five Years*. Available at: http://www.windpower.dk/news/stat1999.htm

[EWEA, 1999a]
Wind Force 10, A blueprint to achieve 10% of the world's electricity from wind power by 2020, European Wind Energy Association, 1999.

[EWEA, 1999b]
European Wind Energy Association. *Wind Energy, the facts, A plan for action in Europe,* 1999.

[Grübler, 1998]
A. Grübler, *Technology and global change*, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1998, pp. 81-86.

[IEA, 2000]
International Energy Agency, *Experience curves for energy technology policy,* OECD/ IEA, 2000.

[Kühn & Bierbooms, 1998]
M. Kühn, W. Bierbooms, *Offshore Wind Energy – A future market under rapid development,* Delft University of Technology, Institut for Wind Energy, Delft, The Netherlands, 1998. Available at: http://www.nemesis.at/publication/gpi_98_2/articles/56.html

[Kydes, 1999]
A.S. Kydes, *Modeling Technology learning in the National Energy Modeling System*, Energy Information Administration / Issues in Midterm Analysis and Forecasting 1999.

[Lund, 1995]
P.D. Lund, *An improved market penetration model for wind energy technology forecasting*, Helsinki University of Technology, Advanced Energy Systems. Presented at the EWEA special topic conference, The economics of wind energy, 5-7 September 1995, Finland.

[Mackay & Probert, 1998]
R.M. Mackay, S.D. Probert, *Likely Market-penetration of Renewable-energy Technologies*, Applied Energy, Vol.59. No 1. pp. 1-38, 1998.

[Madsen, 1999]
B.T. Madsen, *Bringing down the cost of wind*, Windstats newsletter, Vol 12, No. 3, 1999, pp.6-8.

[Milborrow, 1999]
D. Milborrow, *Wind has plenty in reserve in competitive cost stakes*, Windpower monthly, February 1999.

[Neij, 1999]
L. Neij, *Cost dynamics of wind power*, Energy, Vol. 24, pp. 375-389, 1999.

[Neij, 1997]
L. Neij, *Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology*, Energy Policy, Vol 23, No.13, pp.1099-1107, 1997.

[de Noord, 1999]
M. de Noord, *Large-scale offshore wind energy. Cost analysis and integration in the Dutch electricity market*. ECN Netherlands Energy Research Foundation, ECN-I—99-003, February 1999.

[Oanda, 2000]
Oanda Currency Converter, 2000. Available at:
http://www.oanda.com/convert/classic/

[Seebregts et al., 1998]
A.J. Seebregts, T. Kram, G.J. Schaeffer, A. Stoffer, *Endogenous technological learning: experiments with MARKAL*, Contribution to Task 2.3 of the EU-TEEM Project. ECN Netherlands Energy Research Foundation, ECN-C--98—064, December 1998.

[Seebregts et al., 1999]
A.J. Seebregts, T. Kram, G.J. Schaeffer, A. Stoffer, S. Kypreos, L. Barreto, S. Messner, L. Schrattenholzer, *Endogenous technological change in energy system models, Synthesis of Experience with ERIS, MARKAL and MESSAGE*, ECN Netherlands Energy Research Foundation, ECN-C--99—025, 1999.

[Watanabe, 1999]
C. Watanabe, *Industrial Dynamism and the Creation of a 'Virtuous Cycle' between R&D, market growth and price reduction - the case of photovoltaic power generation (PV) Development in Japan*, Presented at the IEA Workshop on experience curves for policy making - the case of energy technologies, 10-11 May 1999, Stuttgart, Germany.

[Wene, 1999]
C.O. Wene, *Stimulating Learning Investments through the 250 MW Wind Programme*, International Energy Agency, on leave of absence from Chalmers University of Technology, Göteborg, Sweden, 1999.

[Ybema et al., 1999]
J.R. Ybema, P. Kroon, T.J. de Lange, G.J. Ruijg, *De bijdrage van duurzame energie in Nederland tot 2020* (The contribution of renewable energy in the Netherlands until 2020), ECN Netherlands Energy Research Foundation, ECN-C--99—053, September 1999.

Appendix A Conversion of cost data into 1997 US dollars

The following steps are undertaken to convert different currencies of different years into US dollars of 1997.

1. The foreign currency is converted into the same currency with the year 1997 as base year.
2. With the exchange rate of this currency of 1997, this currency is converted into 1997 dollars

For the exchange rate of various currencies in 1997, data was used from the Oanda currency web site [Oanda, 2000]. Inflation correction for studies in the US was based on the average Consumer Price Indexes, Bureau of Labor Statistics [BLS, 2000]. Inflation correction for Denmark was based on a publication of Danmarks Statistics [DS, 1999].

Appendix B Discussion of the study 'Wind Force 10'

One of the most detailed forecasts found in literature was the study 'Wind Force 10, a blueprint to achieve 10% of the world's electricity from wind power by 2020' [EWEA, 1999a]. In this study, the authors use the experience curve concept. However this approach differs significantly from the other studies described in chapter 3.2. The application of the experience curve theory in this study is highly questionable, as will be discussed below.

The authors make use of the study of Dannemand Andersen & Fuglsang [Dannemand Andersen & Fuglsang, 1996], and mention that 'studies of the past development of the wind power industry show that progress through R&D effort and by learning result in progress ratios of 0.85-0.8'. Dannemand Andersen & Fuglsang actually report, that the progress ratio is approximately 80% for a type-III curve. For a type-I curve, they quote Lund with 85% [Lund, 1995].
However, the authors of 'Wind Force 10' choose to apply a progress ratio of 85% for a type-IV experience curve, were the costs/kWh are set against the cumulative number of wind turbines (see Figure B1) [13].

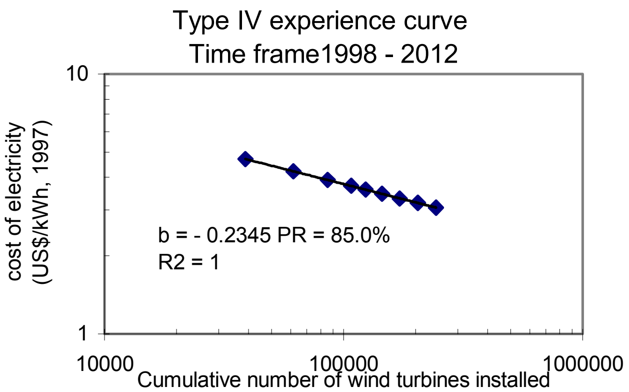


Figure B1 Type IV- experience curve based on the data given in [EWEA, 1999a]

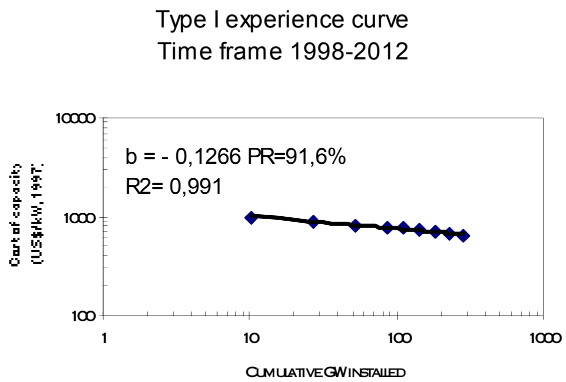
In order to correct for the increasing size of wind turbines, rather arbitrary estimates are given how the average wind turbines size will increase in time (varying from 0.7 MW in 1999 to 1.5 MW in 2020 and 2.0 MW in 2040). Based on this data, also the annual assumed additional added capacity is given. In addition, the costs / kW capacity are given per year. In order to estimate costs / kWh, again (rather arbitrary) estimates for the capacity factor are made. Based on this data from the 'Wind Force 10'-report, a type I and a type III experience curve were constructed (see Figure B2 and B3)

Remarkably, for both the type I and type III curve the identical progress ratio of 91.6% was found. This reveals two errors in the forecast of 'Wind Force 10':

- By applying a progress ratio of 85% from a type-I experience curve for a type IV-curve, actually a progress ratio of 91.6% for the type-I curve was used. In other words, the technological learning rate for the wind turbines (capacity) is much lower in the forecast than was found on basis of the historic reference curve given by Lund.

[13] This progress ratio is maintained from 1998-2012. It later increases gradually up to 100% in 2032. In fact, in the period of 2032-2040 of this study, no learning at all is assumed .

- Furthermore, this approach leads to identical progress ratios for type I and type III experience curves. As discussed in chapter 4.1.2, the progress ratio of a type III curve should theoretically be lower than the one of a type I curve. In other words, the cost decrease for electricity for every doubling of installed capacity is also much lower in the forecast (8.4%) than the historic one given by Dannemand Andersen & Fuglsang (20%).



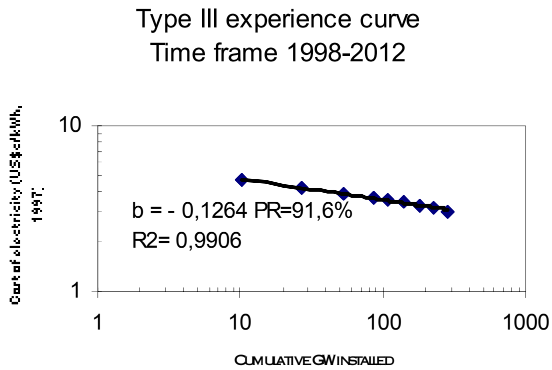


Figure B2 and B3 Type I and Type III- experience curve based on the data given in [EWEA, 1999a].

The reason why yet the lowest costs per kWh are achieved in 2020 (compared to all other studies described in chapter 3.2) is the assumed strong increase in annual capacity, which is necessary in order to achieve 10% of the worlds electricity supply in 2020.

This study is an example, how questionable use of the experience curve concept and progress ratios can cause major uncertainties in future forecasts.

Appendix C Notations and equations

a	learning cost at Cum=1
b	learning index (constant)
C	Cost per unit
C_0	Initial specific cost (at t=0), equals $a*Cum_0^b$
C_{min}	The minimum price given for the maximum cumulative production
Cum	Cumulative (unit) production
Cum_0	Initial cumulative unit production (at t=0)
LR	Learning rate
n	The (assumed) maximum number of times the cumulative production will double
PR	Progress ratio

I	The costs per kW vs. the cumulative number of kW installed/produced
II	The costs per kWh vs. the cumulative number of kWh produced
III	The costs per kWh vs. the cumulative number of kW installed/produced
IV	The costs per kWh vs. the cumulative number of wind turbine units installed/produced

$$C(Cum) = a * Cum^b \quad (1)$$
$$\log (C(Cum)) = \log a + b \log Cum \quad (2)$$
$$PR = 2^b \quad (3)$$
$$LR = 1- 2^b \quad (4)$$
$$C_{min} = PR^n * C_0 \quad (5)$$