CLIMATE CHANGE

SCIENTIFIC ASSESSMENT AND POLICY ANALYSIS

Technological learning in the energy sector

Report

500102 017
NWS-E-2008-14
ECN-E--08-034

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April 2008

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This study has been performed within the framework of the Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change (WAB), project 'Technological learning in the energy sector'

Wetenschappelijke Assessment en Beleidsanalyse (WAB) Klimaatverandering

Het programma Wetenschappelijke Assessment en Beleidsanalyse Klimaatverandering in opdracht van het ministerie van VROM heeft tot doel:

- Het bijeenbrengen en evalueren van relevante wetenschappelijke informatie ten behoeve van beleidsontwikkeling en besluitvorming op het terrein van klimaatverandering;
- Het analyseren van voornemens en besluiten in het kader van de internationale klimaatonderhandelingen op hun consequenties.

De analyses en assessments beogen een gebalanceerde beoordeling te geven van de stand van de kennis ten behoeve van de onderbouwing van beleidsmatige keuzes. De activiteiten hebben een looptijd van enkele maanden tot maximaal ca. een jaar, afhankelijk van de complexiteit en de urgentie van de beleidsvraag. Per onderwerp wordt een assessment team samengesteld bestaande uit de beste Nederlandse en zonodig buitenlandse experts. Het gaat om incidenteel en additioneel gefinancierde werkzaamheden, te onderscheiden van de reguliere, structureel gefinancierde activiteiten van de deelnemers van het consortium op het gebied van klimaatonderzoek. Er dient steeds te worden uitgegaan van de actuele stand der wetenschap. Doelgroepen zijn de NMP-departementen, met VROM in een coördinerende rol, maar tevens maatschappelijke groeperingen die een belangrijke rol spelen bij de besluitvorming over en uitvoering van het klimaatbeleid. De verantwoordelijkheid voor de uitvoering berust bij een consortium bestaande uit PBL, KNMI, CCB Wageningen-UR, ECN, Vrije Universiteit/CCVUA, UM/ICIS en UU/Copernicus Instituut. Het MNP is hoofdaannemer en fungeert als voorzitter van de Stuurgroep.

Scientific Assessment and Policy Analysis (WAB) Climate Change

The Netherlands Programme on Scientific Assessment and Policy Analysis Climate Change (WAB) has the following objectives:

- Collection and evaluation of relevant scientific information for policy development and decision-making in the field of climate change;
- Analysis of resolutions and decisions in the framework of international climate negotiations and their implications.

WAB conducts analyses and assessments intended for a balanced evaluation of the state-of-the-art for underpinning policy choices. These analyses and assessment activities are carried out in periods of several months to a maximum of one year, depending on the complexity and the urgency of the policy issue. Assessment teams organised to handle the various topics consist of the best Dutch experts in their fields. Teams work on incidental and additionally financed activities, as opposed to the regular, structurally financed activities of the climate research consortium. The work should reflect the current state of science on the relevant topic.

The main commissioning bodies are the National Environmental Policy Plan departments, with the Ministry of Housing, Spatial Planning and the Environment assuming a coordinating role. Work is also commissioned by organisations in society playing an important role in the decision-making process concerned with and the implementation of the climate policy. A consortium consisting of the Netherlands Environmental Assessment Agency (PBL), the Royal Dutch Meteorological Institute, the Climate Change and Biosphere Research Centre (CCB) of Wageningen University and Research Centre (WUR), the Energy research Centre of the Netherlands (ECN), the Netherlands Research Programme on Climate Change Centre at the VU University of Amsterdam (CCVUA), the International Centre for Integrative Studies of the University of Maastricht (UM/ICIS) and the Copernicus Institute at Utrecht University (UU) is responsible for the implementation. PBL, as the main contracting body, is chairing the Steering Committee.

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This report in pdf-format is available at www.pbl.nl

Preface

This report was commissioned by the Netherlands Programme on Scientific Assessment and Policy Analysis (WAB) Climate Change. This report has been written by the Science, Technology and Society department (NWS) at Utrecht University, and the Energy research Centre of the Netherlands ECN, as a deliverable in the WAB project ‘Technological learning in the energy sector’.

The authors would like to thank the external reviewers Lena Neij and Gerrit-Jan Schaeffer for constructive comments and significant contributions to this report. In addition, we would like to thank all participants of the policy workshop of 24 January 2008 and especially Klaas-Jan Koops, Reinier Gerrits and René Moor for their comments and input. Roald Suurs is acknowledged for his valuable additions to the systems innovation theory section. Last but not least we would like to thank Erik ten Elshof and Frans Duijnhouwer for their guidance and feedback during the course of this project.

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Executive Summary

Introduction and aims

Technology learning is a key driver behind the improvement of (energy) technologies available to mankind and subsequent reduction of production costs. Many of the conventional technologies in use today have already been continuously improved over decades, sometimes even a century, for example coal-fired power plants. In contrast, many renewable / clean fossil fuel energy technologies and energy saving technologies still have higher production costs, but lower fuel demands and GHG emissions. As most of these technologies are still quite young, their technological development and resulting cost reduction occur at relatively high speeds compared to the conventional technologies. It is thus anticipated that in many cases the gap between conventional and new technologies can be closed, i.e. a break-even point be reached. Crucial questions are however, whether this point will be reached, and if so, when and under what circumstances (especially how this depends on policy support).

One approach to analyze both past and future production cost reduction is the experience curve approach. It has been empirically observed for many different technologies that production costs tend to decline with a fixed percentage with every doubling of the cumulative production. The progress ratio (PR) is a parameter that expresses the rate at which costs decline for every doubling of cumulative production. For example, a progress ratio of 80% equals a 20% cost decrease for each doubling of the cumulative capacity. As a rule of thumb, this cost reduction lies between 10-30% (PRs between 70-90%). The experience curve concept has been applied to (renewable) energy technologies with a varying degree of detail.

Based on a wide-ranging literature review, this study aims to provide:

- A comprehensive review of studies on technological development and cost reductions performed for a large range of energy technologies, including renewable energy technologies, (clean) fossil fuel technologies and energy efficient technologies using the experience curve concept.
- An overview and thorough analysis / discussion of the pitfalls of applying the experience curve approach, based on the issues identified in the various technology studies, and including aspects such as geographical system boundaries, whether the slope of the experience curves is constant or not, statistical error and sensitivity analysis of experience curves, and whether the experience curve approach can also be utilized to quantify improvements in energy efficiency.
- A demonstration how declining production costs can also be translated in $CO_{2eq.}$ reduction costs.
- A discussion to what extent policy interventions (by measures to support ‘learning-by-searching’ and ‘learning-by-doing’) have been successful in accelerating technological learning and associated production cost reductions.

The main scope of the study is a literature review study. A limited additional effort has been made to demonstrate how declining production costs can be translated in trends for decreasing electricity and $CO_{2eq.}$ reduction costs.

Overview of experience curves for energy technologies

Historically, experience curves have been mainly devised for renewable electricity supply technologies, especially for PV and onshore wind technologies. The review also revealed numerous studies for other energy supply technologies, such as offshore wind, concentrated solar power, biomass transportation fuels, natural gas combined cycle plants, pulverized coal plants. Also for energy-efficient demand-side technologies, various studies were reviewed regarding amongst others consumer appliances such as washing machines, fridges and lighting applications, space heating technologies and production of bulk chemicals. These are all described in detail in the various parts of Chapter 3. An overview of experience curves of electricity supply technologies is presented in Figure S.1, and an experience curve for compact fluorescent lamp (CFL) bulbs in Figure S.2 (including a projection until 2020).

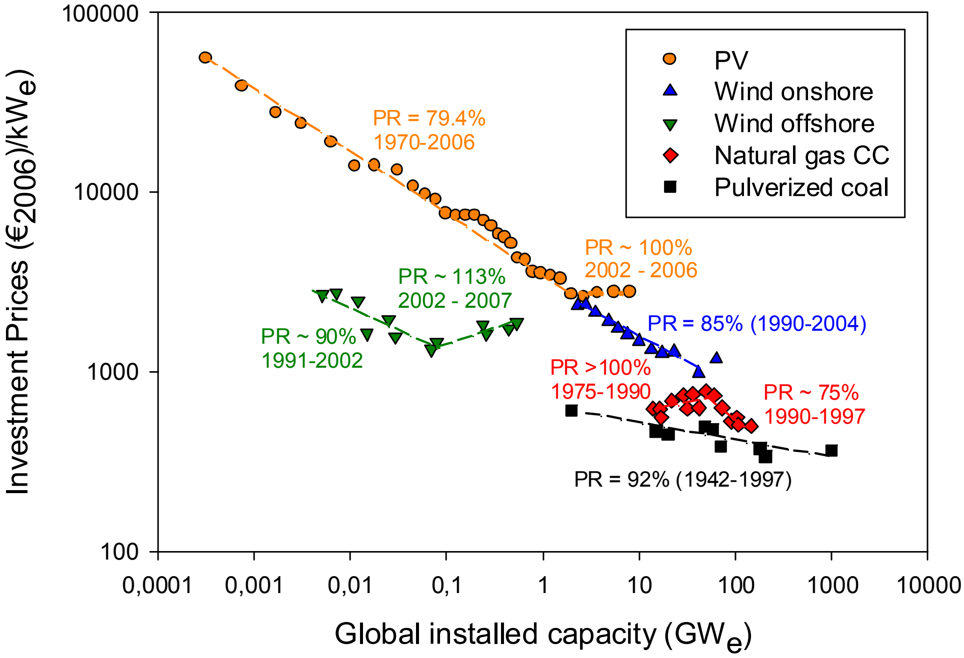

Figure S.1 Comparison of historic experience curves of energy supply technologies. Note that all (renewable) energy technologies investment prices are increasing, from 2002 onwards leading to PRs>100%. This is likely to be caused by a combination of increasing demand for these technologies, rising raw material prices, and rising prices of fossil reference technologies.Data sources: Isles (2006), Van Sark (2008b), Junginger (2005) Claeson Colpier and Cornland (2002), Rubin et al. (2006), Milborrow (2007).

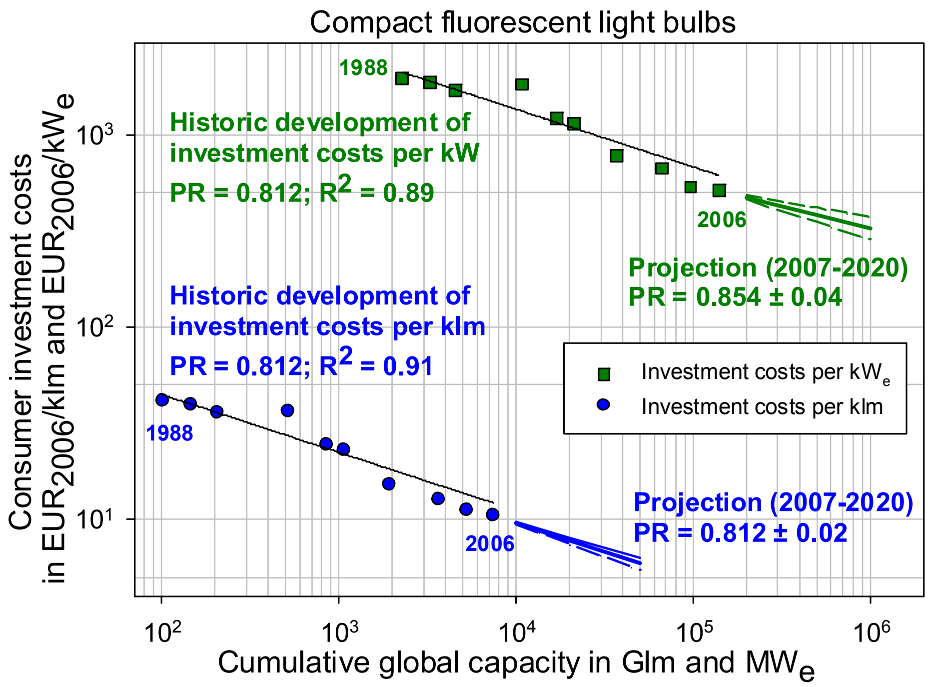

Figure S.2 Overview of historic experience curves and future cost projections until the year 2020 for compact fluorescent light bulbs; data sources: Weiss et al. (2008), Iwafune (2000)

Application of experience curves to determine learning investments

Experience curves can be used to make future projections, which allow an investigation of the development of electricity costs and the necessity of learning investments[1]. To illustrate this, we take the case of onshore and offshore wind development between 2010 and 2020, and compare them to anticipated development of carbon capture and storage (CCS) technologies[2].

As shown in figure S.3, the global support needed for learning investments (i.e. financing the difference between the electricity production costs and the baseline) in this period varies: for onshore wind it lies between 108-230 billion €, though this also depends on the chosen baseline. For offshore wind, even though the costs per kWh are higher, required learning investments between 2010-2020 on a global scale would be much lower (19-32 billion €)[3]. How much of this is to be covered by e.g. the Netherlands strongly depends on how much capacity will be installed in the Netherlands. For example, if the Dutch target of 6 GW by 2020 is to be maintained (which would represent 12% of installed capacity in 2020), learning investments would be on average 340 million €/year (ranging from 260-440 M€/year).

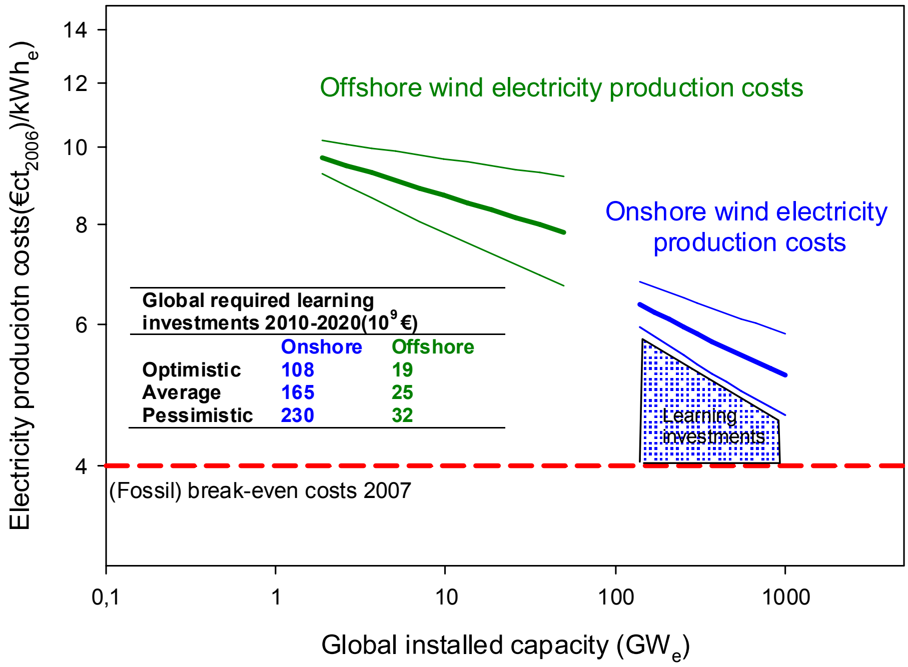

Figure S.3 Illustrative projected development of onshore and offshore wind electricity production costs between 2010 and 2020, including global learning investments and fossil reference break-even cost. Note that in both cases, break-even point is not yet reached[2].

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1 Learning investments are the total expenditures required to bridge the gap between the electricity production costs of the challenging technology and the baseline costs of the incumbent technology until the break-even point is reached. This is illustrated in Figure S.3, though only from 2010-2020, albeit not until the break-even point.

2 We emphasize that the calculations for all outlooks for various technologies are based on straight-forward assumptions, adapted as much as possible for the Dutch circumstances (see appendix D for details, and appendix E for a sensitivity analysis). The outlooks presented should be seen mainly as *illustration* rather than full-blown and well-supported scenarios (which would have exceeded the scope of this review study).

3 Note that in Figure S.3, only the required learning investments between 2010-2020 are shown. As in this period much more onshore capacity is installed than offshore, the total learning investments for onshore are higher, in spite of the higher costs of electricity from offshore wind farms. Under the assumptions used (see appendix D), for both technologies the break-even point is not reached by 2020.

Comparing different technologies on the cost of electricity (CoE)
As a comparison, we also estimated the cost of electricity (CoE) for natural gas combined cycle (NGCC) and pulverized coal (PC) Carbon Dioxide Capture and Storage (CCS) technologies. For this we used experience curve projections of Rubin et al (2006) and Hoefnagels (2008), and adapted these data as much as possible for the Dutch situation[2].

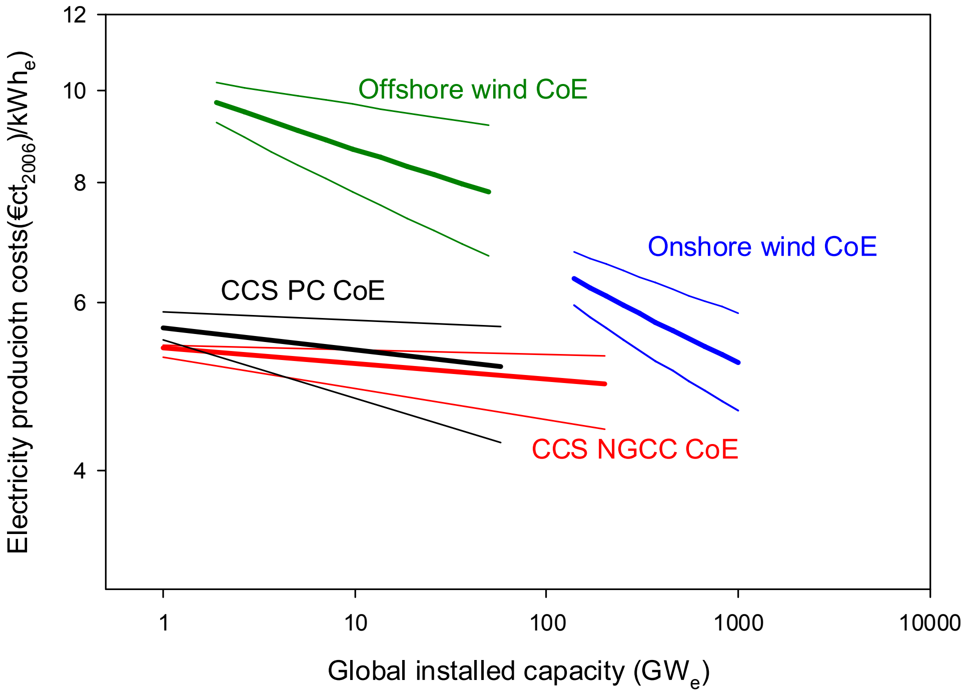


Figure S.4 2010 - 2020 Outlook for the Cost of Electricity (CoE) of onshore & offshore wind vs. CCS PC & NGCC CCS (including transport & storage).

A number of interesting trends are observable in Figure S.4: both the CoE of PC and NGCC plants are expected to be lower than onshore and offshore wind until 2020. However, it is also clear that the slopes of the CCS experience curves are shallower than the slope of onshore wind, and it is likely that on the longer-term, CoE of onshore wind energy will become lower than those of CCS. For offshore wind, the uncertainty in the slope is too high to draw any hard conclusions. It remains clear that while costs may decline by 10-30%, they will remain higher than the other technologies presented here beyond 2020[2].

Translating cost reductions in required CO_2 prices
One aim of this review study was to demonstrate how declining production costs can also be translated in $CO_{2eq.}$ reduction costs. For energy supply technologies, the (in general) higher costs of electricity can be translated into a price of CO_2 which would be required to bridge the gap to electricity from cheaper but CO_2 emitting technologies. We demonstrate this using the example of onshore and offshore wind farms. Assuming that electricity from wind power has a negligible CO_2 emission, and that taking an average emission of 0.59 kg CO_2/ kWh for Dutch centralized electricity production, a certain price of CO_2 per tonne would be needed to cover the additional costs. In Figure S.5, these costs are displayed. For offshore wind, the cost of CO_2 would have to be between 50 - 100 €/tonne to make exploitation of offshore wind farms lucrative. For onshore wind farms, CO_2 prices as low as 20-40 €/tonne might be sufficient by 2020 to render onshore wind farms economically viable without governmental support[2].

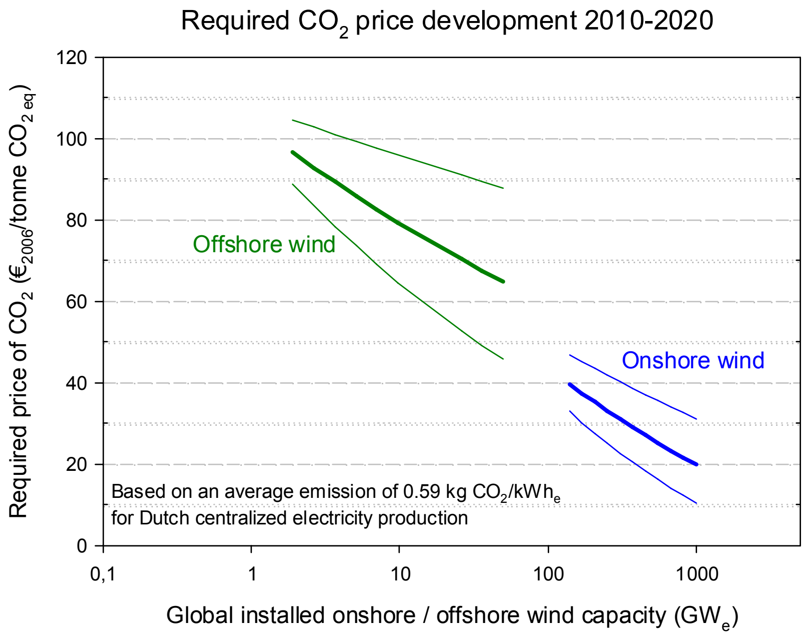


Figure S.5 Illustrative required price of CO_2 from 2010-2020 to cover the additional costs of electricity from onshore and offshore wind farms.

Limitations of the experience curve -methodological considerations

A number of methodological limitations have been described before extensively in the literature (see Section 2.2). Below, very briefly the most recent insights from the literature and from this report are summarized:

- Experience curve theory appears not to include the effects of increasing raw material costs, at least not on the short term. Neither does it include limitations due to geographical potential constraints. These limitations need to be further investigated, e.g. how to include them as well in energy models.
- As discussed above, experience curves can be used to explore future reduction of production costs. However, experience curves ***cannot*** forecast price developments. For example as shown in Figure S.1 various renewable electricity technologies display stabilizing or even increasing prices in recent years. These price increases are due to several reasons (see also previous point), but also because policy support has created a strong demand for these technologies, causing supply shortages and rising prices. These effects are not included in experience-curve based scenarios.
- Experience curves for energy demand technologies face several additional dilemmas compared to supply technologies, due to three reasons: i) changing product characteristics, i.e., the technical components of energy demand technologies changed in the decades since these products are sold at the market; ii) energy efficiency improvements and investment costs can go hand in hand but do not necessarily have to: Putting less isolation material in a refrigerator will make it cheaper, but at the same time less energy efficient; iii) the production of energy demand technology has become cheaper in the past due to the outsourcing of production to low wage countries. This is increasingly a way to reduce production costs of consumer appliances, but has little to do with technological learning.
- Experience curve extrapolation holds clear advantages above 'only' bottom up studies, but error/uncertainty margins have to be included. Experience curves have been shown to be a valuable tool for both analysing past developments and quantifying future cost reductions. As was recently shown by Alberth (2008), they are vastly superior to using time as explanatory variable for forecasts, and they can be especially useful when supported by bottom-up engineering studies. However, especially for long-term forecasts, small variations in PRs can lead to significantly deviating cost reductions in scenarios or completely different model outcomes in energy and climate models. Therefore, calculating error margins in progress ratios as shown by van Sark (2008a) and discussed in Section 2.2. is recommended, both to

express the quality of the fit (compared to the use of R^2 and as yardstick for optimistic and pessimistic scenarios for future outlooks.

- Experience curves and innovation systems theory may complement each other, a hybrid approach for short to medium-term scenario analysis could be explored. So far, the experience curve approach has been mainly utilised in top-down and bottom-up energy and climate models, for which it is well-suited, as it provides an elegant way to model endogenous technological change. However, while experience curves can quantify cost reductions with cumulative market diffusion, by themselves, they cannot forecast whether the actual market diffusion will occur. Especially the transition-management approach, applied by Dutch policy makers a few years ago, could possibly benefit from a hybrid approach of quantifying potential future production costs reduction of a new technology, and qualitatively evaluating the current and future chances of success based on the fulfilment of the various functions of innovation. Especially for technologies expected to gain market maturity in the short-to-medium term (e.g. 5-15 years) such an approach would seem promising. While such a hybrid approach needs to be developed in more detail, and does probably pose serious methodological questions to be solved, it could be developed into a valuable tool to support transition management.

Possibilities and limitations of experience curves for policy support on accelerating technological progress - lessons for policy makers

1. **The optimal distribution between R&D and market support measures remains difficult to determine**
   One of the key questions often brought forward by policy makers is: "what the optimal distribution between supporting R&D and market support measure is", i.e. how much financial support should be given to achieve maximum cost reduction with minimal means. Unfortunately, also after the review of dozens of studies, this 'holy grail' has not been found. **Experience curves by themselves could - at best - only contribute to such an analysis as one component of a set of tools**. While this report shows that much progress has been made on establishing experience curves in many ways, it is clear that the ´black box´ of technology learning has not yet been opened, as we still do not know very much on how learning is occuring and which factors are most influential - an important precondition to determine optimal support policies. Alternatively, more disaggregated methods would be needed for a comprehensive analysis. The current knowledge which is primarily based on analysis of statistics needs to be complemented by in-depth case studies using social science approaches like ethnographic studies, study of company archives, interviews, etc.

2. **No proof is found that policy can '*bend - down*' the experience curve**
   Policy has undoubtedly a crucial role in supporting technological learning and cost reductions of new technologies. However, policy makers sometimes express the hope that by investing heavily in public R&D, technological learning (and thus cost reductions) may be accelerated. In other words, the speed with which the technology learns would be increased. This would imply that the experience curve could be 'bent downwards', i.e. the slope of the curve could be changed either temporarily or constantly (e.g. changing the PR from 90% to 80%). However, in all studies investigated, we seldom find curves which (temporarily) change the slope and curve downwards (i.e. the progress ratio decreases). In none of these cases, this was linked to intensified policy support. While this is no scientific proof that R&D cannot do so, we can state, that from the overview of studies investigated, no structural trend was identified that PRs change over time neither with increasing market diffusion nor with changing R&D support.

   On the other hand, policy support can very likely accelerate the 'riding down' of the experience curve, i.e. using financial policy measures such as subsidies or feed-in tariffs to stimulate extra market volume, which in turn drives down production costs. Determining the exact height of these support measures is however not easy, as shown in the next paragraph.

3. **Over-stimulation of markets may increase demand drastically, which may result in increasing prices - which are not captured by experience curve analysis**
   As shown in various parts of chapters 3, prices for PV, wind onshore and wind offshore, market prices have either stabilized or increased over the past 5 years. One main reason for this is likely the strongly increased demand for these technologies by policy targets and policy measures. For example, for onshore wind farms, turbine manufacturers report full order books for the coming years, indicating a shortage of production capacity.

   However, before attributing all price increases to too high support measures, one should take into account:
   - Increasing production costs because of increasing raw material costs (e.g. steel, copper, silicium) and limited geographical potential (see section 4.2. parts 2 and 3) .
   - Increasing prices of the reference power technologies. In recent years, the investment costs of conventional power technologies (e.g. NGCC and PC plants) have increased drastically as well.
   - Fluctuating exchange rates. For example, most wind turbines are manufactured in Europe. Due to the declining US$ against the Euro, prices in the US for imported turbines quoted in US$ increased even further.

   Stabilizing or increasing prices on the short terms does however not mean that no technological learning occurs. In other words, production costs may still decline, but this is no longer reflected in market prices. Also, it is likely that prices will decline again on the longer term, when production capacity/supply has caught up with demand. Yet, it must be emphasised strongly that **experience curves allow for projections for the development of production costs; they do not forecast the development of market prices, and they are not a short-term tool.** Summarizing, as argued above, support policy is crucial for emerging technologies, yet *over*-stimulating markets may - at least temporarily lead to increasing prices. Careful and long-term yet flexible support policy is required to effectively stimulate the development of renewable energy technologies, while at the same time preventing over-stimulation and free-rider effects.

4. **For experience curves describing energy efficiency, we do find indications that these slopes can be influenced by policy measures such as labelling programmes**
   No proof was found that policy is able to change the slope of the experience curve for production costs. For demand-side technologies, the experience curve approach also seems applicable to measure autonomous *energy efficiency* improvements. Interestingly, we do find strong indications that in this case, policy can bend down (at least temporarily) the experience curve and increase the speed with which energy efficiency improvements are implemented. However this phenomenon needs to be investigated more thoroughly before any firm conclusions can be drawn on the topic.

5. **Experience curves can help policy makers to determine the effect of their support measures on overall technology cost reductions**
   Often, considerable governmental budgets are spent to support the diffusion of renewable and energy-efficient energy technologies and thereby stimulate technological learning. However, it is often unclear to policy makers, to what extent this support will lead to cost reductions. This depends to a large extent on how much capacity is already installed (on a global level), and how much additional capacity will be generated through the policy support. Especially for technologies which already have achieved a considerable market share, market support measures are still vital, but further cost reductions will occur more slowly over time. If the aim of policy support measures is to substantially contribute to technology development and achieve rapid cost reductions, this can probably only be achieved by supporting technologies for which one or a few pilot plants already mean substantial increase of installed capacity (and thus opportunities to learn). If the market is still small, early mover countries that build up a domestic market and support their industry in developing export markets, can develop a considerable competitive advantage within a certain technology area, if they continue this support over a considerable time.

6. **Policy makers should be aware of the possibilities and limitations of using experience curves in energy models when interpreting their results**
   Many energy and climate models exist, designed to support policy decisions, and many of them use experience curves to model endogenous technological change. For a policy-maker, key attention should focus on the question why the model outcomes presented provide justification for the policy suggestions. To this end, one ought to grasp the basics of the model used, and in respect to experience curves, how endogenous learning is modelled. As model results tend to be very sensitive to small changes in PRs, a sensitivity analysis is essential to demonstrate the robustness of model outcomes.

7. **For some new large-scale technologies (such as offshore wind, 2nd generation biofuels & electricity production), more international cooperation and structured knowledge exchange is required**
   Technologies such as large Fischer-Tropsch plants or offshore wind farms do benefit strongly from large scales, e.g. specific investment costs go down, but absolute investment costs are high. Frequently changing and often not-harmonized policies in e.g. EU countries make investors reluctant to commit more international cooperation, coordinated action and support for these technologies could be very beneficial for stable investments. We also note that, while on the national level, information exchange for new technologies is often organized well, structured knowledge exchange on specific technologies on an international level remains limited.

Nederlandse samenvatting

Inleiding en doelstelling

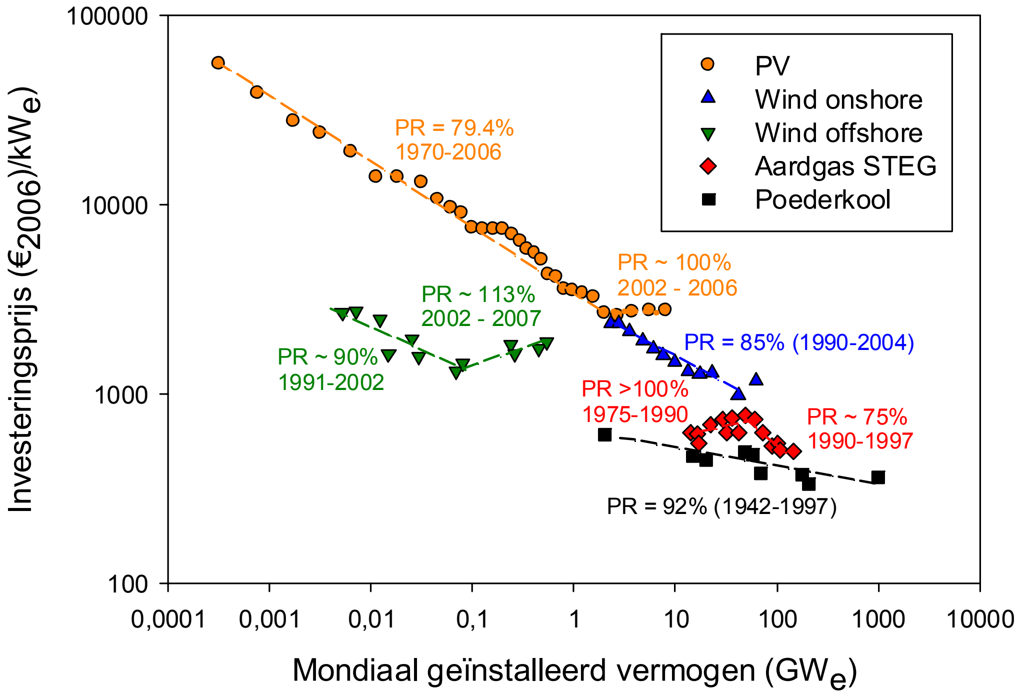
Technologisch leren is een sleutel factor achter de verbetering van bestaande en nieuwe (energie-) technologieën. Een belangrijke vraag is daarbij, in hoeverre en wanneer de kosten van nieuwe energietechnologieën de kosten van de bestaande technologieën kunnen inhalen. Een vaak gebruikte benadering om zowel de in het verleden bereikte kostenreducties te kwantificeren als mogelijk toekomstige kostenreducties in kaart te brengen, is de leercurvebenadering . De leercurve beschrijft de kostenontwikkeling van een product of een technologie als functie van de cumulatieve productie van dit product of deze technologie. Op een dubbel logaritmische schaal vertoont de leercurve meestal een rechte lijn, waarbij de helling van de lijn iets zegt over de snelheid waarmee in de ontwikkeling van de technologie wordt geleerd. De helling wordt beschreven met de zogenaamde progress ratio (PR). Een PR van 80% betekent dat met iedere cumulatieve verdubbeling van de productie, de kosten met 20% dalen. Leercurves zijn in de afgelopen decennia veelvuldig gebruik om de ontwikkeling van een variëteit aan energietechnologieën te beschrijven.

De doelen van dit onderzoek waren:

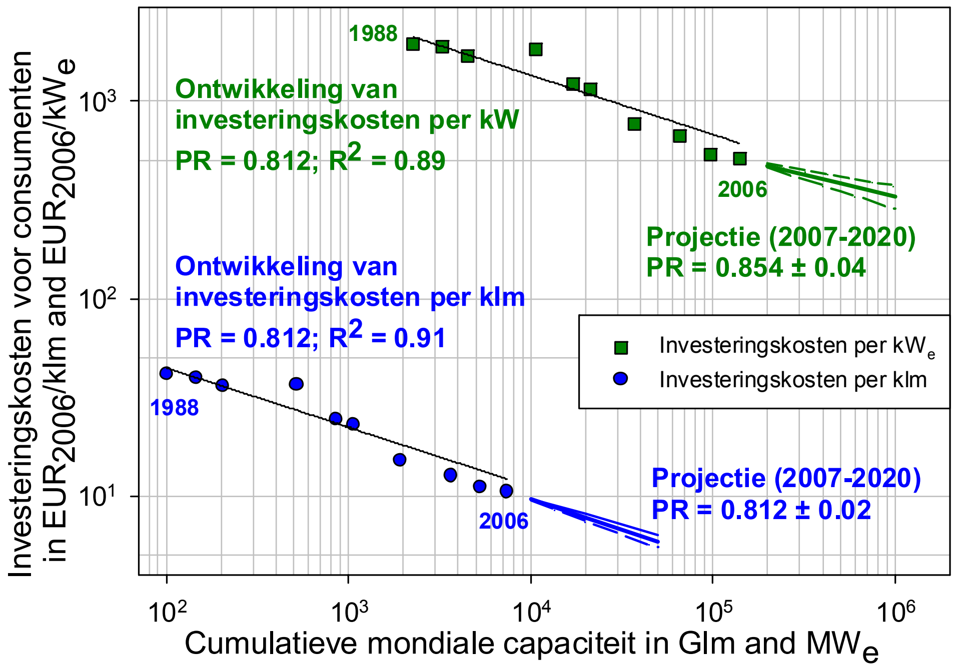
- Een uitgebreide literatuuranalyse van studies die de leercurve methodiek gebruiken om technologisch leren en kostenreducties te kwantificeren voor een groot aantal energietechnologieën, inclusief duurzame energie, (schone) fossiel technologieën en energie-efficiënte technologieën.
- Een overzicht en grondige discussie van de mogelijke voetangels en problemen bij het toepassen van de leercurve methodiek, zoals bijvoorbeeld de geografische systeemgrenzen, de vraag of de helling van een leercurve constant is of niet, het uitvoeren van gevoeligheidsanalyses en de vraag of de leercurve benadering ook gebruikt kan worden, om verbeteringen in energie efficiëntie te kwantificeren
- Een demonstratie hoe dalende productiekosten vertaald kunnen worden in $CO_{2eq.}$ reductie kosten.
- Een discussie in hoeverre beleidsmaatregelen succesvol waren in het accelereren van technologisch leren en daarmee gepaard gaande kostenreducties

Overzicht van leercurves voor diverse technologieën

In Figuren N.1 en N.2 wordt gepresenteerd hoe productie kosten van een aantal energieaanbods- en vraag technologieën met cumulatief geïnstalleerde capaciteit zijn gedaald. In Figuur N.3 is illustratief weergegeven, hoe met behulp van de leercurve trends in de benodigde CO_2 prijs kunnen worden bepaald.



Figuur N.1 *Vergelijking van historische leercurves van energieaanbod technologieën. Merk op dat de prijzen van alle (hernieuwbare) energietechnologieën sinds 2002 constant zijn of toenemen (PRs>=100%). Dit wordt waarschijnlijk veroorzaakt door een combinatie van toenemende vraag naar deze technologieën, toenemende kosten voor grondstoffen, en tevens de hogere kosten voor de fossiele referentie technologieën. Data bronnen: Isles (2006), Van Sark (2008b), Junginger (2005) Claeson Colpier and Cornland (2002), Rubin et al. (2006), Milborrow (2007).*



Figuur N.2 *Historische leercurve en mogelijke toekomstige kostenontwikkelingen tot het jaar 2020 voor energiespaarlampen. Data bronnen: Weiss et al. (2008), Iwafune (2000).*

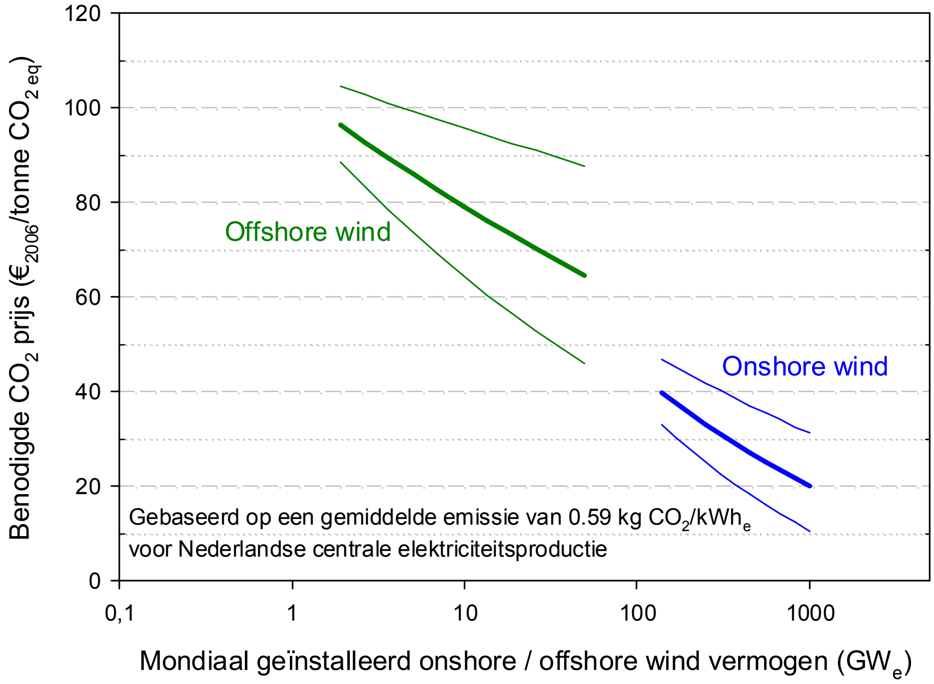


Figure N.3 Illustratie van de benodigde CO_2 -prijs tussen 2010-2020 om de onrendabele top van elektriciteit van windparken op land en op zee te dekken.

Methodologische overwegingen

In de literatuur zijn de diverse valkuilen beschreven, waarvan we hieronder een zeer beknopte samenvatting geven:

- De leercurve theorie neemt niet direct de effecten mee van stijgende kosten van grondstoffen, en ook niet de geografische potentieelbeperkingen van een technologie.
- Leercurves kunnen worden gebruikt om de mogelijke ontwikkeling van productiekosten in de toekomst te analyseren. Ze kunnen echter **niet** de ontwikkelingen van prijzen voorspellen, zoals bij voorbeeld door een verhoogde vraag.
- Het is mogelijk om leercurves voor energie vraag technologieën op te zetten, maar dit wordt bemoeilijkt door drie factoren: i) de productkarakteristieken veranderen vaak over de tijd, ii) energiebesparing en productiekosten lopen niet altijd synchroon, en iii) recentelijk worden besparingen vooral behaald door het verplaatsen van de productie naar lage loon landen, dit heeft echter weinig met technologisch leren te maken.
- Vergeleken met ingenieursstudies bieden leercurves duidelijke (aanvullende) voordelen voor het schatten van kostenreductie potentiëlen. Een kleine variatie in de PR kan echter bij extrapolatie voor de lange termijn tot significant afwijkende kostenschattingen leiden. Het wordt daarom aanbevolen, om foutenmarges in PRs volgens de methode van Van Sark (2008a) bij dergelijke extrapolaties mee te nemen, om de gevoeligheid van de resultaten te verkennen.
- De leercurve theorie en systeeminnovatie theorie zouden elkaar in principe kunnen aanvullen. Een hybride aanpak voor korte tot middenlange termijn scenario-analyse zou verkend kunnen worden. Vooral in het kader van transitiemanagement zou dit waardevolle additionele kwantitatieve inzichten kunnen verschaffen.

Mogelijkheden en beperkingen van leercurves voor beleidsondersteuning om technologisch leren te versnellen - lessen voor beleidsmakers

1. De optimale verhouding van beleidsinspanningen op het gebied van R&D en marktintroductie is lastig te bepalen. De leercurve-methodiek kan dit vraagstuk ook niet

alleen beantwoorden, maar kan hooguit een bijdrage leveren als onderdeel van een set aan analysemethoden.

2. Er is geen bewijs gevonden dat beleid de leercurve ‘naar beneden’ kan buigen door additionele R&D uitgaven. Er zijn maar weinig studies gevonden waarin de helling van de leercurve steiler werd, en in geen enkel geval is dit gekoppeld aan geïntensiveerde beleidsondersteuning. Dit is weliswaar geen bewijs dat extra R&D dit principieel niet kan, maar er is geen trend gevonden, dat PRs met toenemende marktpenetratie of R&D uitgaven veranderen. Beleid kan echter duidelijk het tempo versnellen, waarmee de leercurve wordt afgelopen, al is het bepalen van de juiste hoogte van de financiële stimulering niet eenvoudig.
3. Overstimulering van markten kan de vraag (en daarmee de prijzen) drastisch verhogen - wat niet met de leercurve methodiek geanalyseerd kan worden. Voor duurzame energietechnologieën zoals PV, wind op land en wind op zee is de afgelopen jaren een prijsstabilisatie of toename geconstateerd. Een hoofdredenen hiervoor is waarschijnlijk de stijgende vraag naar deze technologieën - onder meer gecreëerd door ambitieuze beleidsdoelen en steun. Kostenstijgingen kunnen echter ook veroorzaakt worden door stijgende prijzen voor staal koper en silicium, geografische potentieelbeperkingen (vooral voor offshore wind), stijgende prijzen van overige (fossiele) energieprijzen, en fluctuerende wisselkoersen (vooral de US$ ten opzichte van de Euro). Stabiliserende of stijgende prijzen betekenen echter niet, dat er geen technologisch leren plaats vindt. Op de langere termijn kan verwacht worden, dat de prijzen weer zullen dalen. We benadrukken dat leercurves geschikt zijn voor projectie van productiekosten op de lange termijn, niet voor prijsontwikkelingen op de korte termijn.
4. Het lijkt erop, dat met de leercurve methodologie ook de ontwikkeling van efficiëntie-verbeteringen gemeten kan worden. Tevens zijn er indicaties gevonden, dat beleid (bij voorbeeld door labelling programma’s) de autonome trend in efficiëntieverbeteringen actief kan versnellen. Dit fenomeen moet echter nader onderzocht worden, voordat harde conclusies getrokken kunnen worden.
5. Leercurves kunnen beleidsmakers helpen om het effect van beleidsmaatregelen op kostenreducties van technologieën te evalueren. Het hangt er vooral vanaf, in hoeverre de beleidsmaatregel kan zorgen voor een significante (mondiale) toename van het geïnstalleerde vermogen. Dit betekent dat significante kostenreducties met beperkte beleids-maatregelen vooral in nichemarkten behaald kunnen worden. Indien de markt nog klein is, kan met beperkte beleidsinspanningen een early-mover advantage opgebouwd worden, indien de beleidssteun over langere tijd in stand wordt gehouden.
6. De uitkomsten van energiemodellen zijn vaak afhankelijk van de achterliggende aannames op het gebied van technologisch leren. Zo kunnen kleine veranderingen in de gebruikte PRs grote invloed op de uitkomsten hebben. Beleidsmakers zouden bij de interpretatie van deze uitkomsten beter op de achterliggende aannames en beperkingen van de modellen moeten letten.
7. Voor sommige grootschalige technologieën (zoals wind op zee en tweede generatie productie van transportbrandstoffen en elektriciteit uit biomassa), is meer internationale samenwerking en gestructureerde kennisuitwisseling noodzakelijk. Deze technologieën profiteren sterk van toepassing op grote schaal. Fluctuerende beleidssteun en soms niet-geharmoniseerd beleid in verschillende EU lidstaten kan investeerders echter ervoor laten terugdeinzen, om investeringen te doen. Een betere coördinatie van beleidssteun en kennisuitwisseling zou waardevol voor nieuwe investeringen kunnen zijn. Ook het internationaal overdragen van lokaal opgedane kennis zou beter gestructureerd kunnen worden.

1 Introduction

1.1 Background rationale

Technology learning is a key driver behind the improvement of technologies available to mankind and subsequent reduction of production costs. Many of the conventional technologies in use today have already been continuously improved over decades, sometimes even a century (e.g. most bulk chemical processes, computers, cars, ships and airplanes, etc.). Specifically for the electricity sector, coal-fired power plants have been built (and improved) for nearly a century now, while nuclear (fission) plants and gas-fired power plants have been built and developed since the 1960's-1970's on a large commercial scale. Note that these well-established technologies also are continuously further improved, though this mainly leads to incremental improvements and concomitant cost reductions. Due to this long-term development, the established fossil fuel technologies have relatively low production costs, but also a number of negative externalities, especially the emission of greenhouse gases (GHGs).

In contrast, many renewable / clean fossil fuel energy technologies and energy saving technologies still have higher production costs, but lower fuel demands and GHG emissions. Examples are electricity from biomass, wind and photovoltaics (PV), and energy-efficient lighting and space-heating technologies. For many of these new technologies, the potential for further technological development and resulting production cost reductions is deemed substantial, and relatively cost reductions occur at high speeds compared to the conventional technologies. It is thus anticipated that in many cases the cost gap between conventional and new technologies can be closed, i.e. a break-even point be reached. Crucial questions are however, whether this point will be reached, and if so, when and under what circumstances (especially how this depends on policy support). This is specific per technology, and has been subject of much debate, both internationally and in the Netherlands, e.g. the effect of MEP[4]-feed-in tariffs on innovation and cost reductions. Thus the past and future development in time of production costs of (renewable) energy technologies (and the linked cost of $CO_{2eq.}$ emission reduction) are of great interest, as it allows policy makers to develop strategies for cost-effective implementation of these new technologies.

One approach to analyze the production cost reduction is the experience curve approach. It has been empirically observed for many different technologies that production costs tend to decline with a fixed percentage with every doubling of the cumulative production. As a rule of thumb, this cost reduction lies between 10-30%. The experience curve concept has been applied to (renewable) energy technologies with a varying degree of detail.

Existing literature

As mentioned above, several major EU-funded studies have been carried out in the past, mainly Extool for onshore wind energy (Neij et al., 2003) and Photex for solar photovoltaic (PV) energy (Schaeffer et al., 2004a). Also, in scientific literature, numerous other studies can be found, analyzing various energy technologies using the experience curve concept. A first comprehensive overview of the use of experience curves for renewable energy technologies and their application for policy makers was published by the International Energy Agency (IEA, 2000). However, this assessment only covered a limited number of renewable energy technologies, and was mainly based on case studies carried out before 2000. Also the recent NEEDS project (Neij, 2008) provides an overview of technological learning and bottom-up cost assessments.

[4] The MEP (Milieukwaliteit ElektriciteitsProductie) tariffs are a former Dutch policy support measure.

It is concluded that a comprehensive assessment of (renewable) energy technologies could be very useful for Dutch (and international) policy makers to determine the national long(er)-term energy and climate policies for the following reasons:

1. In the past years, a number of varying methodological caveats and approaches regarding the application of the experience curve tool have been identified. However, these lessons are often only drawn on a specific topic or a specific technology. There is a need for a comprehensive overview and synthesis of these issues.
2. Next to methodological lessons, in many studies the effect of policy measures is (partially) evaluated, e.g. whether it can accelerate technological learning or 'bend - down' the slope of the experience curve. However, the specific lessons drawn for different technologies have barely been put next to each other and evaluated and discussed in a comprehensive review.
3. So far most studies focus on the production costs developments of specific technologies. Comparing them and translating production cost reductions in decreasing costs of GHG emission reduction has barely been done so far.
4. Some case studies (such as PV) would benefit from a (minor) update, and it would be worthwhile to investigate whether the cost reduction percentage has changed in recent years compared to older studies.

1.2 Study Objectives

This study aims to provide:

- A comprehensive review of studies on technological development and cost reductions performed for a large range of energy technologies, including renewable energy technologies, (clean) fossil fuel technologies and energy efficient technologies using the experience curve concept.
- An overview and thorough analysis/discussion of the pitfalls of applying the experience curve approach, based on the issues identified in the various technology studies, and including aspects such as geographical system boundaries, whether the slope of the experience curves is constant or not, statistical error and sensitivity analysis of experience curves, and whether the experience curve approach can also be utilized to quantify improvements in energy efficiency.
- A demonstration how declining production costs can also be translated in $CO_{2eq.}$ reduction costs.
- A discussion to what extent policy interventions (by measures to support 'learning-by-searching' and 'learning-by-doing') have been successful in accelerating technological learning and associated production cost reductions.

This study is mainly a review study, based largely on existing literature. It is explicitly the aim to make as much use as possible of existing studies such as the Photex or Extool reports and the results of the recent NEEDS project (Neij et al. 2006). It aims however to be more comprehensive (e.g. to include demand-side technologies), and intends (also building on the lessons drawn by Wene (IEA, 2000) and Neij (2007)) to identify further methodological bottlenecks and compare and synthesize lessons on the use of the experience curve for policy support.

1.3 Structure of this report

The report is organized as follows:

In Chapter 2, a general introduction and history of the experience curve concept will be given. Also, typical caveats and methodological issues of applying the experience curve approach are described. Furthermore, a brief analysis is presented, how the experience curve approach could be related to the systems of innovation theory, and which possible synergies of combining the two approaches may be achieved. Finally, Chapter 2 presents an analysis of how the experience curve approach is used in various energy and climate models, what the main advantages and drawbacks of this endogenous method are, and what policy makers should be aware of when interpreting results from these models.

In Chapter 3, a comprehensive overview of technology studies using the experience curve approach is presented. The chapter is subdivided in three main topics: i) renewable energy technologies, ii) (clean) fossil and nuclear technologies, and iii) energy demand technologies. For each of the technologies, an overview of all (major) studies using experience curves is presented, as are the current economics, past and potential future cost reductions, and past policy support measures. Also, for each technology, an overview of policy recommendations derived from the various studies is presented, and methodological issues arising from the use of experience curves for the specific technology are discussed.

In Chapter 4, first of all, the experience curves for the various technologies are compared in terms of reduction of investment costs, reduction of final energy carriers and GHG emission reduction costs. Second, the methodological issues arising from the individual technology studies are compared and discussed. Third, the lessons for policy makers as presented in the various literature studies are evaluated, and recommendations are given.

2 Experience curve methodology and application

2.1 Introduction

2.1.1 The experience curve approach - history and general applications

Normally, the technical and economic performance of a technology increases substantially as producers and consumers gain experience with this technology. This phenomenon was first described in the literature in 1936 by Wright (1936), who reported that unit labor costs in airframe manufacturing declined significantly with accumulated experience of the workers, and that this cost reduction was a constant percentage with every doubling of cumulative output. When plotted on a log-log scale, he found that this empirical relationship is displayed as a straight line. He noted the particular interest of these curves to investigate 'the possible future of airplane cost'. Wright's discovery is nowadays called a learning curve, as he only measured the effects of learning-by-doing, and recorded the reduction in labor cost (or actually, the time required to complete a certain task) (Neij, 1999).

Wright's work remained relatively obscure until it was revisited a decade later by a group of economists at the then recently founded RAND Corporation (a 'think tank' created by the U.S. Air Force in 1946 to develop a complete 'science of warfare' during the Cold War era) (Yeh et al, 2007). The RAND economists became vitally interested in the application of Wright's work to the production of war materials - a phenomenon they would eventually call 'learning-by-doing' (Yeh, 2007).

Arrow (1962) introduced the notion to general economics that this cost reduction (as a result of learning) was the product of experience. In 1968, the Boston Consultancy Group extended the learning curve concept in two ways (BCG, 1968). First, the concept was applied to the total cost of a product, including the combined effect of learning, specialization, investment and scale (Henderson, 1974). Second, the concept was applied not only on the level of a single company, but also to entire industries. In order to distinguish them from simple learning curves they were labelled experience curves[5].

Since the 1940s, learning curves and experience curves have been used to describe the production cost development of a multitude of industrial products, such as cars, (military) airplanes (Alchian, 1963) and ships (Searle, 1945), the aerospace industry, semiconductors (Irwin and Klenow, 1994) and many different energy technologies (McDonald and Schrattenholzer, 1999). More exotic applications include the productivity of kibbutz farming (Barkai and Levhari, 1973) and measuring the time required for new medical procedures (Beaulieu, 2007). Nowadays, the experience curve concept is a common textbook concept, and used frequently in the industry. For example, the National Aeronautics and Space Administration (NASA) is offering an online 'learning curve calculator', in which amongst others the cost for aerospace, complex machine tools for new models, repetitive electrical operations and repetitive welding operations can be estimated (NASA, 2007).

2.1.2 The experience curve formula

When the cost development of a product or a technology can be described as function of cumulative production, and plotted in a figure with double-logarithmic scale, the result is often a linear curve, the experience curve. The basic experience curve can be expressed as:

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5 Unfortunately, in the literature the term learning curve is sometimes also used as synonym for experience curve. In this report, the term experience curve will be used, describing overall production cost developments against cumulative production.

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

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

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

C_{Cum}	: Cost per unit	C_0	: Cost of the first unit produced
Cum	: Cumulative (unit) production	m	: Experience parameter
PR	: Progress ratio		

The progress ratio (PR) is a parameter that expresses the rate at which costs decline for every doubling of cumulative production. For example, a progress ratio of 80% equals a learning rate (LR) of 20% and thus a 20% cost decrease for each doubling of the cumulative capacity. Both terms are used in the literature. Furthermore, in the experience curve approach costs are expressed in real terms, i.e. corrected for inflation, for example using a GDP-deflator. An example of an experience curve is shown in Figure 2.1, in which an experience curve for solar PV modules is presented.

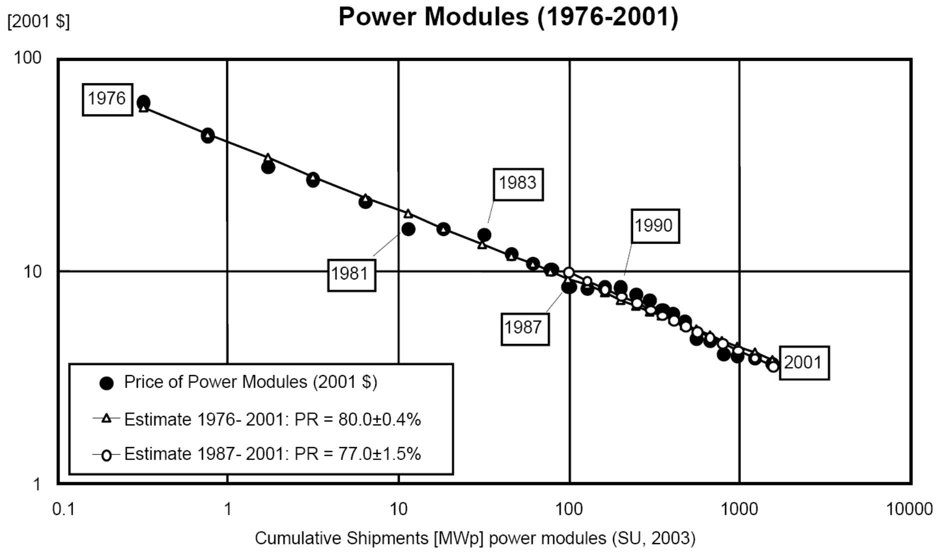

Figure 2.1 Experience curve for solar PV-module prices (Global Average Selling Price), adopted from Schaeffer et al. (2004). Original data from Strategies Unlimited (2003).

2.1.3 Application of the experience curve concept for energy technologies and its use for policy makers

As illustrated above, the experience curve is a widely-applied approach, and its validity empirically has been demonstrated for many different products. As mentioned in Chapter 1, in the last decades, the experience curve approach has increasingly been applied to emerging energy technologies, especially for solar PV modules (see e.g. the Photex study by Schaeffer et al. (2004)) and wind turbines (see e.g. the Extool study by Neij et al. (2003)). For both technologies, several dozens of studies have been published. To a lesser extent, studies have also been performed for other energy technologies, such as various fossil-fuelled power plants or ethanol production from sugarcane. An overview is presented by McDonald and Schrattenholzer (2001), but a more comprehensive overview is given per technology in Chapter 3 of this report.

A first comprehensive overview of the use of experience curves for renewable energy technologies and their application for policy makers was published by the International Energy Agency (IEA, 2000). However, this assessment only covered a limited number of renewable energy technologies, and was mainly based on case studies carried out before 2000. In the recent NEEDS project (Neij et al., 2006), descriptions of studies presenting experience curves for a number of energy supply technologies are given, similar to the work presented in this report, and compared to bottom-up engineering assessments. Our study builds on these studies, but aims to go further in terms of technologies covered (also demand-side) and to synthesize lessons for policy makers.

Users may vary from individual corporations analyzing the speed with which the costs of their products may decline, to energy modellers and national policy makers (Neij et al., 2003). Specifically for policy makers, two main fields of application can be identified:

Direct application[6]
Existing data show that experience curves provide a rational and systematic methodology to describe the historical development and performance of technologies. We use them to assess the prospects for future improvements in the performance of a technology. The curves show that cumulative production for the market reduces prices. Assessments of future prospects are therefore particularly important in developing deployment policies for environmentally friendly technologies. Figure 2.2 indicates how learning acquired through cumulative production reduces the cost of photovoltaic modules. For photovoltaic systems to compete against central power stations, the cost of modules has to be brought down to a 'fossil fuel alternative', as indicated by the horizontal line in the diagram[9]. This requires about a fifty-fold production capacity increase with respect to present day capacity.

The experience curve shows the investment necessary to make a technology, such as PV, competitive, but it does not forecast when the technology will reach break-even. The time of break-even depends on deployment rates, which the decision-maker can influence through policy. With historical annual growth rates of 15% (as assessed in 1997), photovoltaic modules will reach break-even point around the year 2025. Doubling the rate of growth (as was the case between 1997-2007) will move the break-even point 10 years ahead to 2015. Investments will be needed for the ride down of the experience curve, which is necessary for the learning efforts which will bring prices to the break-even point.

Application for policy makers is basically twofold. First of all, experience curves can serve as a ***monitoring tool***. By monitoring price developments and comparing them to the road map[7] for costs, industry parties as well as government players can follow in which market stage[8] the current industry is. For policy makers, it might be interesting to see if it is possible to moderate demand support (but for any effect you have to be either an influential country, or international competition is needed) or if the supply side of the production can be supported, instead of the demand-side. Also government can think what could happen if prices come down seriously and what market rules would be needed to spur support-independent markets.

Second, an indicator for the resources required for learning is the difference between actual price and break-even price, i.e., the additional costs for the technology compared with the cost of the same service from technologies which the market presently considers cost-efficient. We refer to these additional costs as ***learning investments***, which means that they are investments in learning to make the technology cost-efficient, after which they will be recovered as the technology continues to improve. The remaining learning investments for photovoltaic modules are indicated by the shaded triangle in Figure 2.2. The sum of all future learning investments needed to bring module technology to the breakeven point indicated in the figure is 60 billion

[6] The text in this section is an adapted excerpt from the IEA publication "Experience curves for energy technology policy" (IEA, 2000) with additions from Schaeffer (2008).
[7] Experience curves can be used as "road map" by industry. A well-known example of this is Moore´s Law for the IC industry. Also in the PV community, the PV Vision report (EU-PV-TP, 2007) uses the experience curve as a road map for cost development. This road map acts in a way as a self fulfilling prophecy. Companies know that if they do not follow this road map with their cost structure, they will have a competitive disadvantage with regard to their competitors and will finally go bankrupt or taken over if the market gets tight (Schaeffer, 2008).
[8] As defined by the Boston Consultancy Group (BCG), see the first point of Section 2.2.

US$[9]. This is a substantial investment in learning, considering the learning investments of 3-4 billion US$ made in PV modules until 1998. The challenge is to put policies in place which mobilise resources on the market for these investments. Public demonstration programmes and subsidies can only seed this process. The learning investments do include the cost of research and development activities carried out by the commercial market actors, who ultimately have to recover those costs through market revenues. Note however, that after the break-even point, also substantial savings can be achieved compared to the fossil fuel alternative (not shown in Figure 2.2). On the other hand, policy makers should realize that the reference price is not a given. It might go up, e.g. because of decreasing marginal costs of production of the reference technology, or the inclusion of the external costs in the reference technology, or go down because of decreasing marginal cost due to either technology development or lower demand. To make a good assessment of learning investments also insight in the dynamics of the reference technology is needed.

Finally, it should also be noted that other societal costs (e.g. costs of awareness campaigns and information dissemination to promote the new technology) are not necessarily included in the depicted learning investments.

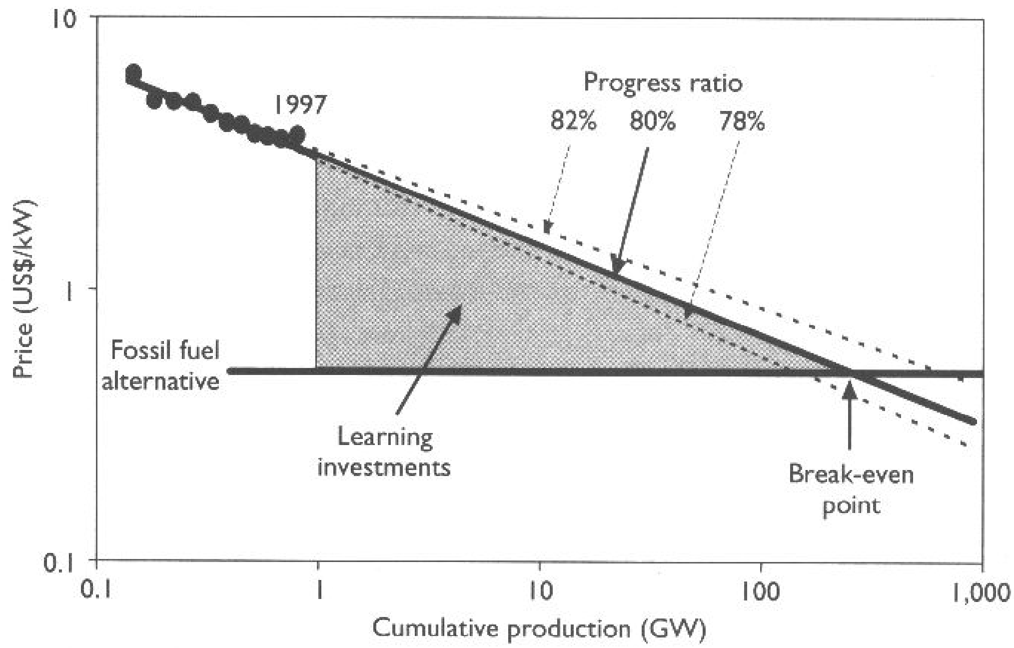

Figure 2.2 Break-even point and learning investments for photovoltaic modules with a progress ratio of 80%.The shaded area indicates the remaining learning investments to reach the break-even point. The figure also shows changes in the break-even point for progress ratios of 78% and 82% (IEA, 2000).

Learning investments are primarily provided through market mechanisms, and they always involve commercial actors on the market. There may be some overlap between learning investments and government expenditures for research, development and demonstration (RD&D), because experimental or demonstration plants may be financed from the public RD&D budget. In specific cases, involving smaller programmes, government expenditures may be a substantial part of total learning investments. However, for major technologies such as photovoltaics, wind power, biomass, or heat pumps, resources provided through the market dominate the learning investments. Government deployment programmes may still be needed to stimulate these investments. The government expenditures for these programmes will be included in the learning investments.

9 Note that in IEA (2000) the break-even price of the fossil fuel alternative was assumed to be equivalent to about 0.5 US$/Wp, which may differ from assumptions in this report.

Indirect application: the results of energy models

In the previous section, the development of a single renewable energy technology was described compared to a single (fossil) competition level. Of course, in reality, many different energy options compete with each other, each having specific advantages and disadvantages. To deal with this complexity, a large number of energy models have been developed over the last decades. A number of renowned energy and climate models make use of experience curves, for example IMAGE-TIMER (Hoogwijk, 2004), MARKAL (Smekens, 2005, Seebregts et al., 1998) or DEMETER (Van der Zwaan and Gerlagh, 2006). These models take into account R&D expenditures and deployment policies, and model possible energy systems and CO_2 emissions. For example, Figure 2.3 displays the outcome of a study by Smekens (2005), using the MARKAL model. This model simulates technological learning of various technologies using experience curves. Such models integrally analyze how differing R&D and deployment policies may result in different global energy mixes, the overall costs for these developments, and the associated CO_2 emission (reductions). In Figure 2.4, Mattson and Wene (1997) show how early learning investments in new technologies can lead to substantially different outcomes after several decades.

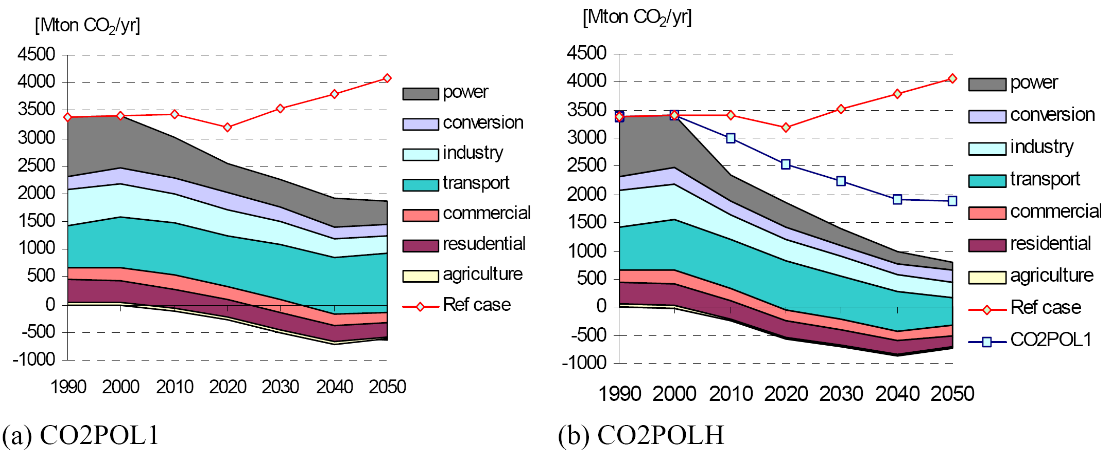

Figure 2.3 Results of the MARKAL model using different scenarios for endogenous technological learning and policies to estimate future CO_2 emissions (Smekens, 2005). Required R&D and deployment incentives and associated costs can also be calculated (but are not depicted here).

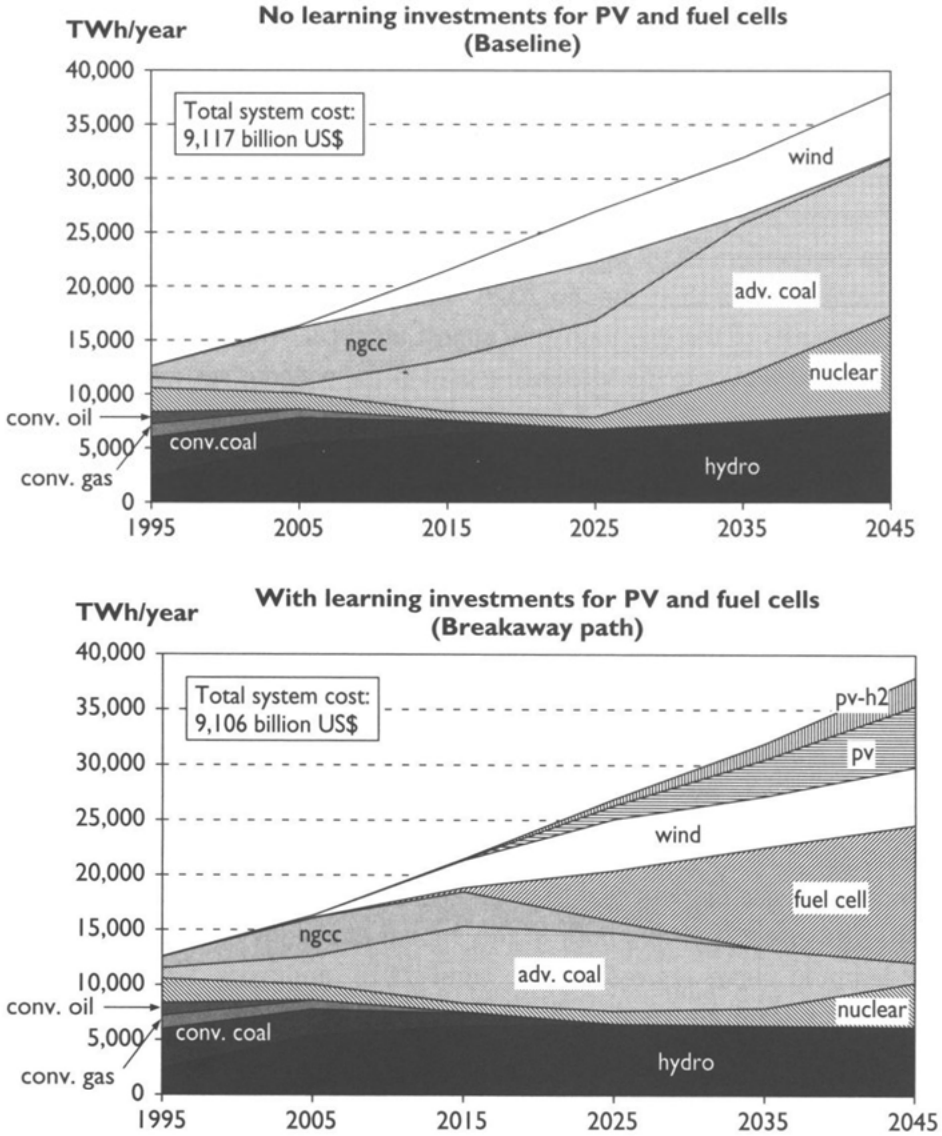

Figure 2.4 Alternative outcomes of the global electricity production system with and without early learning investments for PV and fuel cells (Mattson and Wene, 1997). Note that the overall system costs are almost identical for both scenarios.

Thus, with the help of energy models using endogenous learning through experience curves policy makers can identify optimal and alternative pathways to stimulate clean energy systems and reaching CO_2 reduction levels at low costs. However, using experience curves in energy models may also have drawbacks and needs attention regarding several issues, as is described in Chapter 2.4.

2.2 General aspects and caveats of experience curve analysis

While the basic experience curve principle itself stands out due to its simplicity, using the experience curve is in practice often not as straightforward as it may seem. The attractiveness of the experience curve approach lies in the possibility to extrapolate the trend lines to make estimates for the future. However, a number of points of attention have to be taken into account, concerning the construction of historical experience curves, and the use by policy makers, modellers etc. for extrapolation of experience curves and analysis of future cost developments.

The topics listed below have largely been described in the literature and are of general concern. Issues that arise from the application to specific energy technologies are described in Chapter 3 and 4.

1. An important issue concerns the **relationship between production costs and prices** during the development and market introduction of a new product. In an ideal situation, production costs should be used for devising experience curves. However, often only price data are available. Price data however are not only based on the production costs, but also on the marketing strategy, the demand for the product, the amount of competition, the height of available subsidies, et cetera. The Boston Consulting Group described a possible relationship between prices and costs during the introduction of a new product (BCG, 1968, see also Figure 2.5). The model is divided into four phases: in the first phase a manufacturer introduces a new product at a price lower than the production costs in order to compete with existing alternatives and create a market (also called forward pricing). With increasing production volume, costs decline rapidly while prices are dropping at a lower rate. During this 'umbrella' phase, increasing profit margins may attract competitors producing the same product. Commonly, the prime producer will have a dominant position in the market and is able to determine the market price for an extended amount of time. Later, a shakeout occurs, and prices decline rapidly for a short period of time. Finally, in a stable phase, both prices and costs decline at the same speed, i.e. relative profit margins are constant. In this model, only in the last phase, the slopes of both cost and price curves are identical; and only then prices can be used to estimate cost reduction rates. Thus, if the experience curve is used for future cost projections in these early stages of diffusion, serious errors may occur (Jensen and Dannemand Andersen, 2004). Also, when a stable situation is reached, this does not necessarily guarantee that this situation will remain so forever. Depending on factors like changing demand, changing number of suppliers or declining government support a new 'umbrella' or 'shakeout' phase can occur.

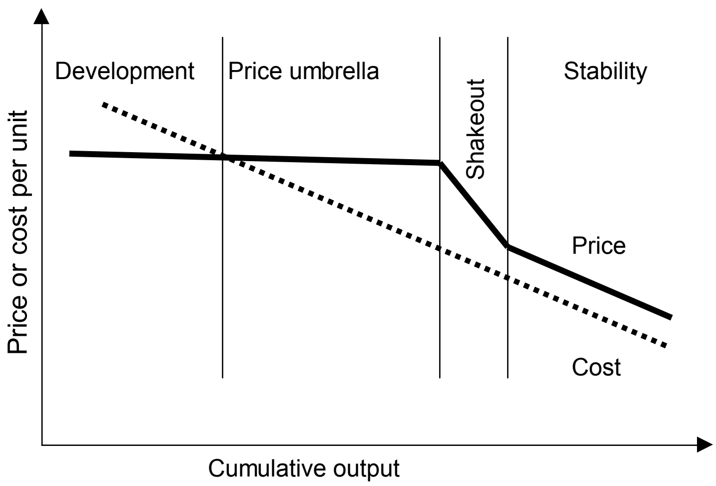

Figure 2.5 Relationship between costs and prices during market introduction of a new product (adopted from BCG (1968)).

However, also if technologies are in a further state of market diffusion, it is by no means guaranteed that prices will follow production costs. If for example market demand increases strongly, prices may remain constant or even increase (strongly), while production costs may continue to decline. On the other hand, prices may also drop sharply. One example is the 'super-saffra', the super-harvest of sugarcane in Brazil in 1999 due to extremely favourable weather conditions (Van den Wall Bake, 2005). The oversupply of sugarcane caused prices for ethanol and sugar to decline sharply for one year, only to return to previous levels the next year.

One particularly controversial issue is the (over-)stimulation of demand by (generous) policy support measures and its effect on market prices. Experience curve theory indicates that if cumulative production and use is stimulated, production costs will come down. Thus, in many countries, (renewable) energy technologies have received generous support to stimulate market diffusion. This has often led to high diffusion rates, and can generally be considered a huge success. However, such policy can also have an effect on prices. For example, in Germany, prices of wind farms remained stable (and list prices of wind turbines even increased) during 1995-2001. This was likely caused by the generous German feed-in tariffs, and subsequently high demand for wind turbines (Junginger et al., 2005)[10]. More general, all over the world, wind turbine prices have increased since 2004, which however may also be attributed to a number of other factors, such as increasing raw material prices, increasing prices of reference technologies, and fluctuating US$ - € exchange rates (see Section 3.1.1. on onshore wind for a more elaborate discussion).

We emphasise that too high market stimulation will not necessarily slow down technological learning and production cost reductions, but it may influence prices, thus compromising the suitability of the price data for experience curve analysis. Surprisingly, in many studies these problems are barely addressed. For historical analysis, it should always be investigated (at least qualitatively) how market demand and supply have developed over the timeframe investigated, and whether it was likely to have a price-distorting effect. If so, the data should be considered unsuitable to determine the ‘true PR’, i.e. the speed with which production costs decline with cumulative capacity.

2. The experience curve uses cumulative output as a substitute for accumulated experience. This implicates that the concept does not indicate at what time a certain cost level may be reached; this depends on the market growth and diffusion of the technology. An open issue is, whether or not the experience curves flattens out with increasing market penetration, i.e. whether the **PR is constant or not**. Intuitively, one would expect that cost reductions cannot be achieved endlessly. Grübler (1998) argues that costs are reduced relatively fast during the innovation/RD&D phase, but that the PR may change to a higher level (i.e. lower cost reductions) when a technology enters the commercial market. McDonald and Schrattenholzer (2002) argue that a constant PR may depend on an exponential market growth. As soon as the turning point in the S-shaped diffusion curve is reached, and annual production volumes become linear or even decrease, the experience curve will eventually flatten out and the PR may reach unity. On the other hand, it can be argued that cumulative doublings of unit production are achieved with relative ease during the innovation and niche market phase of a technology, but as the market reaches saturation, it may take much more time to reach another doubling of cumulative production. Thus, the cost reduction possibilities are also limited by market volume. Cost reduction may then slow down in time, and come to halt when the market is saturated or other technologies take over. This however does not necessarily require the PR to change. Another argument against PRs converging towards 100% with increasing market penetration is the fact that technology development is not necessarily linear, i.e. R&D and market niches phases may be repeated (see also Section 2.3.3.).

3. It is also a question **whether a PR can actively be influenced by policy measures**. The experience curve itself only describes the empirically found trend, and does not open the ‘black box’ of the underlying mechanisms. Several attempts have been made to disaggregate the experience curve, and to describe the effects of RD&D and learning-by-doing[11] separately (see e.g. Kouvaritakis et al. (2000) and Klaasen et al. (2005)). While this approach might yield a more accurate estimation of the past and possible future cost

[10] However, also other factors may have contributed to the price stabilization. In the Extool project, it was found that prices of wind turbines increased in Germany but not in Denmark. As wind turbines being implemented in Germany at that time were much bigger than those being implemented in Denmark, increasing cost may have been also was due to introduction of the really large wind turbines (new concept, higher risk, more difficult to transport) (Neij, 2008).

[11] Note that in this context, “learning-by-doing” represents all (learning) mechanisms occurring during the phases from niche market commercialization onwards.

reductions, it also requires detailed data, which may not be available in many cases. Also, the principal question remains, whether it is possible to forecast the effect of RD&D spending separately, even if it is for a single technology.

4. There is also the issue of **uncertainty** in experience curves, and resulting consequences. Given the empirical nature of the data and related inherent uncertainties, the slope of an experience curve (i.e. the PR) is likely to vary to some extent when key parameters are changed like the assumptions about initial capacity installed, the associated start-off costs, the method of aggregating annual data, correcting for inflation and varying exchange rates[12] and changing the learning system boundaries. As Neij (1999) and van der Zwaan and Seebregts (2004) report, already small changes in PR can lead to strongly deviating results for (long-term) scenarios and energy models using experience curves to model endogenous learning.

5. With the expansion from a corporation level to entire industries, the **system boundaries** are enlarged. This has led to experience curves being devised from an industry perspective (cumulative units produced by a manufacturer or an entire industry) but also from a market perspective (i.e. how much is installed in a country) (Neij et al., 2003). While country-specific experience curves may be suited to evaluate local policy measures in the past, they may not adequately measure the actual rate of cost reduction of a technology at present. For example, for the development of railroad technology, the phases from invention to niche market exploitation mainly occurred in the United Kingdom between 1769-1824. Only later on with the beginning of diffusion into the market, railroads spread to other European countries, the US, and finally all over the globe, a process which took over 70 years (Grübler et al., 1999). Nowadays, with much more advanced communication systems, multinational corporations and an internationally orientated research community, inventions and innovations normally spread much faster. Many modern renewable energy technologies (e.g. wind, biomass and solar) are developed and implemented in different countries simultaneously. Thus, the development of new technologies today is often a global (or at least multinational) process already in early stages of the life cycle. But while experience curves for photovoltaic modules have almost exclusively been devised for globally produced/shipped modules, for wind turbines, the large majority of historical studies covers country-specific installed capacities. This is of particular importance, especially when PRs based on national experience curves are used in global energy models. Analyzing parts of a learning system only may provide misleading results and deviations in the PR.

6. It has been empirically found that **PR may depend on the type of technology**. Neij (1997) distinguishes three categories of technologies: module technologies (e.g. solar modules), large and small plants (e.g. power plants) and continuous processes (e.g. the bulk production of chemical compounds). Typically, the PR for modular technologies is found to range from 70-95% (average 80%), for plant technologies from 82->100% (average 90%), and for continuous processes from 64-90% (average 78%). While it is probably not possible to determine exact progress ratios for all technologies based on their physical and production properties, a general higher progress ratio for larger plants and a lower progress ratio for modular technologies is empirically found. Schaeffer (2008) remarks that ´plant technologies´ all are technologies that combine several learning components. Wind offshore for instance combines the learning of wind turbines with the learning of cable making and installation in the sea with construction of the support structures at sea (see e.g. Junginger, 2005). The wind turbines can be seen as having evolved from the onshore wind turbines, cable making and installation at see have been done for a longer time already etc. Something similar is the case with natural gas combined cycles, where steam turbines have been used before and gas turbines also, even in other industries (like aviation). One way of getting a better insight into the PR of these technologies, a ´clustering and spill-over approach´ could be used, such as being done in the MARKAL model (Seebregts et al. 2000).

[12] Often, experience curves are devised for one country, and thus one currency, which allows for inflation correction with the national CPI (consumer price index) or GDP (gross domestic product) deflator. As soon as several countries with different currencies are involved, the choice of reference currency and method of converting other currencies to the reference currency can seriously influence the PR (Snik, 2002).

Within the field of renewable energy technologies, the experience curve concept has been applied so far to modular products mainly, such as PV modules and wind turbines. Far fewer studies have been performed on cost development of plant technologies, such as biomass power plants, or the cost of energy carriers (e.g. advanced fuel from biomass). Little is known on the kind of learning processes being responsible for experience accumulation and cost reductions in these cases. Thus, for these types of energy technologies and energy carriers, the possibilities and limitations of constructing experience curves and understanding the learning processes involved need to be further explored. Wene (2007) presented a novel approach of considering technology learning systems as non-trivial machines, and discussed further reasons why progress ratios of different technologies may differ, e.g. grafted technologies and (series of) radical innovation.

7. In the construction of experience curves for renewable energy technologies, mostly data on **Best Available Technology (BAT) production cost**[13] are used, especially for modular technologies such as wind turbines and PV modules. For these technologies, the investment costs largely determine the overall electricity production costs. Also, after the first few years of operation the electricity production costs for these technologies tend to remain constant (or even rise with increasing O&M costs at the end of the economical lifetime). However, for plants producing a certain commodity (such as biomass plants producing electricity), also significant learning could occur during the operation of the plant. Typically, a plant achieves a rather low load factor in its first year of operation, and only achieves the design load factor after several years, when all start-up problems have been solved. In addition, electricity costs are influenced by fuel costs; these costs may decline over the entire lifetime of a plant as an effect of more efficient supply chains. O&M costs may decline because of automation and efficiency gains on one hand, but rise due to increasing age of the plant on the other hand. Therefore, it may also be interesting to analyze the **average production cost** development. Empirically, it was shown that the experience curve approach can also be applied to describe the development of average production costs. For example, average data have been used in experience curves describing the cost development of different chemical commodities, the production of electricity in the United States (BCG, 1968) and the carbon intensity of the global economy (IEA/OECD, 2000).

8. Often within a learning system, different **sub-learning systems** can be distinguished. For example, for the case of PV systems, a subdivision can be made for the PV module costs and the BOS (balance of system) costs (the remaining costs, e.g. the inverter, power control, cabling and installation costs). This approach may also be possible to other renewable electricity technologies, such as offshore wind farms (which may be separated into the wind turbines, marine foundations, electrical infrastructure and installation costs) or biomass plants. By making separate analyses for each subsystem, it may be possible to use the experience curve approach for technologies, which in itself have too short a history to use the concept straightforwardly.

9. Progress ratios are used for forecasting development of many technologies as a means to model endogenous technical change in for instance climate-economy models. These forecasts are highly sensitive to uncertainties in the progress ratio. As a progress ratio is determined from fitting data, a coefficient of determination R^2 is frequently used to show the quality of the fit and accuracy of the progress ratio. Although this is instructive, we recommend using the **progress ratio error** σ_{PR}. This error can be directly determined from fitting the data, using Equation (1). The error σ_{PR} in the progress ratio can be calculated from error propagation theory as given by Bevington (1969):

[13] The term BAT *production costs* is used here in the sense that only cost data from recent shipments of a technology are used, to calculate the production costs of e.g. electricity. The term *average production costs* implies that also the production costs of operating plants built in previous years are taken into account.

$$\sigma_{\mathrm{PR}} = \left(\frac{\mathrm{d}\left(2^m\right)}{\mathrm{d}m} \right)_m \sigma_m = \ln 2 \cdot 2^m \cdot \sigma_m = \ln 2 \cdot PR \cdot \sigma_m \quad (4)$$

in which σ_m is the error in parameter m, resulting from non-linear fitting of Equation (1). To illustrate the method, three technology examples are given in Van Sark (2008a): wind farm development (data from Junginger et al, 2005), bio-ethanol (data from Goldemberg, 2004), and photovoltaic technology (data from Parente et al, 2002, Maycock, 2002, and Strategies Unlimited, 2003). Analysis of wind farm development in the United Kingdom was shown to yield 0.805±0.010 for the period 1992-2001; for Spain PR=0.851±0.016 is found for the period 1990-2001. Fitting analysis of the bio-ethanol experience curve showed that PR = 0.832±0.013 for the period 1985-2002. The values of PR determined by our fitting method are in excellent agreement with the reported values for wind farm and bio-ethanol development, and an error to these values is added. The case of PV technology development yielded PR=0.794±0.004 for the period 1976-2001, based on the dataset from Strategies Unlimited, see also De Moor et al (2003). Comparison with results reported by Parente et al. (2002) revealed a clear difference in PR values, which apparently is due to the fact that another dataset, from Maycock (2002), was used. The difference in PR values is larger than the error σ_{PR} that we determined. A 'correct' value of PR is therefore difficult to specify, and a detailed study on the origins of the difference in datasets is needed.

Thus, scenario developers can directly use the PR values and their errors for justification of the range of PR in sensitivity studies. They should be aware that progress ratios may not be constant, although historical data provide evidence that assuming constant progress ratios is a valid approach to include endogenous technological learning in their climate models. Re-evaluating progress ratios when new data become available is therefore always needed and up-dating experience curves should be part of technology development research.

Fitting the data may be limited by the use of data sets that consist of one data point per year. These data points are determined by averaging several data points available for a particular year. The resulting data points are taken as being accurate, i.e., as having no error, while determination of the standard error of the mean is easy. In fact, using errors in these data points in fitting the curves, will lead to larger errors in the progress ratio. One may even consider weighted fitting. Therefore, the error in PR as presented above for the three technology cases should be regarded as the lowest that one can determine. We therefore recommend that in future studies experience curves should be depicted and fitted using errors also in individual data points. Scenario developers should choose their range in sensitivity studies using the error in PR as the lowest bound of their range.

10. Progress ratios are derived from historical data represented in experience curves. Fitting the double logarithmic graphs is easily done with Microsoft Excel spreadsheet software, by adding a trend line to the graph. However, it is unknown to many that Excel performs data transformation prior to fitting: the data are transformed to linear data before a fit is performed. This leads to erroneous results or a **transformation bias** in the progress ratio as is demonstrated using the updated experience curve for photovoltaic technology (Van Sark, 2008c). Using Excel one finds PR=0.805; using non-linear fitting one finds PR=0.794. Generally, PR values obtained from Excel are larger than values obtained from non-linear fitting. Other graphing and analysis software able of performing non-linear fitting is therefore recommended, e.g., Origin, Sigmaplot, or Mathematica.

2.3 Putting experience curves in context: links between technological development, market diffusion, learning mechanisms and systems innovation theory

2.3.1 Introduction

As far as the experience curve approach goes, the focus is mainly on the development of the technological artefact (e.g. a wind turbine or biomass power plant). However, the experience curve offers no explanation by itself why costs should decline in the first place. As illustrated in section 2.2, circumstances such as market developments, knowledge diffusion, sectoral and geographical system boundaries all can have an impact on (the applicability of) the experience curve approach. Yet, many studies do not place experience curves in a broader context. Therefore, in this section it is explored, in how far theories on market diffusion and learning mechanisms can contribute to the better understanding of cost reduction mechanism; and whether systems innovation theory is suitable to place experience curves within the broader context of an innovation system.

2.3.2 The classical linear model of technology development and market diffusion

For each new technology, different stylized stages can be described over time using a life-cycle model, from invention, (applied) research, development, demonstration, niche market commercialization, pervasive diffusion and saturation to senescence (see Table 2.1). Generally, the diffusion follows an S-shaped growth pattern, i.e. slow growth during the invention and RD&D stages, high growth during the niche market commercialization and pervasive diffusion stages, and again low growth during market saturation stage (and negative growth during the senescence stage). Each stage typically takes several decades (Grübler, 1998), but the stages often display significant overlap, and are difficult to separate.

Table 2.1 Stylized stages of linear technological development and typical characteristics (slightly adapted from Grübler et al. (1999)).

Stage	Mechanism	Cost	Commercial market share
1. Invention	Seeking and stumbling upon new ideas; breakthroughs; basic research	High, but difficult to attribute to a particular idea or product	0%
2. RD&D[a]	Applied research, research development and demonstration (RD&D) projects	(Very) high, increasingly focused on particular promising ideas and products	0%
3. Niche market commercialization	Identification of special niche applications; investments in field projects; 'learning by doing"; close relationships between suppliers and users	High, but declining with standardization of production	0-5%
4. Pervasive diffusion	Standardization and mass production; economies of scale; building of network effects.	Rapidly declining	Rapidly rising (5-50%)
5. Saturation	Exhaustion of improvement potentials and scale economies; arrival of more efficient competitors into market; redefinition of performance requirements	Low, sometimes declining	Maximum (up to 100%)
6. Senescence	Domination by superior competitors; inability to compete because of exhausted improvement potentials	Low, sometimes declining	Declining

a Grübler et al. (1999) refer to this stage as 'innovation stage'. However, the term 'innovation' is generally used much broader, covering the first and third stage too.

2.3.3 Limitations of the linear technology development model[14]

Within the classical conception of a linear image of technology development, every technology develops according to predefined lines, e.g. from invention to research to demonstration to market. In certain ´stages´ of technology development experience curves would behave differently than in other stages. However, the concept of such a necessary linearity of technology development has been criticised since the early 1980s by science and technology study researchers, such as Bruno Latour, Michel Callon, Wiebe Bijker and Arie Rip. They showed that very often in practice technology development does not follow such a linear path. Also within energy technologies, one can easily find examples of different paths being chosen. Wind and solar energy are typically technologies where market penetration and research/development activities have been undertaken in parallel. This in contrast to for instance the development of fuel cells, where research and demonstration are the main features of their development, but market penetration has not been chosen as a development path[15]. An interesting study by Joergensen and Karnoe (1995) shows that also in the development of wind energy technology the linear approach (by the US) and the parallel approach (by Denmark) were tried out at the same time, where the linear approach failed and the parallel approach succeeded. These insights are relevant for experience curves for the following reasons:

1. As there is no necessary order of stages of technology development, also there is no predefined need for PRs to go up or down.
2. PRs will depend on the character of the different activities (e.g. as described by innovation theory) and how they are interlinked.
3. For technologies that are predominantly characterised by research and demonstration for a long time (e.g. fuel cells or nuclear fusion), the experience curve might not be the best approach. Time trends might be a lot better in that case. For fuel cells a very good fit of cost versus time could be constructed (Schaeffer, 1998).
4. Also the stages described by the Boston Consultancy Group are not per se finished after one cycle. `Earlier´ stages might come back or the cycle might be repeated several times. (see also Section 2.2, point 1)

2.3.4 Learning mechanisms

In each of these stages, different learning mechanisms play a role in the improvement of the technology, which typically result in a higher conversion efficiency and reliability, easier use and lower investment, operation and maintenance costs. Different learning mechanisms have been described by, amongst others Utterback (1994), Garud (1997), Grübler (1998; Grübler et al., 1999), Kamp (2002) and Dannemand Andersen (2004)[16]. These authors have developed different approaches to conceptualize knowledge and learning. Most authors identify several of the following mechanisms influencing both the production process and the product itself (Neij et al., 2003) behind technological change and cost reductions:

Learning-by-searching, i.e. improvements due to RD&D, is the most dominant mechanism in the stages of invention and RD&D, and to some extent also during niche market commercialization. Often also during the stages of pervasive diffusion and saturation, RD&D may contribute to technology improvements.

Learning-by-doing (Arrow, 1962) takes place especially in the production stage after the product has been designed. Typically, the repetitious manufacturing of a product leads to improvements

[14] This section is a slightly altered version of review comments given by Schaeffer on an earlier draft of this report (Schaeffer, 2008).

[15] An interesting case where science development (aerodynamics in this case) has followed technology development and market penetration is the aviation industry.

[16] For renewable electricity technologies, different studies have investigated these mechanisms during the RD&D and niche market commercialization stage, see for example Kamp (2002) and Garud and Karnøe (2003) for wind energy, Raven and Gregersen (2004) for biogas digestion plants, and Schaeffer et al. (2004) for solar photovoltaics.

in the production process (e.g. increased labor efficiency, work specialization and production method improvements).

Learning-by-using (Rosenberg, 1982) can occur as a technology is introduced to (niche) markets. A technology cannot be fully developed inside laboratories and factories. Feedback from user experiences often leads to improvement of the product design.

Learning-by-interacting is related to the increasing diffusion of the technology. During this stage, the network interactions between actors such as research institutes, industry, end-users and policy makers generally improve, and the above-mentioned mechanisms are reinforced (Kamp, 2002, Lundvall, 1988). In other words, the diffusion of knowledge itself supports the diffusion of the technology[17].

Upsizing (or downsizing) and redesigning a technology (e.g. upscaling a gas turbine) may lead to lower specific unit costs (e.g. the costs per unit of capacity).

Economies of scale (i.e. mass production) can be exploited once the stage of large-scale production and diffusion is reached. Standardization of the product allows upscaling of production plants, and producing the same product in large numbers.

Often, combinations of these factors occur in each stage, and the contribution of each may change during the development of a technology over time. Also, not all factors may apply to all technologies. Some authors differentiate between effects of (technological) *learning* (such as the first three factors) and *scale effects* (such as the last two factors) (Abell and Hammond, 1979).

However, in practice these factors often overlap and are difficult to separate (Neij, 1999a). Also, in most cases both upscaling and mass production of a technology or production process requires many steps[18]. During each step, experience is gained by learning-by-doing and learning-by-using, which is then incorporated in the next generation of the technology[19].

While these factors describe the mechanisms behind cost reductions qualitatively and in hindsight, it is a different matter to quantify the effects of each mechanism separately, and to make projections about their possible contribution in the future when developing a technology. Further knowledge development in this field would be interesting and highly relevant to understand how technological development can be influenced in a cost-effective way. Future projections may be based (at least to some extent) on past achievements, e.g. returns on investment from RD&D expenditures, but RD&D expenditures are no guarantee for cost reductions and returns on RD&D investments may vary. Scaling laws can be used to project potential cost reductions. Yet, upscaling a plant normally requires considerable RD&D expenditures and investments in pilot plants to solve problems arising from the larger scale and to make investment risks known and acceptable. In the end, it is the combination of learning mechanisms causing cost reductions, which makes quantifying the effect of each mechanism separately difficult. A concept, measuring the aggregated effect of these mechanisms is the experience curve approach.

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[17] Somewhat related to this mechanism, Rotmans and Kemp (2003) also mention 'learning by learning', indicating that the primary learning processes themselves can improve over time. In addition, Schaeffer et al. (2004) distinguish 'Learning by expanding', recognizing the fact that more actors, organizational structures and industrial sectors become involved in, focused on, dependent on and adapted to the new technology. Arthur (1988) calls this mechanism 'increasing returns on adoption'.

[18] For example, it took over 20 years and over one hundred plants to scale up steel plants from 0.3 to 8 million tons of steel output capacity (Grübler, 1998). A similar trend and time span was found for fluidized bed boilers (Koornneef, 2007). Cost reductions due to mass production are of course not all related to learning. Larger production volumes will for example allow manufacturers to negotiate lower prices for raw materials and reduce relative overhead costs. Yet, it is clear that to design, build and operate larger production plants, learning will be required as well.

[19] This process is documented in detail for the development and upscaling of Danish wind turbines by Neij et al. (2003).

Finally, it is important to point out that as the learning leading to price decreases in experience curves is a very complex process, it does not only include technology learning (Schaeffer, 2008). It also includes:

- Economic learning (e.g. shifting production to low-wage countries)
- Financial learning (e.g. banks/investors that get confidence in a new technology and reduce their Return on Investment requirements interest rates). This is especially important for experience curve analyses based on Cost of Electricity.
- Social learning (actors that get to know and trust each other better).

2.3.5 Technological change and systems innovation theory[20]

There is strong need to influence both speed and direction of innovation and technological change (e.g., to accelerate energy efficiency improvements). Many concepts have been developed to open up and describe what's inside the black box of innovation and technology development. Innovation is described by various different approaches, including neo-classical economics, evolutionary economics, industrial networks, quasi-evolutionary and large-technical systems approach. Most innovation theories are either very broad in scope (e.g., quasi-evolutionary economics) or narrow in its focus (e.g., neo-classical economics).

Over the last decades, learning theories combined with evolutionary economics have led to the innovation systems theory that expands the analysis of technological innovation, covering the entire innovation system in which a technology is embedded. An innovation system is thereby defined as the network of institutions and actors that directly affect rate and direction of technological change in society. The concept of innovation systems was designed as a heuristic attempt to guide the analysis of complex economic structures and processes. There are multiple innovation systems approaches, i.e. national, regional, sectoral, and technological.

Technology, or the knowledge it embodies, is hardly ever embedded in just the institutional infrastructure of a single nation or region, since - especially in modern society - the relevant knowledge base for most technologies originates from various geographical areas all over the world. We find a similar argument for the relevance of a strictly sectoral delineation. Thus, by taking a specific technology as a starting point, the technological system approach cuts through both the geographical and the sectoral dimensions. This is illustrated in Figure 2.6, which schematically shows how the Technology Specific Innovation System (TSIS) relates to the geographical and sectoral dimensions of respectively the national systems innovation and the sectoral innovation systems approach. It shows that the Technology Specific Innovation System overlaps with parts of various national innovation systems and with various sectoral innovation systems which, in turn, are embedded in national systems of innovations.

[20] Section 2.3.5 is a brief description of the systems of innovation theory. We thank Roald Suurs for helpful comments and additions.

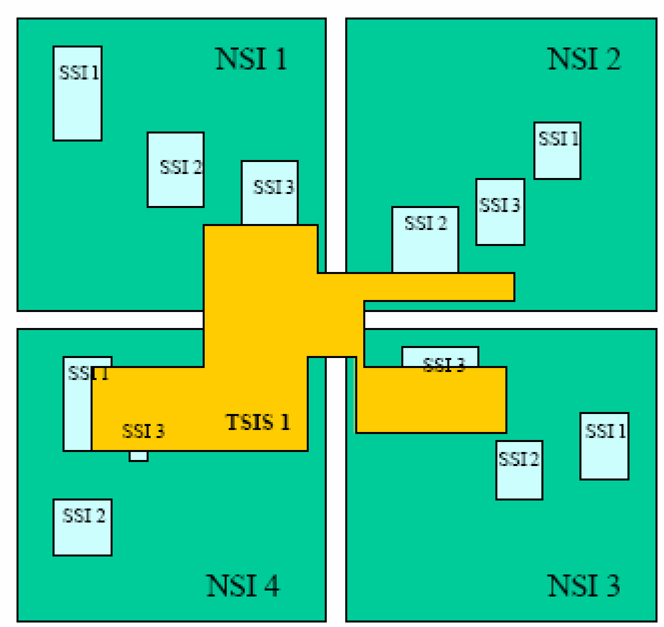

Figure 2.6 Boundary relations between national, sectoral and technology-specific innovation systems (Hekkert et al. 2007) .

The systemic character of technological change explains why technological change is often a very slow process and why it is difficult to influence it. The rate and direction of technological change is in general not so much determined by simple conflicts or complementarities between different technologies, but predominantly by the interactions between various existing innovation systems. There can be inertia between, e.g., technology-innovation systems and the underlying technology or between two technology-innovation systems that may result in relatively rigid technological trajectories. In other words, the key reasons why technological progress often proceeds along certain trajectories are explained by the complex interactions between technology-innovation systems. Understanding technological change implies therefore creating insight in the relations between incumbent technologies and the incumbent (innovation) systems in relation to the emerging technologies and the emerging innovation systems.

The Multi-Level-Models approach pays attention to the context of a technological system and the interactions between its various levels. The Multi-Level-Models approach can be especially suitable to analyze the circumstances under which a niche technology is so successful that it becomes part of the existing technology regime.

The situation can be illustrated using the example of PV development. Advances in PV depend on technological progress made in research institutes and universities all over the world. Thus, the PV innovation system overlaps with those parts of national innovation systems that concentrate on PV research. In turn, global diffusion strongly depends on different national policy regimes that stimulate the adoption of PV by means of investment subsidies or feed-in laws. Again, the PV innovation system overlaps with various national innovation systems in terms of stimulating institutions for solar cell diffusion. Furthermore, the production conditions for PV panels strongly depend on the microelectronics sector due to competition over silicon wafers. Silicon wafers are produced for the microelectronics sector, but the surplus of wafers is sold to solar cell manufacturers. High growth rates in the microelectronics sector lead to silicon shortages and higher prices of solar cells (van Sark, 2007). Furthermore, the application of PV strongly depends on the housing sector, including architecture and ownership characteristics. PV friendly architecture can greatly influence the potential for PV in the building environment and the subsequent energy output. Thus, the technological progress, price, and diffusion of one technology is influenced by the various national and sectoral innovation systems.

Analyzing innovation systems requires hence a broad scope including the multiple factors and agents influencing innovation on the various spatial and time scales. The use of the innovation system framework to understand technological change has, however, two shortcomings, i.e., (i) in most analyses, innovation systems are treated as quasi-static rather than dynamic in character and (ii) the explanatory power of the framework lies mainly in the part of institutions (macro level), and less on the actions of the entrepreneurs (micro level) (Hekkert et al., 2007). A dynamic innovation systems approach that covers both micro and macro dynamics is hence needed to better understand and guide innovation.

To solve existing shortcomings, Hekkert et al. (2007), proposed the so-called functions of innovations approach. This approach focuses on a number of processes that are highly important for innovation systems. Hekkert et al. (2007) argue that the analysis of technological change should focus on the systematic mapping of activities that take place in innovation systems. Several researchers (e.g., Edquist and Johnson (1997), Hekkert et al. (2007)) identified crucial functions that are required both to map key activities and to describe shifts in technology-specific characteristics in innovation systems. They can be summarized as follows:

- Entrepreneurial Activities: At the core of any innovation system are the entrepreneurs. These risk takers perform the innovative commercial experiments, seeing and exploiting business opportunities.
- Knowledge Development: Technology research and development are prerequisites for innovations, creating variety in technological options. Research and development activities are often performed by researchers, but contributions from other actors are also possible.
- Knowledge Diffusion: The typical organisational structure of an emerging innovation system is the knowledge network, primarily facilitating information exchange.
- Guidance of the Search: Often within a transition trajectory, various technological options exist. This function represents the selection process that is necessary to facilitate a convergence in development, involving for example policy targets, outcomes of technical or economical studies and expectations about technological options.
- Market Formation: New technologies often cannot outperform established ones. In order to stimulate innovation it is necessary to facilitate the creation of (niche) markets, where new technologies have a possibility to grow.
- Resource Mobilisation: Material and human factors are necessary inputs for all innovation system developments, and can be enacted through e.g. investments by venture capitalists or through governmental support programs.
- Support from Advocacy Coalitions: The emergence of a new technology often leads to resistance from established actors. In order for an innovation system to develop actors need to raise a political lobby that counteracts this inertia, and supports the new technology.

Based on an analysis of case studies (involving mainly energy technologies), Hekkert et al. (2007) propose that the majority of these functions have to be adequately satisfied to enable an innovation system to succeed.

2.3.6 Combining Innovation Systems Theory and the Experience curve approach

As described in Section 2.1 the focus of experience curves is mainly on the development of the performance of the technological artefact (e.g. a wind turbine or biomass power plant). A few studies using the experience curve approach in historic analyses pay some attention to the broader frame of strategic niche management and changing regimes to explain mainly why the technology did (or did not) penetrate the market. However, as illustrated in section 2.2 on methodological pitfalls, circumstances such as market developments, knowledge diffusion, sectoral and geographical system boundaries all can have an impact on (the applicability of) the experience curve approach. Thus, it is worthwhile exploring, to what extent general innovation theory could contribute to support the experience curve approach. It should be noted that this a considered an interesting idea for future work rather than a current application of experience curves.

On the other hand, innovations system theory typically aims to describe historical developments in hindsight. Only few attempts have been made to apply this knowledge to make (quantitative) forecasts regarding the market penetration and/or development of production costs. The latter is typically a strong point of the experience curve approach.

In Table 2.2, the strengths and weaknesses of the experience curve approach in comparison to the innovation systems approach are briefly summarized.

The two approaches both have strengths and weaknesses, which are to a certain extent complementary. The experience curve approach and the innovation functions approach could possibly be combined in the following two ways:

(i) In historic studies using the experience curve approach, cost reductions are a sole function of market formation/deployment. While ideally such an analysis should go hand in hand with a description of technological, political, and market developments, a complementary analysis of the entire innovation system and the relevant innovation functions could possibly provide more detailed insights into the drivers for continuous market formation and subsequent cost reductions.

(ii) In prospective studies using the experience curve approach, scenarios for future cumulative production are often based on policy targets (e.g., with respect to the shares of energy produced from renewable resources or the amount of energy saved due to energy efficiency measures) and the accompanying market diffusion rates necessary to reach these policy targets. Exploring the likelihood of reaching the established policy targets is however impossible solely based on the experience curve approach. Here, the systems innovation approach with its innovation functions could provide valuable insight into the extent to which system functions need to be changed to increase the likelihood of achieving the established market diffusion targets.

Table 2.2 Strengths and weaknesses of the experience curve approach in comparison to the innovation systems approach

Criteria	Experience curve approach	Innovation systems approach
Strengths	• Allows to quantify the dynamics of total production costs as function of cumulative production • Allows to estimate the costs for policy measures to make a technology competitive compared to the incumbent technology • Supports the projecting of future trajectories of energy technologies in energy and emission models • Methodology is simple and requires only limited data input for analyzing future cost reductions	• Takes into account multiple aspects of learning as well as stakeholder and technology interactions, thereby: • Accounting for the entire innovation system, including also actors, institutions, and their relations. • Takes into account historical developments, including past successes and failures in the development of technologies or the innovation systems around them • Includes different functions of innovation, of which most can be quantified either directly or using proxies
Weaknesses	• Focuses only on the dynamics of production costs (e.g., economics of scale, learning by doing) but excludes other innovation functions • Does not provide an understanding of drivers for the observed cost dynamics • Treats cost dynamics as black box thereby not separating cost components that depend and do not depend on technological learning • Provides only limited insight into market potentials of products because only production costs of technologies are quantified	• Provides very limited quantitative information to assessable future market penetration potentials of technologies • Provides limited quantitative analysis for cost dynamics to support policies in creating, e.g., niche markets

While such a combined analysis so far has not been carried out, such a hybrid approach could particularly be interesting for prospective studies for technologies currently at the beginning of commercial market penetration, such as offshore wind energy, super-critical coal combustion, coal/biomass gasification or various heat pump applications. For these technologies, in general data for experience curves may be available form niche market applications, and all functions of the TSIS can be well-described. Also of interest could be technologies on the verge of (niche) market introduction, such as micro-CHP (combined heat and power), 2^{nd} generation biofuel production, various CCS (carbon capture and sequestration) technologies, advanced pyrolysis / torrefaction concepts and use of fuel cells in transportation vehicles. For these technologies, no or limited data is available for historic cost reduction achieved, but progress ratios could be estimated by comparison with existing technologies, and again, such system can be well-described with the innovation systems approach.

From a methodological point of view, it could be worthwhile exploring whether in historic case studies reduction of production costs can be linked statistically to increasing entrepreneurial activity, market formation and/or resource mobilisation, which could enable the increasing quantification of systems functions.

2.4 The use of experience curves in energy models

2.4.1 Introduction

Forecasting, the principal aim of many energy models, inherently implies uncertainty. The more complex the system is modelled, the more difficult forecasting future developments becomes. To reduce the uncertainty that is related to future events one can change exogenous, pre-described cost reductions into endogenous, model-driven cost reductions. The latter cost reductions are modelled often via experience curves. Experience curves can handle the complexity of realizable cost reductions better.

Model-endogenous cost reductions enable the possibility to evaluate the impact of policy measures on realizable future cost reductions. However, the more complex a model becomes, the harder it is to interpret the model outcomes. If one acknowledges the new uncertainties that are introduced by experience curves in energy models, one is also better equipped to interpret the endogenous learning included model outcomes in general, and the significance of model forecasted future cost reductions in particular.

This section briefly recalls exogenous learning methods. For endogenous learning, a distinction is made between top-down models that are typically macroeconomic models, and bottom-up models that are often system-engineering models. For both types of models, examples using endogenous learning are given from literature. It is followed by an overview of new uncertainty that might be introduced by the experience curves. This section ends with literature's reflection on the pros and cons of the use of experience curves in energy models.

2.4.2 Exogenous learning

Typically, models that do not use the concept of experience curves for endogenous learning, do take future cost reductions of technologies into account. The costs of technologies change in time following an autonomous, exogenous decline path. On aggregated level in macro-economic analyses, it has long been an acceptable approach. These top-down models are typically general equilibrium models. In these models, technological change is a substitution effect that is driven by price changes of the input factors. For all non-price driven improvements in technologies, an Autonomous Energy Efficiency Improvement (AEEI) parameter describes the cost decline.

2.4.3 Endogenous learning in top-down models

The top-down models are by nature more generic than bottom-up models, although the use of experience curves introduces some hybrids approaches in top-down modelling. Table 2.3 shows a selection of top-down models.

Table 2.3 A selection of top-down energy models using endogenous learning, from Kahouli Brahmi (2008).

Model	Focus of analysis	Reference
DEMETER	Optimal carbon tax profile. Optimal abatement profile. Abatement costs and timing	Van der Zwaan et al. (2002) Gerlagh and van der Zwaan (2003)
ETC-RICE	Compliance costs of Kyoto Protocol with and without trading regime. Impacts of induced technological change	Buonanno et al (2003)
RICE	Impacts of technological learning relative to exogenous technological change model results. Effect of endogenous technological change on consumption, physical capital, emissions, abatement rates and R&D expenditures	Castelnuovo et al (2005)
FEEM-RICE	Relationship between the endogenous technological change and climate policies. Assessment of the economic costs for achieving different stabilization targets	Bosetti et al (2006)
MIND	Linkage between energy sectors and the macro-economic environment. Economic mechanisms underlying opportunity costs and the optimal mix of mitigation options	Edenhofer et al (2006)
E3MG	Inducement of further technological change by mitigation policies so as to reduce greenhouse gas emissions and stabilize atmospheric concentrations	Barker et al (2006)
IMACLIM-R	Induced technological change affecting costs of emissions stabilization. Sensitivity of total stabilization costs to accelerate turnover of equipments and non-energy choices	Crassous et al (2006)

Endogenous learning in macro-economic models is modelled in two ways. First, the AEEI can be modelled as function of the energy price. That is, with rising energy prices the costs decline faster than autonomously. Second, investments in R&D increase the cost decline rate. As example of the latter, the RICE model has been improved (Castelnuovo et al. 2003) to make the cost decline as a function of capacity expansion and of accumulated R&D stock. Note that capacity or expansion thereof is not native to top-down models. As such, the RICE model appears to have made a hybrid choice of using a bottom-up system-engineering approach in a top-down macro-economic model.

In 1999, Nordhaus updated his DICE model on the innovative aspects (Nordhaus and Boyer 2000). In DICE, capital and labour can substitute carbon energy. As update, the use of carbon energy is controlled by induced technological change. By comparison, he concluded that the substitution effect is of greater importance than the endogenous technological change. Goulder and Schneider (1999) included learning as increased R&D efforts. They showed that increased R&D efforts in the energy sector can happen on the expense of R&D in other sectors. As such, they concluded that such R&D efforts can have a slowing impact on output and GDP. Goulder and Mathai (2000) used a combined approach, where technological learning is divided into a R&D component representing the 'learning-by-searching' and a learning-by-doing component. This approach of subdividing the learning development is an approach common to many bottom-up models nowadays as well.

2.4.4 Endogenous learning in bottom-up models

The system-engineering perspective common to many bottom-up energy models enables a more technology-specific description of potential future costs decline. The experience curve in its simplest form is a technology-specific function of installed capacity (or comparable variable such as production). This was implemented first by Messner in MESSAGE, who made the specific investment costs a function of cumulative installed capacity. Similar work was performed by Mattson (1997).

Sometimes, the progress ratios are defined for different modules within the same technology (e.g. BioTrans, see Londo et al. (2008)), as an important problem in determining these experience curves is the establishment or definition of the technology in question. Barreto and Kypreos (2004) analyzed that inclusion of endogenous learning in bottom-up models can lead to significantly different model outcomes. See Table 2.4 for some examples of bottom-up energy models.

Table 2.4 Examples of bottom-up energy models, mostly taken from Kahouli-Brahmi (2008)

Model	Focus of analysis	Reference
MESSAGE	Effects of learning-by-doing incorporation on costs and timing	Messner (1997) Grübler and Messner (1998) Gritsevskyi and Nakicenovic (2000)
GENIE	Emergence of new energy technologies, competition between technologies and lock-in effects. Effects of learning-by-doing incorporation on costs and timing.	Mattson (1997) Mattson and Wene (1997)
MARKAL	Effects of learning-by-doing incorporation on costs.	Seebregts et al (2000)
POLES	Marginal and total abatement cost variations. Consequences of changes in public R&D on technology choices.	Kouvaritakis et al (2000)
MERGE-ETL	Impact of learning-by-doing on energy choice and on carbon control.	Kypreos and Bahn (2003)
MERGE	Impact of learning-by-doing on costs and timing.	Manne and Richels (2004)
ERIS	Optimal R&D support for new energy technologies. Crowding-out effects. Effects of emission constraints. Role of optimal allocation of R&D among competing technologies.	Miketa and Schrattenholzer (2004) Barreto and Kypreos (2004) Barreto and Klaassen (2004)
DNE21+	Cost-effectiveness evaluation of technological options to stabilize emissions concentrations.	Sano et al (2006)
GET-LFL	Effects of technological learning. Scenarios for stabilization of atmospheric emissions.	Hedenus et al (2006)
MESSAGE-MACRO	Role of technological change and spillovers in energy transition pathways	Rao et al (2006)
BioTrans	Competition between first generation and second generation biofuels.	Londo et al. (2008)

2.4.5 Learning-by-searching in bottom-up models

The capacity-based experience curve requires a technology to be deployed in order to achieve cost reduction. The final outcome of the model is often subjected to a path dependency. It shows the need for up-front investments to overcome a possible technology lock-in. Near term investments are important for long term developments. However, Manne and Richels (2004) have shown with the MERGE model that it is not necessarily the case that the inclusion of these experience curves supports early action. The up-front investments need not lead to increased market penetration or deployment in niche markets. They might also be targeted at the R&D

budgets. So, a distinction is made between learning-by-doing (with market deployment) and learning-by-searching (through R&D).
The R&D expenditures have some inherent characteristics that make them difficult to incorporate in energy models. First, cost reductions are up to several years behind the R&D expenditures. Second, knowledge depreciates. R&D carried out years ago bears little weight compared to recent R&D. Third, public R&D and private R&D have a different character. However, as public R&D funds can be used to facilitate private R&D efforts, the distinction can be difficult to quantify. Even more, actual and historic private R&D expenditures are hard to quantify and data is often not publicly available.

Bottom-up models project the optimal rather than the actual behaviour of a system. They have inherent difficulties in incorporating macro-economic effects; for example, the opportunity costs of R&D in the energy sector are difficult to include. The opportunity costs dictate that - given a fixed R&D budget - R&D in the energy sector occurs at the expense of R&D in other sectors. Thus R&D in the energy sector may slow economic growth, which can have an impact on the demand that is fed to the model. One can also regard R&D in new energy technologies as insurance against rising energy prices, even when the new technologies are not yet deployed. As stated, these effects are hard to include in bottom-up models.

2.4.6 Learning-by-doing in bottom-up models

The experience curve is an aggregated representation of cost reductions through the combined effects of improvements in the production process, improvements in the product itself and changes in the input prices. The focus of the analysis whereto the model is constructed, determines partially the detail of the experience curve. Specific attention is warranted for the early stages of the experience curve.

Many experience curves or progress ratios are derived for established technologies. Energy models, not uncommonly, have special focus on emerging technologies. Especially for emerging technologies, the impact of policy measures on future cost reductions can be significant. Many uncertainties that are accompanying the use of experience curves, occur in these initial stages of market introduction of emerging technologies.

Consequently to the concept of learning-by-searching, expertise has been accumulated in the R&D phase. The learning-by-doing experience curve does therefore not start at zero production. The first commercially installed capacity does not reduce the production costs as much as expected, since one should take the R&D expertise into account. The first learning in the commercialization phase occurs slower than one might expect based on a single experience curve.

Furthermore, in the early stage of commercialization, often a cost increase is observed. This is considered to be a consequence of shortfalls in performance and reliability, and general problems due to the upscaling of the technology.

Judging the literature, the experience curves applied are subject to a large uncertainty. The large uncertainty might induce modellers to take a default value for the progress ratio’s, e.g. 80%, although comparisons between technologies cannot be justified by such a model anymore. The underlying explanations for the uncertainty should be sought in the topics of price of input (which is learning-independent), cost reductions through scale effects, estimations of cumulative capacity and specific definition of the technology in question. Especially for new and barely deployed technologies, estimation of experience curves is trying. BioTrans, a myopic cost optimization model for biofuel production and use in Europe, includes endogenous learning for the barely deployed second generation biofuels (Londo et al, 2008). In BioTrans, the REFUEL project (Londo et al. 2008)) significantly reduced the uncertainty by expanding the experience curve into a learning-by-doing component and a scale component, assuming that for emerging technologies the up-scaling of facilities mostly determines the early cost reductions. Similar approaches of more detailed model-description of the technological learning have been made in other bottom-up models. Given the uncertainty in experience curves and the importance of path dependence on the outcomes of bottom-up models with endogenous learning, a stochastic run of the model might show many different potential outcomes of the same model, based on slightly different input parameters. As such, the stochastic run or uncertainty analysis provides an indication of the robustness of the model outcome.

2.4.7 Partially exogenous

Models might still use exogenously defined parameters which interfere with endogenously defined experience curves. This makes comparisons between model outcomes challenging. The most striking example is the interaction between costs and performance. In many technologies, a trade-off exists between specific investment costs and process efficiencies. However, as investment costs are typically endogenously defined, process efficiencies not always are. Sometimes, mostly in top-down models, the process efficiencies are left outside the model, which circumvents the issue raised.

Other interactions between exogenous and endogenous functions complicate model interpretations further. For example, the BioTrans model (Londo et al, 2008) uses endogenous learning in conversion technologies, but used exogenous cost reduction in the supply of feedstock (or input prices). Consequently, as BioTrans is a year-based myopic optimization model, the first emerging technology might not be the optimal one in long-term perspective, nor the winning. Furthermore, as a trade-off exists between low-priced input/expensive technology and expensive input/low-priced technology, the model output might no longer show a clear relation between accumulated experience in the technology and the costs of the technology output, see Figure 2.7.

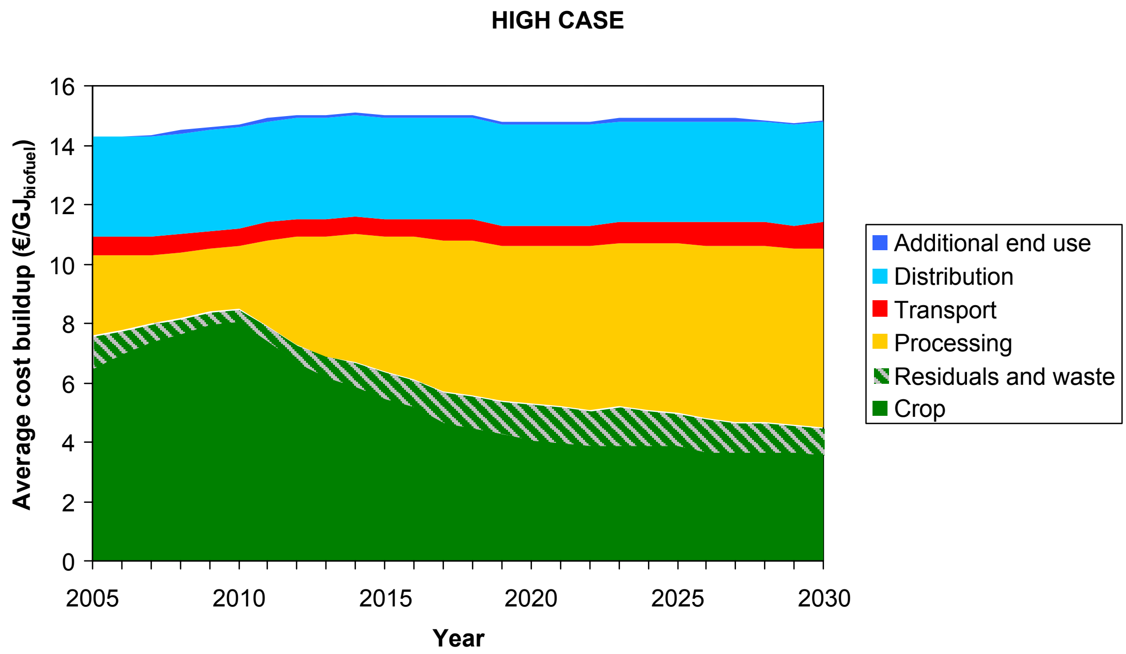

Figure 2.7 Example of the BioTrans model: cost development of biofuels in Europe. Although the average costs of using biofuels is fairly constant between 14 and 15 €/GJ, the biofuel share rises from 2% to 25% and a significant shift towards 2nd generations biofuels occurs. Source: Londo et. al (2008).

It is not inherent to energy models to include limits on technology implementation, although introduction speed and penetration levels allowed are not uncommon. A combined technology-input model, such as BioTrans, creates an external upper limit on technology use. The availability of the input goods can hinder further use of a certain technology. Therefore, one should be aware of how technology penetration is limited by the model, as the concept of experience curves does not limit penetration by itself.

2.4.8 Pros and cons of top-down versus bottom-up learning

Berglund et al (2006) noted that top-down models are better in modelling technology diffusion as technology diffusion is often modelled in relation to R&D. Bottom-up models encounter more difficulties in modelling technology diffusion. Contrarily, top-down models lack detail in the technological options. Bottom-up models can model the learning-by-doing-phase better. As improvement, bottom-up models can use technology clustering to model the spill-overs over technological development between similar technologies, e.g. MARKAL (Seebregts et al, 2000).

The learning-by-searching phase in the emerging energy technologies is typically supported by governmental R&D expenditures, whereas the support for continuous deployment has been formulated as production obligations or production subsidies. Not uncommon in environmental policies, these policies have a stop-and-go character. In reality, cost increases have been observed after production cuts and temporarily stopping of the technologies. As ‘forgetting’ can typically be linked to R&D stocks, top-down models have an advantage in modelling the effects of such discontinuities. Forgetting is more difficult to implement in bottom-up experience curves, as accumulated capacity is a rising function in time.

Finally, environmental technologies are supposed to be attributed with several positive external effects. An aggregated, monetized value can be allocated to these effects more easily the more aggregated the model is. Therefore, top-down models are by nature better equipped to incorporate external effects than bottom-up models.

Bottom-up models and top-down models can co-exist, as each type of model has its strengths and its weaknesses. Despite the pros and cons mentioned for the types of model, there is no a-priori impossibility to include all the side effects mentioned in either of the models.

2.4.9 Pros and cons of endogenous learning

Endogenous technological learning has several advantages over exogenous learning, such as avoidance of ‘learning-without-doing’ (a technology that is not applied, cannot learn by doing). Models with endogenous learning can show the potential benefits of early action better. They can also show the benefits of policy aimed at further market integration of a technology, which models with exogenous learning cannot to the same extent. Other aspects of which the dynamics can be addressed nicely in endogenous learning models are the lock-ins and crowding-outs of technologies.

Issues that enhance the dynamics of technological learning in bottom-up energy modeling are technology clustering and spillover issues (technologies learn from related or other technologies) (Seebregts et al, 2000). As the progress ratios used for the specific technologies can determine the model outcomes to a large extent, one should always guard to draw decisive conclusions on the competitiveness of one technology compared to another. A sensitivity analysis should provide further insight on these issues (Gritsevskyi and Nakicenovic, 2000).

Top-down models using endogenous learning more often focus on innovation and the diffusion process of the experiences gathered, and can be applied for strategic analyses which encompass more than just the energy sector; for example, top-down models are often used in abatement policies, where energy technologies are one of the possible means to the same end of the policy goal.

2.4.10 Policy-makers' points of attention

On energy topics, many advisory studies for decision-makers and policy-makers use models to quantify or at least justify certain remarks and suggestions. For a policy-maker, key attention should focus on the question why the model outcomes presented provide justification for the policy suggestions. To this end, one ought to grasp the basics of the model used.

Does the model use endogenous learning?
When it comes down to timing effects of support policies for competing energy technologies, the model is best to include endogenous learning. The same goes for remarks concerning realisable cost reductions of competing technologies: endogenous learning seems almost essential.

Are the progress ratios based on historic trends or based on generic estimations?
Small differences in progress ratios can cause huge variations in model outcomes. In its extremity, insignificant variations in the progress ratios can lead to significantly different model outcomes, even as to mistakenly warrant different policy suggestions.

Is a sensitivity analysis performed?
The more robust the model outcomes are, the better the model can be used to justify policy recommendations. To find out how robust the model outcomes are, a sensitivity analysis can be performed. For these sensitivity analyses, it is essential that the uncertainties in the progress ratios are included in the analyses.

Is the model top-down or bottom-up?
Both models have biases, and are complementary to one another. The right type of model should be applied to the right study. If investments in the energy sector should be compared to investments in other sectors, or compared to external costs through non-action, top-down models are preferred. If studies claim remarks on specific energy technologies, such as wind power or nuclear energy, a bottom-up model is a priori more suitable.

To what end is the model constructed?
As unattainable ideal, every policy question requires its own model. It is a consequence of the notion that a model is a simplified representation of reality. A modeller's greatest fear is that model outcomes are interpreted by 'casual readers' on details which are not significant. A top-down model that comments on 'renewable energy' does not comment on 'wind power'. A bottom-up model that quantifies potential cost reductions in the renewable energies does not comment on any potentially more beneficial cost reduction in other economic sectors.

Be aware of insignificant details and causal relations
Many models are used by scientists to understand system dynamics. If business-as-usual is continued, in what direction will the energy system evolve? If one imposes a certain policy measure, how does the energy system respond? The outcome of these models are mainly to be judged qualitatively and not quantitatively. If any conclusion is drawn based on (graphic) results of these models, the validity should be checked with the robustness of the model in that respect. This warning is especially valid for bottom-up models.

On the other end, integrated assessment models are designed to produce quantitative results. All the previous questions are valid for these models as well. However, as integrated assessment models often become extremely complex, it is difficult to understand the system dynamics. Through the model complexity, it might no longer be clear how and why the energy system changes on a given incentive.

3 Technology cases

In this chapter a review and analysis is presented of studies performed on technological learning of renewable energy technologies, (clean) fossil and nuclear technologies and energy demand technologies

For each of cases, the technology is described in terms of maturity, market diffusion, geographic dispersion, and (if applicable) market stimulation, and studies on technological learning of the technology are analyzed and reviewed with attention for Progress Ratios calculated in a specific timeframe and -if applicable- for a specific geographic area.

In this part of the chapter comprehensive overview of technology studies using the experience curve approach is presented. The chapter is subdivided in thee main topics: i) renewable energy technologies, ii) (clean) fossil and nuclear technologies, and iii) energy demand technologies. For each of the technologies, an overview of all (major) studies using experience curves is presented, as are the current economics, past and potential future cost reductions, and past policy support measures. Also, for each technology, an overview of policy recommendations derived from the various studies is presented, and methodological issues arising from the use of experience curves for the specific technology are discussed.

3.1 Renewable energy technologies

3.1.1 Wind energy onshore.

Introduction
Wind turbines are one of the oldest forms of renewable energy known to mankind, and are based on the principle of converting the kinetic energy of the wind into useful mechanical energy (e.g. water pumping), and more recently, from mechanical energy via a generator into electricity. Wind turbines for electricity production have been developed since the early 20th century, but first large-scale implementation started in the late 1970's, mainly in Denmark and the USA. At that time, a variety of horizontal - and vertical axes wind turbines with varying number of blades (1-4) were built, typically in the capacity range of 10-30 kW. Since then, the three-bladed horizontal-axis wind turbine has emerged as dominant design, and was scaled-up over the last three decades up to 5 MW nowadays commercially available, and 6 MW as prototype (by Enercon). In 2006, the average capacity of wind turbines installed onshore was 1.5 MW (BTM consult, 2007), but for example in the Netherlands varied from 0.8-3 MW (WSH, 2007). Technology development is still going on, but the wind turbines currently deployed can be considered as technically mature.

Traditionally, a small number of countries have dominated the production and installation of wind turbines. After Denmark and especially the USA were main driving forces in the 1980s, from the early 1990s Germany (and later Spain) took over this position as main driving forces, as can be seen in Figure 3.1. The globally installed wind capacity has grown exponentially in this timeframe, averaging about 25% growth per year, though during the last 5 years, average market growth was 17%. In between 2001-2006, about 75% of the global wind capacity was installed in the top-5 countries (see Figure 3.1), but expectations of the future are that the geographical distribution of new capacity will strongly diversify in the near future. Only six manufacturers (Vestas, Gamesa, GE Wind, Enercon, Suzlon and Siemens) currently deliver almost 90% of all wind turbines sold in 2006 (BTM, 2007).

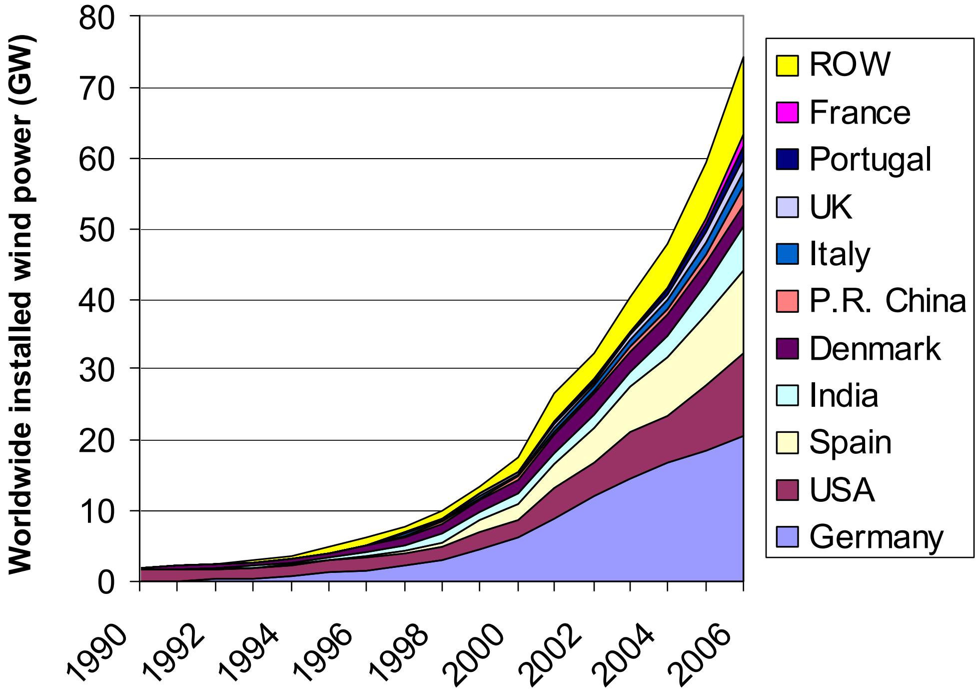

Figure 3.1 Development of global installed onshore wind capacity 1990-2006.

Experience curves and onshore wind energy

Experience curves for onshore wind power have been presented in many publications in the literature, see for an overview Table 3.1. The price development pattern illustrated by these studies varies considerably. Junginger et al. (2005) and the Extool study (Neij et al., 2003) show that several types of experience curves can be developed (cost of turbines produced /installed, by country or globally, by manufacturers, by sizes and for different time periods). In Table 3.1, the overview is differentiated for studies analysing the cost reductions of wind turbines or wind farms, and studies scrutinizing the reduction of the cost of electricity

Most commonly, the cost reductions per specific installed capacity for wind turbines or entire wind farms are investigated. Before 2003, a range of studies had published a whole range of experience curves for onshore wind farms in various countries, e.g. the US, Germany and Denmark. In 2003, the Extool report was published, the most comprehensive overview and analysis of experience curves for onshore wind energy, analysing wind energy developments in Denmark, Spain, Sweden and Germany.

Taken into consideration all these types of variations, general findings of the Extool study are: the experience curves both for wind turbines produced and find farms installed show a range of progress ratio of 91-94% found for Germany, Denmark and Spain (see Figure 3.2). When taking global cumulative installed capacity as measurement for experience, Junginger et al. (2005) present progress ratios of wind farms of 81-85% (see Figure 3.3), Taylor et al. (2006) find 85%.

The Extool project also published an experience curve for wind turbines in terms of levelised production cost of electricity (CoE) produced, showing a progress ratio of 83%. Basically, an experience curve for levelised production cost is the closest approximation possible for an experience curve for produced electricity. It does include improvements in operation and maintenance (O&M), efficiency etc., but does not take into account the production based on improved siting and wind capture. Neij (2008) argues that based on these findings, the progress ratio of wind electricity is approximately 80%.

These experience curves include not only cost development of wind turbines but also cost development related to installation, efficiency improvements and reduction of O&M cost[21]. For specific production CoE, PR ranging between 87-88% were found[22].

Economics
As the global market has grown, wind power has seen an impressive decrease in cost. A modern wind turbine annually produces 180 times more electricity and at less than half the cost per unit (kWh) than its equivalent twenty years ago (GWEC, 2005). The prices of onshore installed wind farms were approximately 980 €/kW in 2004, but have increased to 1175 €/kW by 2006 (Morthorst, 2007)[23]. Wind turbine prices may also vary widely between countries. The cost of generating electricity today is approximately 4-6 €c/kWh in high wind areas (e.g. in Scotland) and 6-8 €c/kWh in medium wind speed sites (e.g. the Netherlands) (GWEC, 2006, Morthorst, 2007). This large variation is due to the fact that the energy contained in the wind increases to the third power with wind speed, but of course also depends on assumed interest rates and economic life time.

Policy measures
Substantial *public RD&D support* for wind energy was given in the 1980s in Germany, the USA and the Netherlands (Redlinger et al., 2002, Söderholm and Klaasen, 2007). Especially in the former two, R&D support was mainly aimed at developing large-scale turbines in the MW-size area. However, in all these three countries, R&D efforts were relatively ineffective, due to a variety of reasons, such as technical problems and the failure to establish a stable and reliable domestic demand. Many countries granted various kinds of *investment subsidies or investment tax credits*, such as the USA (especially California), Germany, Finland, the Netherlands and Sweden. Especially in California, the incentives were very effective to stimulate growth of installed wind energy capacity, but were also misused, as mainly capacity (rather than electricity production) was subsidized. By far the most successful policy incentive have been long-term guaranteed *feed-in tariffs, tax credits or other electricity production incentives*. Countries that have implemented such support measures include Germany, Denmark, the USA, Spain, and the Netherlands. Well-known is the feed-in tariff in Germany, which has since 1991 (slightly modified over time) been up until present the main driver to install over 20 GW of wind capacity in less than two decades. For a more comprehensive overview of the technology and policies, see e.g. Redlinger et al. (2002).

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[21] The levelised production cost of electricity, expressed as cost/kWh is based on the specific electricity production of wind turbine produced in Denmark (at roughness class 1), cost reduction of installation of wind turbines in Denmark, a lifetime of 20 years, an interest rate of 6%, and O&M costs calculated according to a model developed from the results of a number of questionnaires surveys (Redlinger, et al., 2002, pp. 77-80).

[22] Ibenholt (2002) also presents experience curves for electricity, but in this study, the height of feed-in tariffs and other policy support measures is used to represent production cost data, which is in our opinion not an adequate proxy for production costs, therefore, these studies are not included in Table 3.1

[23] Reasons for this price increase are discussed in the last section of this chapter.

Table 3.1 Overview of experience curves for wind energy published in the literature.

Author	PR	Time frame	Region	n	R^2	Data qual.	Notes
Capacity of turbines / wind farms							
Mackay and Probert, 1998	85.7%	1981-1996	US	6.5	0.945	II	
(Durstewitz and Hoppe-Kilpper, 1999	92%	1990-1998	Germany	5.6	0.949	I/II	
(Neij, 1999	92%	1982-1997	Denmark	n.a.	n.a.	I/II	Danish-produced wind turbines
Seebregts et al., 1998	87% / 90%	n.a.	Denmark	n.a.	n.a.	II/III	
Lund, 1995	85%	n.a.	Denmark	n.a.	n.a.	II	
Neij et al., 2003	92-94%	1981-2000	4 countries[c]	n.a.	n.a.		Turbines *produced* per country
Milborrow, 2002	84.7%	n.a.	Danish manufacturers	7.1.	n.a.	II	
Neij et al., 2003	92-94%	.	Several WT manufacturers	varying	0.74-0.99	I	Produced wind turbines in Denmark and Germany
Neij et al., 2003	89-96%	1981-2000	4 countries[c]	varying	0.85-0.94	I/II	Turbines installed in a country
Junginger et al. 2005	81-85%	1990-2001	Global	3.3/3.6	0.875-0.978	II	Price data from the UK and Spain combined with global installed capacity
Junginger et al. 2005	91-101%	1991-2001	Germany	7.3	0.80-0.995	I/II	Turbine prices / wind farm prices, two clear phases: 1991-1995 (PR 91%) and 1996-2001 (PR 101%)
Taylor et al., 2006	85%	1982-2000	Global	n.a.	n.a.	II	Price data from California combined with global installed capacity
Cost of electricity							
Neij et al., 2003	86-88%	1981-2000	4 countries	n.a.	0.87-0.97	I	specific electr. production by a country, x-axis measures cum cap. (MW) installed
Neij et al., 2003	83%	1981-2000	Denmark	n.a.	0.97	I	levelized electr. production by a country, x-axis measures cum cap. (MW) installed
Taylor et al. 2006	85.5%	1981-2002	California	n.a.	0.88	II	

± Data estimated from a figure, as exact numbers were not given.
n Number of doublings of cumulative production on x-axis.
R^2 Correlation coefficient.
n.a. Data not available.
I cost/price data provided (and/or confirmed) by the producers covered
II cost/ price data collected from various sources (price lists, books, journals, press releases, interviews)
III cost/price data (or progress ratio) being assumed by authors, i.e. not based on empirical data

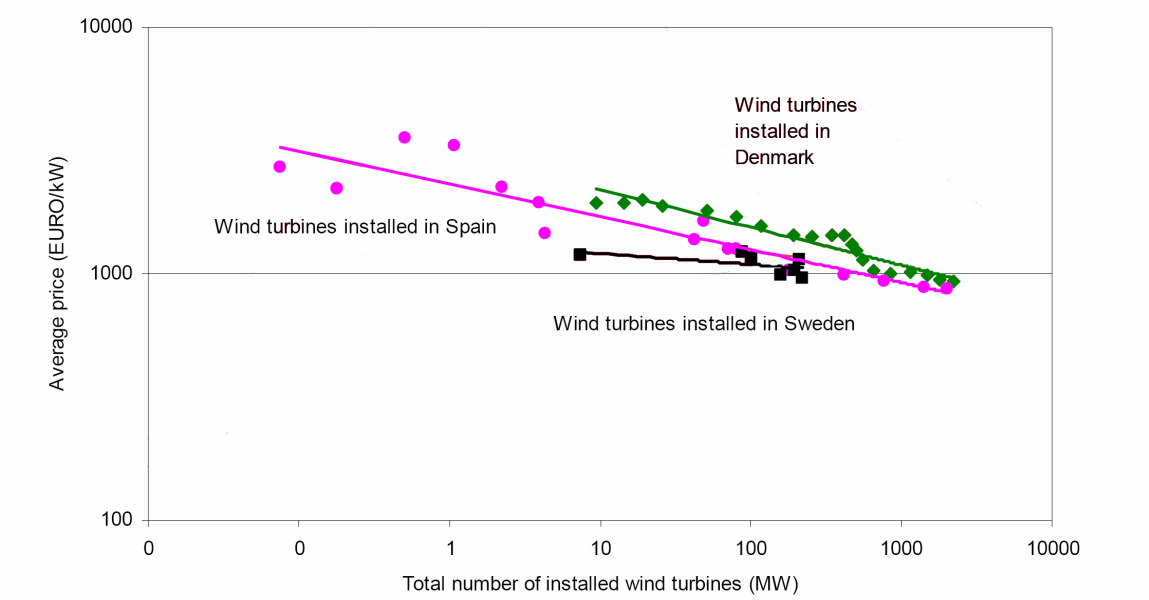

Figure 3.2 *Experience curves for wind turbines installed in Denmark, Spain and Sweden, based on total installation cost, as a function of total number of wind turbines installed in each country (Neij et al., 2003).*

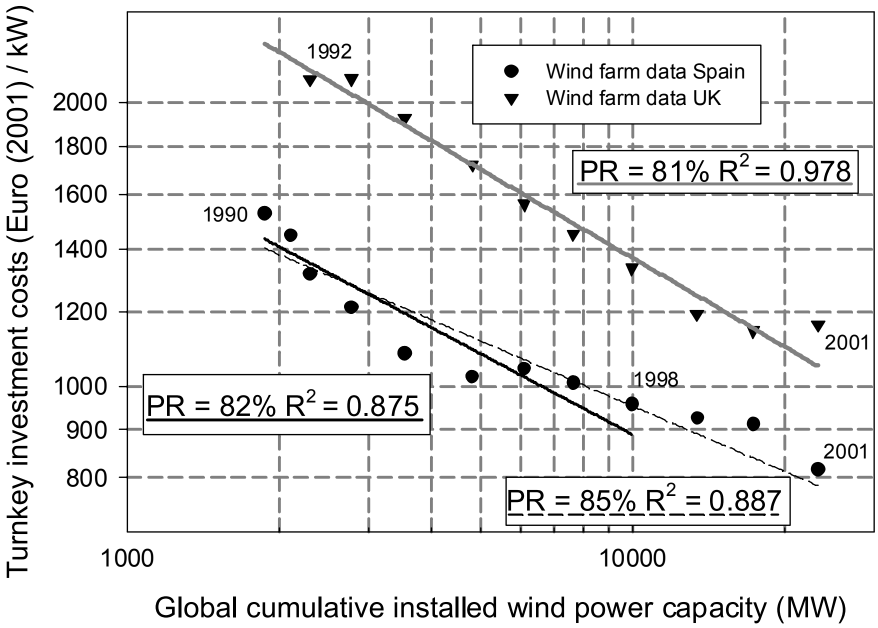

Figure 3.3 *Experience curves for wind farms, using price data from British and Spanish wind farms plotted against cumulative installed wind capacity (Junginger, 2005).*

Reasons behind the cost reductions / bottom-up assessments

The production cost of wind turbines have declined significantly, which has resulted in a drop of prices of more than 50% per installed kW since the early 1980s. The upscaling of the size and capacity of wind turbines has been a key driver behind lower investment costs (Neij, 1999). This process has happened gradually, starting from 15 kW turbines in the early 1980s, and evolving to 5 MW turbines nowadays. The gradual upscaling of turbines had the advantage that the setup of every new turbine class was based on past experiences, but also allowed a slow introduction of new technological developments, such as the application of pitch-regulation, the use of synchronous generators, the development and use of new materials for blades that grew larger and larger, development of power electronics, and the specialization of standard components from other industry sectors for the wind energy sector such as gear boxes, transformers and inverters (EUREC, 2002, Neij et al., 2003). Costs have been reduced due to reduction of cost related to foundations, electrical installations, grid connection, etc. - these costs have decreased by almost 60% from 1980 to 2000 (Redlinger et al., 2002).

The most important indicator is the cost of electricity. This cost has not only been reduced due to lower investment costs, but also due to higher electricity yields per installed capacity due to e.g. larger rotor areas and higher hub heights, the introduction of pitch variation, better siting of wind farms and lower operation and maintenance costs.

Future scenarios and cost reduction potentials
BTM (2007) predicts that the combined annual growth rate until 2011 will be 17%, roughly the same as for the last five years. This means that by 2011 the global market will represent about 33 GW per year. Regionally, Europe will continue to be the most important area, with an estimated additionally installed capacity of around 59 GW over the next five years, which would bring the total installed wind power capacity in Europe to 108 GW, more than double its current level. As Germany and Spain reach saturation points, other countries such as the UK, France, Portugal and Italy are expected to take over. According to BTM, the Americas will see 33 GW of additional capacity, while in SE Asia, the market is expected to grow rapidly, with a total of 28 GW of new wind by 2011, up from about 9 GW today. The OECD-Pacific region is expected to roughly triple its total installed capacity, reaching 8 GW by 2011, while the rest of the world will expand rapidly but remain marginal - it is only predicted to have a total combined capacity of less than 4 GW by 2011. Thus, cumulative global capacity is expected to double once within the next five years, which could imply investment cost reductions between 9-19% (assuming PRs of 81-91%)

Several other foresight studies of wind power technology present several cost reduction pathways for the future (see for example EWEA, 2004; GWEC, 2005; BTM Consult 2005a and 2005b; EREC, 2004; EUREC, 2002).

Sources of future cost reductions include design improvements and up-scaling, larger capacity generators per unit of rotor area and high voltage generation. Today 2-3 MW wind turbines are being installed, on-shore and off-shore. The turbines are expected to be up-scaled further, however, this will require light and strong material to reduce overall weight of the turbine and facilitate logistics. The cost reduction patterns are described as incremental, as the historical pattern of cost reduction (Neij et al., 2003). Furthermore, wind farms have increased in size, not only by installed capacity per turbine, but also in absolute turbine number, allowing the mass production of identical turbines. Junginger et al. (2005) find a negative correlation between the order size of a batch of turbines and the price paid per turbine. In case that turbine size stabilizes at e.g. the 2-3 MW level, in the future both incremental improvements on the same platform and mass production could be drivers for further cost reductions.

Lessons for policy makers
While many individual studies have been carried out for wind energy, the Extool study provides by far the most comprehensive overview and evaluation. Below, the main policy recommendations from the Extool study are quoted[24]:

"The Extool project showed that experience curves can be used to assess the effect of combined policy measures in terms of cost reductions. Moreover, the results of the project show that experience curves could be used to analyse international 'learning systems', i.e. cost reductions brought about by the development of wind power and policy measures used in other countries. Nevertheless, the use of experience curves for the assessment of policy programmes has several limitations. First, the analysis and assessment of policy programmes cannot be achieved unless relevant experience curves based on good data can be developed. The authors are of the opinion that only studies that provide evidence of the validity, reliability and relevance of experience curves should be taken into account in policy making. Second,

[24] Combined and shortened quote from Section 8.2, pages 110-112 (Neij, 2003).

experience curves provide an aggregated picture of the situation and more detailed analysis of various sources of cost reduction, and cost reductions resulting from individual policy measures, requires additional data and analysis tools. Third, we do not recommend the use of experience curves to analyse learning investments and cost effectiveness of policy measures. Based on the results of our study, we can make no statements concerning any other combinations of measures. In general, it is difficult to say how funds are best used. The experience curves, in general, however, illustrate the need for experience in the production and use of turbines and the potential need for market pull measures. This indicates that RD&D measures alone will not always be sufficient for the commercialisation of new products. Based on this study, for example, we could see that the large amount of money spent on RD&D in Germany and Sweden (in comparison to the amount spent in Denmark) might not have been necessary for the development of wind power. In general, the combination of measures and the best way to use funding will depend on the product and the innovation system in question. Such an analysis will require methods and tools in addition to experience curves. However, we recommend the traditional use of experience curves as a tool to support strategic decisions. Based on experience curves, strategies and policy measures of relevance for new emerging energy technologies could be discussed, e.g. R&D measures to effect radical innovations versus market based policy measures to effect learning and incremental cost reductions. Used in the right way, experience curves can assist several actors, such as financial analysts, researchers and policy makers, in analysing and assessing strategies and policy measures."

General discussion

Production costs vs. prices - the recent price increases

Since 2002, global market prices for wind turbines and wind farms have been constant at best, and in most cases rising. Morthorst (2007) shows a 20% price increase from 980 €/kW in 2004 to 1175 €/kW in 2006 for European wind farms, and a recent US DoE report for wind farms in the USA (Wiser et al, 2007), shows that turbine costs have increased from 700 US$ in 2002 to about 1100 US$ in 2006. Finally, at an IEA ETP workshop in June 2007, Travecedo (2008) of Iberdrola confirmed that also in Spain prices have been increasing, and that current global prices for wind farms vary between 1100-1500 €/kW with 1300 €/kW on average, figures even higher than those of Morthorst for 2006.

This recent price increase has triggered the question whether the experience curve concept still applies to wind turbines, and whether the concept can be used to analyse future cost reductions. To discuss this question, first a number of reasons for the price increase have been identified:

- *Increasing raw material costs*, mainly of steel, copper, oil, and carbon fibres. Maltepe (2007) stated that wind turbine investment costs (and final CoE) are very sensitive to these raw material costs, quoting that a wind turbines will 'yield about 3 W capacity/pound of steel' compared to 23 W/pound of steel for a gas turbine.
- *The US$/€ exchange rate.* The costs of turbines/kW have increased in the US by 57% from 2002-2006, but at the same time, the Euro gained about 44% against the US Dollar. As the majority of the turbines in the US is still sold in Euro, this explains almost 80% of the price increase in the USA, putting it much closer to the 20% price increase mentioned by Morthorst.
- *Increasing prices for all power technologies.* Maltepe (2007) pointed out, that the prices of many conventional technologies have increased also, even more strongly (claimed up to 50%) for e.g. gas turbines, steam turbines etc., due to increasing steel prices and increasing general demand for electricity world-wide. In comparison, the rise of wind turbine prices was said to be even modest.
- *Strongly increasing demand for wind energy and a supplier oligopoly.* Probably the most important development is the strongly increasing demand for wind turbines all over the world (and especially in many European countries) because of all the national policy support measures. Currently existing manufacturing capacity is not able to keep up with this demand. Due to bottlenecks in delivery of specific wind turbine components, many manufacturers have full order books for the next several years.

Thus, the current market can be characterized as being in the ‘umbrella phase’ (see also point 1 of Section 2.2). It can be expected, that on the longer term, in a well-functioning market, production capacity of wind turbines may expand, causing prices of wind turbines to decrease again.

More importantly, experience curve theory only allows analysis of production cost developments. Even though prices are almost in all studies used as a proxy for production costs, theory indicates that this only is possible if the ratio between prices and costs is more or less constant. It is likely that *production costs* have declined (and will decline further). Whether wind turbine prices will follow them, is a question concerning many more factors, especially the extent of market (over-) demand.

Use of national vs. global experience curves
As shown in the sections above, using national system boundaries yields less benign PRs (in the range of 91-94% than when considering the global installed cumulative wind capacity (PRs of 81-85%). The ratio behind the latter approach is that experience gained in the wind turbine manufacturing industry has continuously spilt over, and that turbines produced by a handful of (mainly Danish and German) manufacturers have been installed all over the world (for a more comprehensive argumentation, and explanation of the resulting different PRs on a national level, see Junginger et al., 2005). During a recent IEA workshop[25], there was consensus that onshore wind energy has been learning on a global level, and thus experience curves too should use the global installed capacity on the x-axis. Yet, determining general ‘global wind turbine market prices’ is also hard given the variety of markets in different countries. The progress ratio clearly depends on what system boundaries are used and in all the range of experience curves is probably between 85-91%. For further calculation in chapter 4, we assume a progress ratio of 88.5% ±3.5%.

Given the fact that prices for wind turbines have basically increased over the past few years (see below), it is practically impossible to analyze the recent development of production costs. Thus it remains hard to ‘prove’ which of these two ranges (81-85% vs. 91-94%) is the correct one to measure the true speed of technological learning for onshore wind energy. It is recommended to use both ranges for future scenarios and energy models, and to take into account the sensitivity of the choice of the PR on scenario/model results.

To complicate matters, probably in the future, it would be better using experience curves analyzing the reduction of the cost of electricity, and not so much capacity (see below).

Measuring costs reductions of installed capacity vs. electricity
Qualitative technical developments / technology trends, outlook for future costs
According to Mete Maltepe (Maltepe, 2007) upscaling of wind turbines will continue a little longer. Currently, new wind turbines ordered are mainly of 2 MW capacity, but it is expected that in the next years, average capacity per turbine may rise up to 3 MW. After that, the logistical challenges may become too large for further upscaling onshore. Also components of the wind turbines (blades, gearboxes, etc.) are increasingly manufactured by specialized separate firms, and traditional manufacturers will increasingly ’only’ assemble turbines. Maltepe however stressed that he expected further cost reductions for electricity will mainly come from increasing capacity factors, and lower O&M costs. Making the existing turbines more efficient and more reliable will be the key factors for future improvements and cost reductions.

As pointed out earlier, costs reductions for the CoE of wind energy have been larger than those of installed capacity. With these qualitative expectations, using the cost of installed capacity may increasingly become inaccurate, and the emphasis should preferably lie on analysing either the levelized or specific costs of electricity.

[25] International Workshop on Technology Learning and Deployment, IEA, Paris: 11-12 June 2007, see also: http://www.iea.org/textbase/work/workshopdetail.asp?WS_ID=308

3.1.2 Offshore wind

Technology description
Offshore wind farms were built from 1990, starting with a single turbine in Sweden. In the ‘demonstration stage’, wind farms with turbines up to 2 MW and up to 10 turbines each were built. Around 2000, a period of commercialisation started based on wind farms with rather large turbines of 2 MW and more. By the end of 2006, a total of 19 wind farms were operational with a combined capacity of 890 MW. At least the following EU countries have offshore wind farms:

- Denmark (6)
- UK (6)
- Sweden (4, including a single turbine at Nogersund, decommissioned in 2007)
- The Netherlands (1, NSW, Near Shore Wind farm Egmond aan Zee)
- Ireland (1, Arklow Bank)
- Germany (1, a single turbine at Rostock - Breitling).

The capacity of wind turbines increased from 2 to 5 MW until 2007. Today, only offshore wind farms with turbines of 3 MW or more are built, except in case of Horns Rev II. Based on capacity built, under construction, or firmly planned (Appendix A), cumulative offshore capacity in the EU may increase as follows:

- About 1,100 MW by the end of 2007.
- About 1,500 MW by the end of 2008.
- About 7,000 MW by the end of 2009.
- By 2012, the offshore wind capacity in the EU - operational farms, and farms under construction or firmly planned - may be up to approximately 16.8 GW (Appendix A).

Experience curves offshore wind
A number of studies investigate learning effects for offshore wind. They focus on learning effects for investment costs, and to lesser extent for operation and maintenance costs. In this paragraph, only learning effects for specific investment costs are reported. These studies are:

- Lako (2002), a comprehensive study on learning effects for onshore wind, offshore wind, and photovoltaics, of which the part on offshore wind summarises the state-of-the-art of the ‘demonstration stage’ and highlights possible cost reductions until 2030.
- Junginger (2005) (part of the PhD thesis). This in-depth analysis addresses learning effects for several renewable technologies among which on- and offshore wind. With regard to offshore wind, Junginger reports learning effects observed or deduced for 11 existing wind farms and 7 wind farms under construction or planned (estimated investments).
- Isles (2006), which presents an overview of offshore wind farms and of learning effects, making a distinction between a period of ‘normal’ market development and correspondingly ‘normal’ PR and ‘an apparent disconnecting between price and cost data which is predominantly due to a lack of competition amongst turbine manufacturers’.

According to Lako (2002), rotor and nacelle show a Progress Ratio of 90%, towers 96%, offshore constructions 95%, and grid connection and cabling 97.5%. Based on onshore wind learning (Neij, 1997 and 1999), PRs for offshore wind are deemed to be in the range of 90-96%.

Junginger (2005) assumes that offshore wind turbines - excluding foundation, grid connection, and installation - show PRs of 81-85%, based on data for onshore wind farms built in the UK and Spain, plotted against the cumulative installed wind power capacity (Chapter 3 of the thesis). With regard to foundations, he presumes that steel prices will show a decline of 1-2% per year, which is why the cost reduction for foundations until 2020 is estimated at 15-20%.

For grid connection, Junginger looked at the cost reduction for cables of submarine HVDC (High Voltage Direct Current) transmission, which showed a PR of 62%. He analysed the cost reduction of HVDC converter stations, which showed a PR of 71%. Finally, he looked at the marginal installation time for offshore wind turbines built in Denmark (Horns Rev 1, and Nysted), which showed a PR of 77%. Base on these findings, he assumed that some part of the installation cost would experience a PR of 77%, and another part a PR of 95%.

Isles (2006) explores cost reduction for offshore wind, starting with a summary of studies performed before, and analyses investment costs of 22 wind farms, 19 of which operational in 2006. These wind farms represent a cumulative capacity of some 1,300 MW, equivalent to approximately 8 doublings of cumulative capacity. She presents a Progress Ratio for the timeframe 1991-2007, but also PRs for a phase of 'normal' market development and correspondingly 'normal' PR and for one with 'disconnection between price and cost data' (Figure 2.1). Table 3.2 gives an overview of characteristic experience curves (assumed) in these studies.

Table 3.2 Overview of experience curves or PRs assumed for offshore wind in literature

Source	Progress Ratio		Period	n [a]	R^2	Data quality	Notes
Lako, 2002	Rotor and nacelle	Balance of plant	1991-2007 (?)	~ 6.9 (NS [b]) - ~ 10 (OS [b])	N/A	III	PRs for on- and offshore Reference case wind are assumed in the range of ~ 90 - 96%
'Reference'	90%	95-97.5%				III	
'Low'	90%	92.5-95%				III	Case *low* analyses sensitivity to lower PR values
Junginger, 2005	Offshore turbine	81-85%	1991-2007 (?)	~ 7.8	N/A	II	Based on learning Cost reduction of 1-2% per year for steel: 15-20% cost reduction for foundations until 2020 observed for onshore wind
	Foundation	See text		N/A	N/A	III	
	Grid connection	62-71%		N/A	0.966-0.583	I	PR for HVDC cables 62%, PR for HVDC converter stations 71%
	Installation	77-95%		N/A	0.967	I	Marginal turbine installation time PR 77%
Isles, 2006	One-phase case (see note)	97%	1991-2007	~ 8.0	0.0578	I	Initially, Isles determined a Progress Ratio for the total period (one stage) of 97%
	Two-phase case (see note)	90-113% ('price umbrella')	1991-2007	~ 8.0	0.623-0.172	I	Learning (PR 90%) ends at approx. 300 MW cumulative capacity, after which prices increase (PR 113%)

a n = number of doublings of cumulative capacity.
b NS = Near Shore, defined as wind farms near the shore of Baltic Sea (Denmark and Sweden), and IJsselmeer (Netherlands); OS = Off Shore, defined as the balance, viz. the North Sea, Irish Sea, etc. (Lako, 2002)
I Data based on prices of offshore wind farms.
II Data based on scarce prices of offshore wind farms.
III Data based on scarce evidence or assumption.
Sources: Lako, 2002; Junginger, 2005; Isles, 2006.

The data pertain to published prices of offshore wind farms, with some evidence for component prices. The quality of the data used is fair in case of (Lako, 2002), and good in case of Junginger (2005) and Isles (2006). The database for offshore wind still increases, as elucidated below. Although the PRs in the studies are somewhat different, comparison of the studies may explain these differences. Figure 3.4 shows learning effects in the second case described by Isles (2006), with a phase of cost reduction followed by increasing prices. The second phase may be predominantly due to a lack of competition amongst turbine manufacturers, but also rising prices for steel and copper have contributed to price escalation for offshore wind farms.

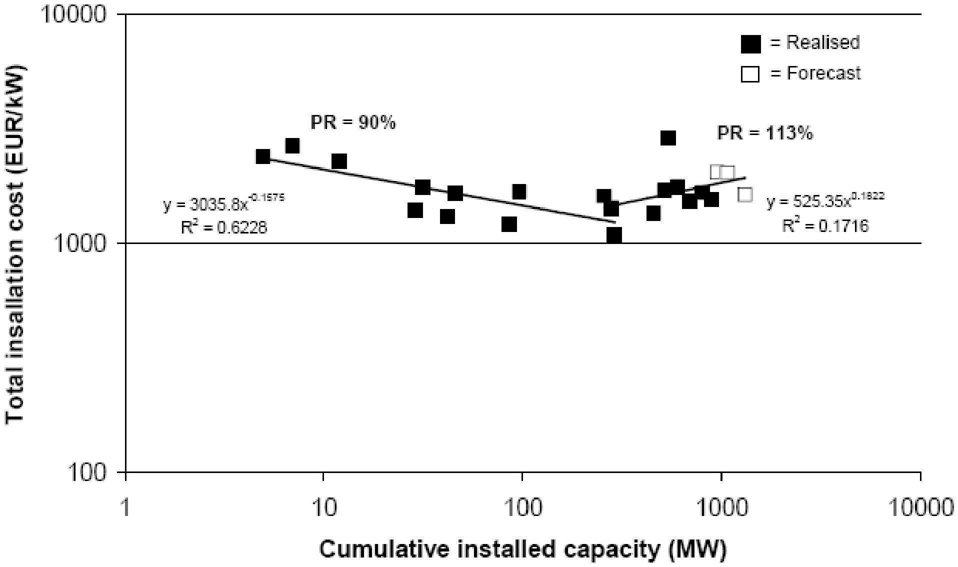

Figure 3.4 *Experience curve for offshore wind farms.* Source: Isles (2006).

Economics

Tables 3.3 and 3.4 present data of reported investments costs of offshore wind. Table 3.3 shows that the specific investment cost decreased from approx. € 2,300-2,650/kW ($€_{2000}$) at the start of the 1990s to a level of approximately € 1,675/kW ($€_{2000}$) for the commercial offshore wind farm Horns Rev (Denmark), commissioned in 2002, and similar prices for other wind farms.

Table 3.3 European offshore wind farms (11) with reported investment cost, 1990-2003

Country	Project	On line	Capacity	Lako, 2002		IEA, 2005a	
				Investment cost	Specific investment cost	Investment cost ($€_{200X}$: year on line)	Specific investment cost
			[MW]	[$€_{2000}$ mln]	[$€_{2000}$/kW]	[$€_{200X}$ mln]	[$€_{200X}$/kW]
DK	Vindeby	1991	4.95	13.2	2,660	10.25	2,071
NL	Lely († 2006)	1994	2.0	5.3	2,600	4.50	2,250
DK	Tuno Knøb	1995	5.0	11.6	2,326	10.35	2,070
S	Bockstigen	1998	2.75	4.2	1,527	4.7	1,709
S	Utgrunden	2000	10.0	18.3	1,833	13.9	1,390
UK	Blyth	2000	4	6.44	1,610	6.32	1,580
DK	Middelgrunden	2001	40	48.96	1,224	51.3	1,283
S	Yttre Stengrund	2001	10	13.0	1,300		
DK	Horns Rev	2002	160	268	1,675	300.0	1,875
DK	Samsø	2003	23			35.0	1,522
DK	Nysted	2003	165.6			268.8	1,623

Sources: Lako, 2002; Frandsen et al, 2004; IEA, 2005a.

Table 3.4 confirms price increases, *inter alia* due to lack of competition amongst turbine manufacturers (Isles, 2006). Offshore wind farm prices jumped from € 1,600/kW ($€_{2006}$) in 2006 to an unprecedented level of approx. € 3,100/kW ($€_{2007}$) for Q7 (Netherlands) and Rhyl Flats (UK). Other projects due for 2008-2012 show prices of approximately € 2,300 to € 2,900/kW ($€_{2007}$). The investment cost of 11 offshore wind farms with a combined capacity of 1,548 MW - Lillgrund, Burbo Bank, Q7, Lynn & Inner Dowsing, Rob Rigg, Horns Rev II, Rhyl Flats, Gunfleet Sands I & II, Thanet, and Teesside - amounts to approximately M€ 3,827 or € 2,475/kW ($€_{2007}$).

Table 3.4 European offshore wind farms (17) with reported investment cost, 2003-2012

Country	Project	On line	Capacity [MW]	Investment [€200X mln]	Specific investment [€200X/kW]	References
UK	North Hoyle	2003	60	143 (€2006)	2,055 (€2006)	Internet Source 1
UK	Scroby Sands	2004	60	114.1 (€2006)	1,901 (€2006)	Internet Source 2
UK	Kentish Flats	2005	90	153.6 (€2005)	1,706 (€2005)	Internet Source 3
UK	Barrow	2006	90	147 (€2006)	1,630 (€2006)	Internet Source 4
NL	Egmond aan Zee	2006	108	200 (€2005)	1,852 (€2005)	Shell Venster, 2005
S	Lillgrund	2007	110	195 (€2007) [a]	1,766 (€2007)	Internet Source 5
UK	Burbo Bank	2007	90	159 (€2007) [a]	1,761 (€2007)	Internet Source 6
NL	Q7 (IJmuiden)	2008	120	383 (€2007)	3,192 (€2007)	REW, 2007
UK	Lynn & Inner Dowsing	2008	194	444 (€2007) [a]	2,286 (€2007)	Internet Sources 7-8
UK	Robin Rigg	2009	180	481 (€2007) [a]	2,675 (€2007)	Internet Source 9
DK	Horns Rev II	2009	200	470 (€2007) [a]	2,349 (€2007)	Internet Source 10
UK	Rhyl Flats	2009	90	281 (€2007) [a]	3,128 (€2007)	Internet Source 11
UK	Gunfleet Sands I	2009	108	268 (€2007) [a]	2,486 (€2007)	Internet Source 12
UK	Gunfleet Sands II	2009	64.8	188 (€2007) [a]	2,899 (€2007)	Internet Source 13
UK	Thanet	2009	300	733 (€2006)	2,444 (€2006)	Internet Source 14
UK	Teesside	2011	90	207 (€2007) [a]	2,305 (€2007)	Internet Source 15
UK	London Array	2012	1,000	2,260 (€2006)	2,260 (€2006)	Internet Source 16

a Based on exchange rates for 2007 of: 1 € = 0.1342 DKK, 1 € = 0.1083 SEK, and 1 € = 0.675 £.
Sources: IEA, 2005a; Shell Venster, 2005; REW, 2007; Internet Sources 1-16.

Appendix B presents an overview of the investment costs of the 28 aforementioned offshore wind farms, applying Producer Price Indexes (PPIs) and conversion to the currency Euro 2006.

Policy measures
Development of offshore wind is intimately linked to energy and climate policies and R&D policies. Focusing on 2008, the following countries have market stimulation policies in place, which are generally based on feed-in tariffs, unless otherwise stated (in brackets):

- Denmark (tendering)
- UK (capital grants and Renewables Obligation Certificates, ROCs)
- Sweden
- The Netherlands (feed-in premium)
- Germany
- Ireland
- Belgium
- Spain
- France.

According to Lako and Ros (2006), publicly financed wind R&D did not increase substantially from 1994 to 2004, although the trend is increasing. Six IEA countries stand out in this respect:

- USA
- Germany
- Japan
- Netherlands
- Denmark
- Sweden.

Reasons for cost reductions / bottom-up assessments
In the *demonstration stage* (1990-2000) some turbines proved to be unsuitable for the harsh offshore conditions. Therefore, wind farms in the Netherlands and Sweden have been dismantled and Blyth (UK) has gone offline temporarily. *Commercial* wind farms - Horns Rev and Nysted (Denmark) - also experienced setbacks. However, offshore wind turbines are becoming mature:

- Vestas employed its 2 MW and 3 MW turbines. Vestas employed its 2 MW and 3 MW turbines. Recently, Vestas resumed offering its 3 MW turbine for offshore application after having solved technical problems.

- General Electric employed its 3.6 MW turbine at Arklow Bank in Ireland (2003), but does not seem to offer for offshore wind farms since then.
- Siemens (formerly Bonus) offered a 2.3 MW turbine, followed by a 3.6 MW turbine.
- REpower offers a 5 MW turbine used in the UK (Moray Firth), Germany, and Belgium.
- Multibrid is another 5 MW turbine due to be used in Germany and France.

Junginger (2005) shows learning for cables and transformers based on HVDC (High Voltage Direct Current) instead of AC (Alternating Current). Figure 3.5 shows that HVDC is apt for large wind farms far offshore (DTI, 2007; Djapic et al, 2006), or as Normark and Nielsen (2005) state:

> *'For the UK projects in a number of projects HVDC would be feasible particularly if 'joint connection' (combination of transmission for a number of wind farms) is applied. The studied range in power and transmission distance is 64-1000 MW and 30-100 km'.*

The 400 MW offshore wind farm 'Borkum 2' (D) will be based on HVDC (Internet Source 17).

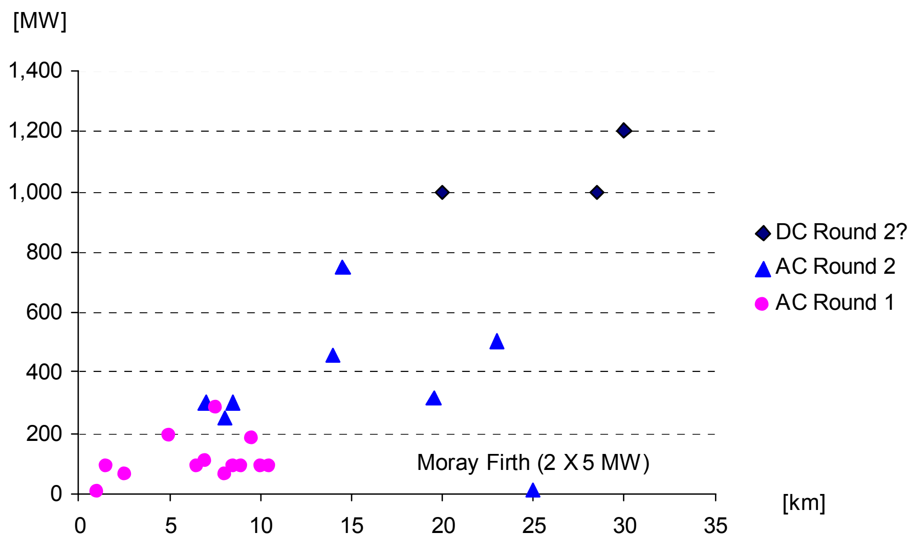

Figure 3.5 Interconnection of UK offshore wind farms, AC or DC (round 2, contemplated). Sources :DTI, 2007 ; Djapic et al, 2006.

The main reasons for cost reductions that have been reported or are to be expected are:
- Increasing capacity of wind turbines, from 500 kW in the early 1990s to 2 MW in 2000, and 5 MW and more today (economies of scale of offshore wind turbines).
- Increasing numbers of turbines and correspondingly increasing capacity of wind farms, up to 400-1,000 MW around 2010 (economies of scale by series production).
- Fewer platforms are needed as wind turbine capacities increase: for example, Thornton Bank (Belgium) will have 60 turbines of 5 MW, whereas Thanet (UK) will have 100 turbines of 3 MW. The anvil, the connecting piece between piling hammer and pile, reaches its limit at a diameter of six metres. The pile diameter for a 5-MW machine in water 30 metres deep would surpass that limit (Mathis, 2006; Internet Source 18).
- Economies of scale with regard to lifting equipment, reported by Söger et al. (2006).
- Reduced cost of cables, transformers, and grid connection (Junginger, 2005), which may be a function of the size of the wind farm. It is acknowledged that HVDC appears to be economical for large wind farms (400-1,000 MW) relatively far from the shore.
- Junginger (2005) also shows that significant learning by doing has occurred during turbine installation, e.g. the time to install offshore wind turbines was reduced from over two days to less than eight hours.

- Due to the development of dedicated offshore turbines, it can be expected that Operation and Maintenance (O&M) costs will be reduced.

Future scenarios and cost reduction potentials

Offshore wind is expected to grow fast in the UK, Germany, and Denmark, and to a lesser extent in Sweden, the Netherlands, Belgium, and Ireland, to a total 16.8 GW in 2012 (Figure 3.5).

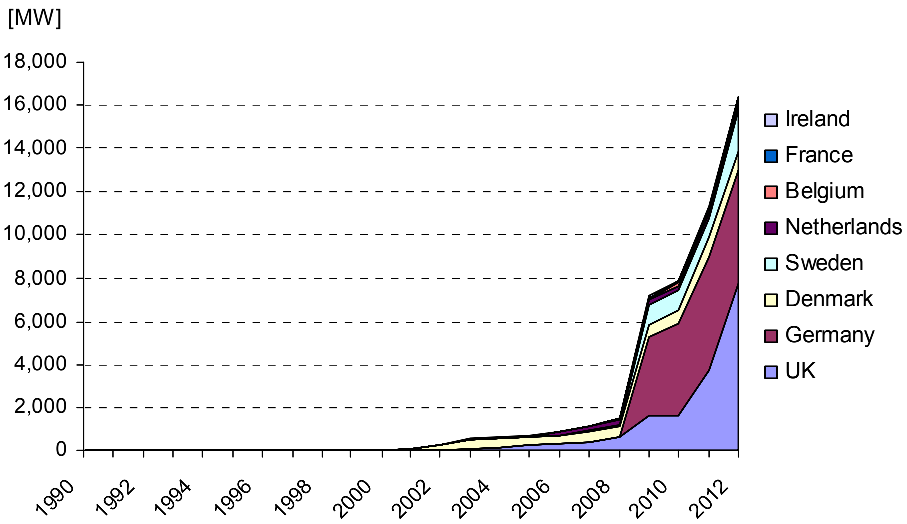

Figure 3.6 Offshore wind capacity in the EU based on projections included in Appendix A

How this projection may be compared to studies of Douglas Westwood (2007) and BTM Consult (2007) - with projections of 2,400 MW and 4,830 MW, respectively, for EU offshore wind in 2010 - and of Greenpeace (2004) and EWEA[26] (2007) is depicted in Figure 3.6. The projection of Greenpeace seems to be hardly achievable, contrary to EWEA's 40 GW in 2020.

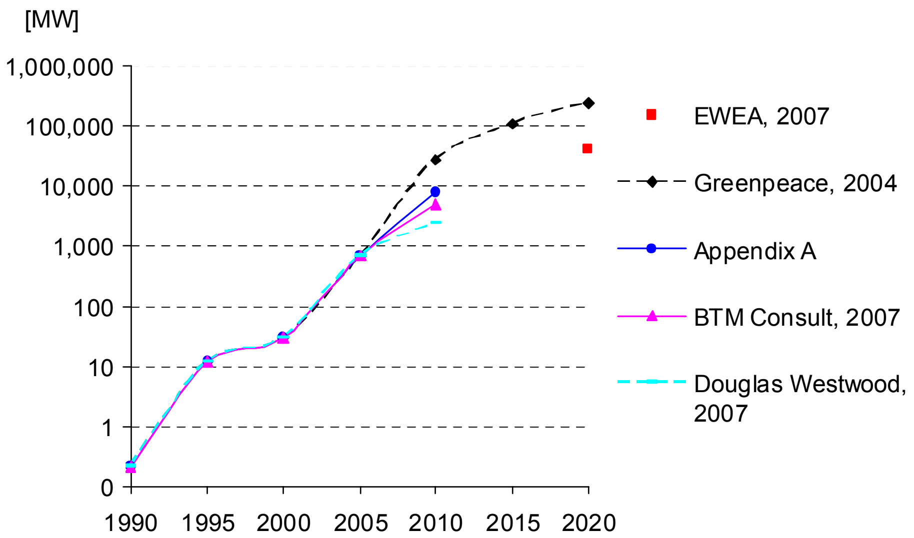

Figure 3.7 Offshore wind capacity in the EU based on three different projections. Sources:Greenpeace, 2004; BTM Consult, 2007; Douglas Westwood, 2007; EWEA, 2007.

[26] EWEA = European Wind Energy Association.

Lessons for policy makers

The development of offshore wind is evidently intertwined with energy and climate policies. Starting in 2008, nine countries in the EU have policies in place to further development of offshore wind, and other countries will follow suit. The main wind turbine manufacturing companies are located in Germany, Denmark, Spain, and the USA. Other countries, however, have the ambition to advance manufacturing of wind turbines or wind turbine components, among which the Netherlands, Finland, etc. For offshore wind, several technical competences are required. Therefore, the offshore wind industry is rather diversified compared to, e.g., onshore wind.

Junginger (2005) states that long-term stable offshore prospects may support cost reductions, especially for the installation costs, but also for (offshore) wind turbine manufacturers. No single (European) country has the potential to satisfy this requirement over an extended period of time. Thus, a key policy recommendation is to consider a joint European policy regarding the stimulation of offshore wind farms, as this might be a great benefit both to ensure offshore wind diffusion and cost reductions.

The specific investment costs of offshore wind farms recently jumped by double digits compared to the level of 2002-2004. Isles (2006) identifies this disconnect between price and cost data as a result of market structure. The factors influencing the market structure that predominantly relate to a lack of competition have been determined to be: the booming onshore industry, the high risk associated with involvement in offshore projects, limited competition amongst (offshore) turbine manufacturers, uncertainty regarding government policy and approvals, difficulty of access to funding, limited potential for experience related cost reduction and a shortage of both installation vessels and skilled contractors. However, on the longer term, prices may come down again because of learning effects related to larger turbines, larger offshore wind farms, etc. For the medium term, financial incentives - e.g., feed-in tariffs - appear to be necessary, although the gap between the generation cost of offshore wind and conventional power (based on gas, coal, or nuclear power) is narrowing. Furthermore, policy makers could also contribute to diminish other price-increasing factors (e.g., uncertainty regarding government policy and approvals, difficulty of access to funding).

General discussion

The offshore wind capacity in the EU - operational farms, and farms under construction and firmly planned - is estimated to amount to approximately 16.4 GW in 2012. Investment costs have been reported for 28 offshore wind farms, 18 of which have been built since 1991, and the balance under construction or firmly planned. From the early 1990s until about 2004 learning effects may be observed. It is hard to unambiguously quantify learning effects since recent price increases have different causes. Price increases may be predominantly due to a lack of competition amongst turbine manufacturers (Isles, 2006), but also rising prices for steel and copper have contributed to price escalation for offshore wind farms. The investment cost of 11 offshore wind farms with a combined capacity of 1,548 MW amounts to approximately M€ 3,827 or € 2,475/kW ($€_{2007}$). Appendix B shows that specific investment costs may come down to € 2,200/kW ($€_{2006}$) around 2010[27]. The cost reduction for offshore wind in Europe depends on:

- The level of the Progress Ratio (PR), which is reportedly 90% or slightly higher (92.5%).
- The cumulative installed capacity, e.g., 40 GW in 2020 and up to 230 GW in 2030.
- The extent to which offshore wind potential not too distant from the shore is available[27].

Although lack of competition in the offshore wind market may have occurred, it seems that this is a temporary phenomenon. There are five wind turbine manufacturers with turbines of 3 MW and more that are capable to offer for the offshore market. One of them (GE) decided to pull out

[27] Appendix B shows that the figure of € 2,200/kW (€ of 2006) corresponds to two offshore wind farms in the UK, viz. the 90 MW wind farm Teesside which is only 1.5 km from the shore and the 1,000 MW wind farm London Array which is 20 km from the shore. For a 'deep offshore' wind farm like the 400 MW wind farm 'Borkum 2', the length of the offshore and onshore HVDC cable amounts to over 200 km, and the specific investment cost of converter stations and main cable amounts to €750/kW, which is approximately two times higher than for the offshore wind farm Horns Rev in Denmark.

in the past, but will probably re-enter the market. Other manufacturers are keen to develop and commercialise offshore wind turbines, both in North America and Europe:

- In the USA, two offshore wind projects are due to be constructed within five years from now, unless environmental objections would prove to be insurmountable, viz. Cape Cod (Massachusetts) and Long Island (New York), possibly with U.S. wind turbines (Musial, 2005).
- Bremen-based BARD Engineering GmbH develops a 5 MW offshore wind turbine to be deployed in the German offshore market and elsewhere in the EU (Internet Source 19).

3.1.3 Photovoltaic solar energy

Introduction

Photovoltaic (PV) technology involves the direct conversion of (sun) light into electrical energy. It generally exploits semiconductor materials in various device configurations to create and collect charged carriers from light. Although the photovoltaic effect had been discovered by Becquerel in 1839 (Butti and Perlin, 1980), it took until 1954 before the first semiconductor p-n junction solar cell was developed at Bell Laboratories (Butti and Perlin, 1980). At present, the most common material used in PV technology is silicon (Van Sark, 2007), with a market share over 95%. Solar cells are based on mono- and multicrystalline material (silicon, III-Vs), and amorphous or microcrystalline thin films (silicon, II-VIs). Emerging technologies employ nanosized plastic materials. Commercial PV cells have efficiencies from 5 to near 20%, while the maximum laboratory efficiencies reach 35% (Green, 2007); the Carnot thermodynamic limit is 95% (Marti, 2004). Current research is focused on increasing the conversion efficiency by investigation of so-called third- or next-generation photovoltaics (Green, 2003a; Marti, 2004). PV cells employing light concentration of up to 1000 times are increasingly employed in regions with abundant direct sunlight.

PV systems are comprised of PV modules in which many cells are interconnected and which convert sunlight into DC electricity, inverters, which convert DC into AC, and additional components such as the electrical connection and the mounting structure. The latter are usually referred to as Balance of System (BOS) components. PV modules are classified by their rated power, i.e., the power they deliver at standard test conditions (STC) of 1000 W/m^2 irradiance (AM1.5 spectrum) while the module is at 25 °C. A 1-m^2 PV module may thus be rated at 150 Wp, where the 'p' denotes peak performance. PV system performance suffers from losses occurring in BOS components as inverters and cables but also from site-specific circumstances such as shading by chimneys or trees. The so-called performance ratio is presently around 0.8 kWh/Wp, which means that annually PV systems deliver about 800 kWh per installed kWp in the Netherlands (Bucher, 1997).

Typically, PV systems can be divided in four categories: 1) large centralized, grid-connected systems as analogue to conventional power plants; 2) grid-connected distributed generation systems, mostly in urban areas, to first supply the building with electricity and feed the excess back to the grid; 3) off-grid domestic systems (solar home systems) providing power to local households and villages; and 4) off-grid remote systems to power applications such as telecommunication appliances, water pumping, buoys. Grid-connected systems constitute about 70% of the PV world market of which over 90% in distributed form (EPIA, 2004). The world annual production capacity of PV manufacturers is 2.5 GW_p in 2006 (Maycock, 2007, Hirschman, 2007), which leads to a cumulative installed PV power of 8.6 GW_p. Market growth has been on average 40% over the past 10 years. Figure 3.8 shows the development of global installed capacity. Clearly, Japan has dominated the market for many years, but due to the favourable policy schemes, Europe, with Germany in particular is rapidly catching up. Also, renewed attention in the US is reflected in the latest growth data.

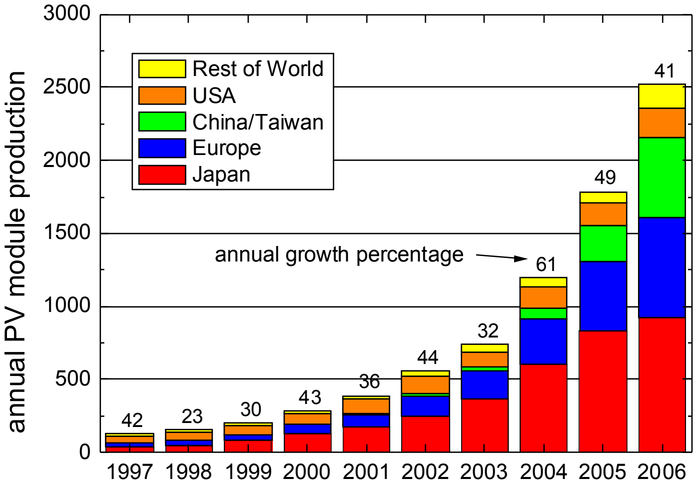

Figure 3.8 Development of annually produced PV modules 1997-2006. Note the persistently high annual growth percentages. Data from Maycock (2007).

Experience curves and PV technology

Experience curves for PV technology have been reported by several authors; an overview of selected sources is shown in Table 3.5. Three different types of experience curves can be discerned, depending on the parameters plotted on *y*- and *x*-axis. A type I curve is defined as the experience curve with cost per capacity ($/Wp or Euro/Wp) versus cumulative capacity (MWp); a type II curve shows cost per generated electricity ($/kWh) versus cumulative electricity produced (TWh); a type III curve graphs cost per generated electricity ($/kWh) versus cumulative capacity. Type I curves are most widely used in literature, and these are constructed from price data, as cost data are difficult to collect. Type II and III curves are constructed using system performance ratio, irradiance, but also inverter efficiency and interest rate (Staffhorst, 2006) Here, we will focus on type I curves.

Table 3.5 shows the progress ratio, the time period and region for which the curve is constructed and cumulative doublings (n) in the specific period. If the correlation coefficient (R^2) is calculated, it is given as well.

Table 3.5 Overview of experience curves published in the literature for photovoltaic solar energy measuring capacity

Study	PR and error	Time frame	Geogr. Region	n	R^2	Data qual.	Comments
Wolf (1972)	79-69%	1957-1972	US	9.5	n.a.	I	Cell cost $/W vs cumulative power
Chabbal (1977)	80%	1958-1976	US	9	n.a.	n.k.	Cell cost $/kW vs cumulative power
Williams (1993)	81.6%	1976-1992	Global	9.7	n.a.	II	PV Module Price ($(1992)/Wp) vs. Cum. PV Sales (MWp)
Harmon (2000)	79.8%	1968-1998	Global	13.2	0.9927	II	Module Price ($(1994)/Wp) vs. Cum. Module shipments (MWp)
McDonald & Schrattenholzer (2001)	78%	1959-1974	US	n.a.	0.94	II	Sale Price ($/Wp) vs. Cum. Cap. (MWp) Data from Maycock (1975)
McDonald & Schrattenholzer (2001)	79%	1968-1996	Global	n.a.	0.99	II	Investment Price ($/Wp) vs. Cum. Cap. (MWp) Data from IEA (2000)

Study	PR and error	Time frame	Geogr. Region	n	R^2	Data qual.	Comments
Nemet (2006)	74%	1978-2001	Global	11	n.a.	II	Module Cost ($/Wp) vs. Cum. Production (MWp) Based on data from Maycock (2002)
Nemet (2006)	83%	1976-2001	Global	13.	n.a.	II	Module Cost ($/Wp) vs. Cum. Production (MWp) Based on data from Strategies Unlimited (2003)
Swanson (2006)	81%	1979-2005	Global	10	n.a.	II	Module Cost ($/Wp) vs. Cum. Production (MWp)
Tsuchiya (1999)	82.4%	1979-1998	Japan	11.6	0.9632	I	Module Cost ($/Wp) vs. Cum. Production (MWp)
Parente (2002)	77.2%±1.0[s]	1979-1998	Global	10	0.988	n.k.	Module Cost ($/Wp) vs. Cum. Production (MWp)
Schaeffer (2004a)	80%±0.4 77%±1.5	1976-2001 1987-2001	Global	13 5	n.a	II	Module Cost ($/Wp) vs. Cum. Production (MWp) Based on data from Strategies Unlimited (2003)
Schaeffer (2004a)	81%	1992-2001	The Nether-lands	9	0.93	I	BOS Cost ($/Wp) vs. Cum. Dutch Capacity (kWp)
Schaeffer (2004a)	77.9±1.1	1992-2001	Germany	6	0.878	I	BOS Cost ($/Wp) vs. Cum. German Capacity (MWp)
IEA (2000)	84% 53% 79%	1976-1984 1984-1987 1987-1996	Global	9 4 10		II	Module Cost ($/Wp) vs. Cum. Production (MWp)
Van Sark (2008b)	79.4% ± 0.3	1976-2006	Global	15	0.992	II	Module Cost ($/Wp) vs. Cum. Production (MWp)
Staffhorst (2006)	94.7%	1990-2003	Germany	8	n.a.	I	Cost of Electricity (€/kWh) vs. Cum. German Capacity (MWp)
IEA, 2000 Mattsson & Wene, 2001	65%	1980-1995	EU	4.9	n.a.	II	Cost of Electricity (ECU(1990)/kWh) vs. Cum. Electricity Production (TWh)

± Data estimated from a figure, as exact numbers were not given.
n Number of doublings of cumulative production on x-axis.
R^2 Correlation coefficient.
n.a. Data not available.
I cost/price data provided (and/or confirmed) by the producers covered
II cost/ price data collected from various sources (books, journals, press releases, interviews)
n.k. not known
s calculated in Van Sark (2008b)

We can conclude from the table that substantial differences are found in *PR* values, depending on the data source and the time period considered. For example, Nemet (2006) has compared crystalline silicon PV module experience curves on the basis of two datasets and found differing *PR* values of 74% and 83%, for datasets from Maycock (2002) and Strategies Unlimited (2003), respectively. Although Nemet (2006) does not attempt to explain the *PR* differences from these two datasets, they appear to be primarily caused by different data for the beginning of the experience curve, i.e., below 30 MW cumulative capacity. Van Sark (2008b) has constructed an updated curve including 2006 data, see Figure 3.9. Fitting the complete dataset yields *PR*=79.4%±0.3%, where the error is determined using Eq. (4) (section 2.2). The recently occurring silicon feedstock supply shortage problem, which results from the sustained high growth of the PV industry (Hirschman, 2006; Hirschman, 2007; Van Sark, 2007) has led to module price increases in the past years, but also increased demand may have contributed to this (Schaeffer, 2008). This is expected to lead to an increase of the progress ratio, with respect to earlier determined *PR*s, however this is only apparent from moving time analyses, as is shown in Figure 3.10. In addition, one could infer a *PR* of about 1 considering only the period 2002-2006. It is generally expected that this price increase is only temporarily, and the PV industry will continue riding down the experience curve within a few years.

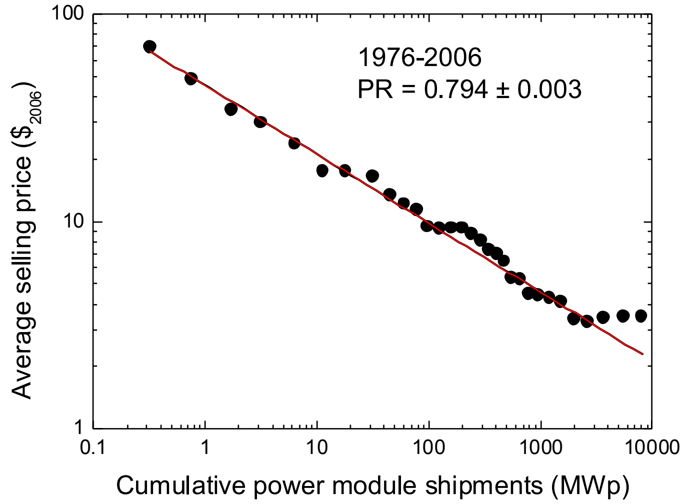

Figure 3.9 Updated crystalline silicon PV module experience curve showing average module price in 2006 US$/Wp as a function of cumulative power module shipments. Data from Strategies Unlimited (2003) are combined with data from Swanson (2006) and Hirschman (2007).

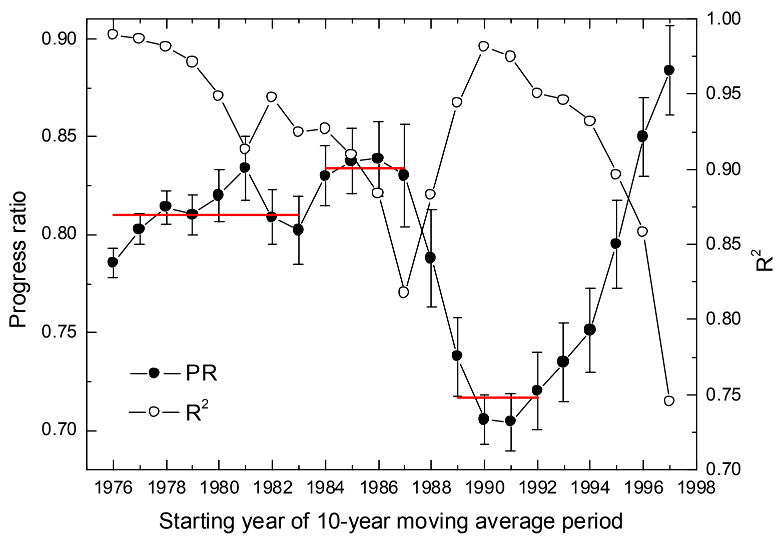

Figure 3.10 Consecutive set of PRs and associated R2 values determined from fits using 10-year time windows over the experience curve data presented in Figure 3.9. (Van Sark, 2008b)

The Photex study (Schaeffer, 2004a) concluded that module technology is to be considered as a *global learning system;* the progress ratio has been around 80% if the period from 1976 to 2001 is considered. However for the last 15 years there seems to be a steeper experience curve with a PR around 77% or even lower. Other authors had already reported similar results (e.g. Parente (2002). Adding recent data (2001-2006) contradict this, and lead to the present value of 79.4% (1976-2006).

For BOS of residential grid-connected PV systems a comparable *PR* of 80% has been realised in both Germany and the Netherlands. Schaeffer (2004a) have argued that BOS learning will occur mainly in a national context due to differences in building practices and codes and customer preferences. This assumption has important methodological consequences for the experience curve analysis, which can give rise to erroneous results if ignored. The sharp BOS price reductions that were observed were unexpected beforehand. On the other hand, prices of inverters have shown only moderate reductions and a *PR* around 92%. It may well be, however, that the *life cycle cost* of inverters have gone down more steeply because of increased performance in terms of efficiency, reliability and life time. The moderate result for inverters implies that learning for non-inverter BOS (support, cabling, installation) has seen an even better (i.e. lower) Progress Ratio than 80%.

Policy measures
Varying *public RD&D support* for photovoltaic solar energy was given in the past decades; it varied between 100 and 300 million Euros between 1980 and 2005 (IEA, 2006b, IEA PVPS, 2005). Between 1976 and 1980 the public RD&D budget increased enormously, with the USA taking the largest share; due to the 1973 oil crisis solar energy was regarded an alternative for the dependency on fossil fuel. However, since the Reagan administration, budgets have remained fairly constant. Japan started R&D programmes in the early 1980s. In the early 1990s Germany, the USA and Japan were the major funders of public RD&D. In the last few years the budget of Germany is seen to be declining, while the budget of Japan increases.

Besides RD&D support, four major market support systems are in use: feed-in tariffs or feed-in premiums systems (FIT or FIP), renewable portfolio standards (RPS), investment subsidies and tendering systems. In addition, governments may wish to empower consumers to influence the market (Jansen, 2005). Total *market subsidies* have been the largest in Japan up to 2002. In the USA, the subsidies peaked in 2003 at 250 million Euros(IEA, 2006b, IEA PVPS, 2005) . Presently, Germany is the country with the largest support scheme. Also in other countries, support is fluctuating. The success in Germany started with the 1000 roof programme, followed by the 100,000 roof programme, after which the feed-in tariff scheme was introduced and by which many renewable technologies are stimulated. In fact, a very large part of the present solar energy industry in the Eastern part of Germany (the former DDR) would not have existed without this support scheme! Nowadays, many European countries have implemented a similar feed-in tariff (Mendoça, 2007).

Economics
The costs of PV systems have been steadily decreasing from several hundreds of US$/Wp in the 1960s to the present cost of around 5 US$/Wp. This can be translated, using realistic assumptions for irradiance, system performance, depreciation time, and interest rate into an electricity price of about 0.5 US$/kWh in a wide-ranged equatorial area (EU-PV-TP, 2007). This is by far higher than costs for conventional generation of 3-6 $c/kWh. Using assumptions for future perspective PV technologies, the cost of electricity could be further reduced to first reach so-called grid parity for *consumer* prices of some 20 €c/kWh. For Southern-Europe, this is estimated to be the case in 2013, while for Northern Europe grid parity will be reached in 2020. Module costs are in general half of the system cost, thus equalling BOS cost. In order to become competitive, module cost has to come down to below 1 US$/Wp. The Strategic Research Agenda as formulated by the European PV Technology Platform (EU-PV-TP, 2007) specifies cost targets for systems, modules, and BOS to be realistically reachable in the short (2013), medium (2020), and long (2030) term. The cost targets for modules are used for *all* flat-plate PV module technologies considered. They are 0.8-1.0 €/Wp, 0.60-0.75 €/Wp, and 0.3-0.4 €/Wp, for 2013, 2020, and 2030, respectively.

Reasons behind the cost reductions / bottom-up assessments
The Photex study (Schaeffer, 2004a), similar to the Extool (Neij, 2003) study, has attempted to clarify the causes for the cost development. Schaeffer et al conclude the following from their analysis of price developments in different countries and policy contexts:

1. *There are many different national strategies*
   This is often related to geographical, cultural or political differences between the countries.
2. *Support and incentive programs cover system costs for PV in each country*
   We have seen that whatever the policy is, for the investor in one way or another in the end the system costs have to be recovered. There might be some environmentally keen people that put some of their own money in PV, but this number is limited.
3. *Steady decrease of given market support per MWp*
   Since the market support necessary to cover system costs has declined, also the market support per MWp has declined in all the countries observed.
4. *Shift from technology-push to market-pull policies*
   The expenditures for market support in some of the countries observed have been growing enormously over the last 10-15 years, whereas the R&D expenditures have remained in the same order of magnitude. This means that the balance between market support and R&D has shifted considerably in favour of the former.
5. *International spill-over in learning of Balance of System prices happens*
   Balance of System prices are different in different countries. But countries that start later with developing their markets do not start at the same high-level prices as the early-mover countries. They profit from the experience developed in these countries by making use of developed components and adapt them to their situation.
6. *BOS-prices lowest in countries with largest markets*
   As can be expected with experience, BOS-prices are lower in countries with the largest markets that started their market development earlier than other countries.
7. *Large increase in market support temporarily leads to higher module prices*
   When favourable policies are introduced this leads to a sudden increase in market size. For all countries addressed in this study, it could be observed that at this point local prices for modules increase. These short-lasting increases are observed in all countries. These increases are not occurring at the same time in the various countries and are therefore certainly related to the launching of new funding programmes.

Nemet (2006) has performed a detailed bottom-up study for the past decades and the following causes for cost reduction (Neij, 2008) were identified:
- The efficiency and the rated output per square meter has almost doubled.
- The yield has increased due to improved processing techniques.
- The silicon consumption (per watt) was reduced by a factor of 1.5.
- The cost of silicon was reduced by a factor of 12.
- The share of poly-crystalline modules increased and it may be assumed that these modules cost 90% of the mono-crystalline modules.
- Improved crystal growing methods made it possible to increase the cross-sectional area by a factor of four.
- The manufacturers enlarged their production facilities.

The recent silicon feedstock supply shortage has had, and still has, a large influence on the feedstock price, and consequently on the module price. It is desirable to update the PV experience on a regular basis to assess the progress in the PV industry, and to show how the PV industry has coped with the feedstock problem. High material costs have already prompted a faster development in reducing wafer thickness. When feedstock supply capacity is extended to cater for the growing needs of the PV industry, the module price is expected to be decreasing faster than projected due to the wafer thickness developments. In addition, it will be difficult to represent all PV systems and technologies with one experience curve. As the thin film based PV technology will gain market share, a separate experience curve should be constructed, as suggested by Green (2003b). Finally, it will also be difficult to provide a progress ratio for PV generated electricity.

Recently, other reasons for the present sustained high price of PV modules have been suggested (Schaeffer, 2008). Surprisingly, despite a sharp increase in market demand by increased political support (Feed-in-Tariffs) the prices have not come down. The industry was making a loss on their PV business until about 2002. This loss was small and bearable because until that time the PV industry consisted almost completely of large industry players (e.g., Shell, Siemens, Kyocera, Sharp), for which losses in their PV business were negligible compared to their other businesses. In 2002 cost and prices started to match. Since then, due to the high market demand, prices have remained constant, but profit margins have increased dramatically, which has attracted also new players in the market. Rogol (2006) showed that real module production costs were 1.76 Euro/Wp, and turn-key installation costs were about 2.88 Euro/Wp, figures that fit well with continued *PR*=80%. It seems that the PV industry has reentered a \`Development and Price Umbrella´ stage, which means that many new players will be attracted and that at some point in the future a large oversupply will lead to sharp decreasing prices and an industry shake out. Some analysts predict this will happen already by the end of 2008.

Future scenarios for cost reduction potentials

As an example why consideration of uncertainty is important we can consider PV implementation scenarios. In such scenarios a relatively minor variation of the progress ratio for PV has an enormous influence on the total ‘learning investment’, which is defined as the cumulative excess cost for PV generation above the break-even level where PV installations become competitive with conventional electricity generating plants (Van der Zwaan, 2003;, Schaeffer, 2004b). If the break-even unit cost is taken as 1 $/Wp, the learning investment is calculated to be 211 billion US$ for a *PR* of 80%, which is reduced to one-third for a progress ratio of 75% (Van der Zwaan, 2003). This example clearly shows the importance of correct values of the progress ratio, or at least of adding an uncertainty indication to the *PR* value, for example 80%±5% (Van Sark, 2008a) Scenarios using *PR*s should always include sensitivity studies to show the effect of different *PR*s, and the given error should indicate the range of possible values.

Using the experience curve as shown in Figure 3.9, one can extrapolate the price development beyond the 1000 GW range, assuming that the *PR* will remain constant, within say 5%. Figure 3.11 shows an extrapolation up to 10,000 GW_p cumulative installed capacity, which would constitute about 1% of the global energy demand in 2050 (Graßl, 2004). It is then interesting to compare the extrapolated data with presently used PV technology R&D roadmaps. As an example, the Strategic Research Agenda as formulated by the European PV Technology Platform (EU-PV-TP, 2007) specifies cost targets to be realistically reachable in the short (2013), medium (2020), and long (2030) term. These cost targets are used for all flat-plate PV module technologies considered. They are 0.8-1.0 €/Wp, 0.60-0.75 €/Wp, and 0.3-0.4 €/Wp, for 2013, 2020, and 2030, respectively, and are shown in Figure 3.11 as horizontal lines. For the conversion from € to US$ we used the 2006 annual average interbank exchange rate of 1 US$=0.797043 € (Oanda, 2007). The cost ranges reflect the ranges in efficiency. Modules with lower efficiency need to be cheaper than modules with higher efficiency to yield comparable overall system cost.

The sources of future cost reductions include efficiency improvements in cells, modules and inverters, lowering the amount of materials needed (in gram Si per Wp), up-scaling of manufacturing facilities such as GW-sized turn-key factories, standardized mounting structures.

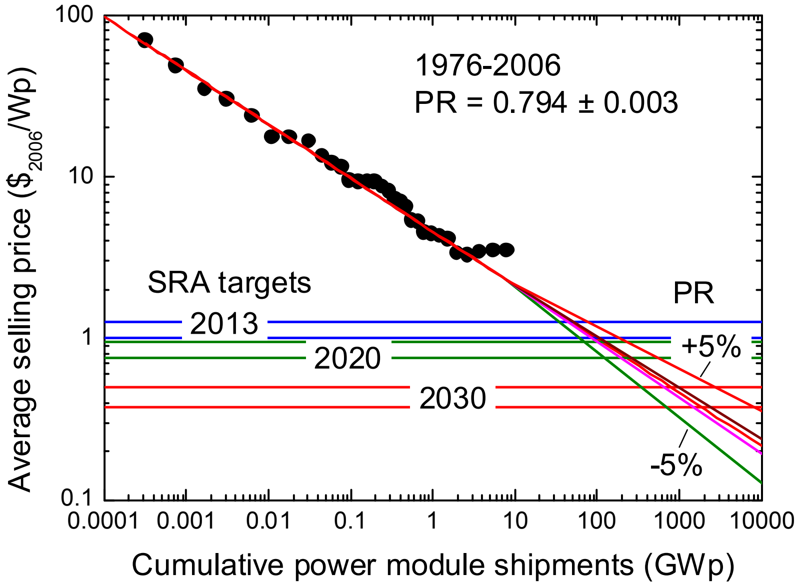

Figure 3.11. Extrapolated experience curve up to a cumulative installed capacity of 10000 GWp, extending Figure 3.8. Also indicated are the cost targets for the years 2013, 2020, and 2030 as specified in the Strategic Research Agenda (SRA) from the European Photovoltaic Technology Platform (EU-PV-TP,2007) and the effects of a 1% and 5% up- and downward variation of the progress ratio (Van Sark, 2008b)

The amount of cumulative installed capacity required to attain the SRA cost targets can be calculated using Eqs. (1) and (2) to find:

$$x_t = x_{2006}\left(\frac{c_t}{c_{2006}}\right)^{\frac{1}{m}} \tag{5}$$

where x_t and x_{2006} are the cumulative capacities corresponding to the target year *t* and the year 2006, respectively, and c_t and c_{2006} the cost targets in $/Wp corresponding to the target year and the year 2006, respectively. Note that two cost targets are set per target year. Assuming a constant annual market growth rate r_a one can find this rate knowing that the cost targets are set at a certain target year *t*, as follows:

$$r_a = \left(\frac{x_t}{x_{2006}}\right)^{\frac{1}{(t-2006)}} - 1 \tag{6}$$

We thus derive a range in installed capacity of 49-96, 117-228, and 774-1841 GW_p, for 2013, 2020, and 2030, respectively. To reach these large amounts a sustained *annual* growth rate of the PV module capacity would be needed of 29-42, 21-27, and 21-25 %, until 2013, 2020, and 2030, respectively. These numbers are somewhat lower than the 30-40% annual increase of capacity as realized in the past 5-10 years (Hirschman, 2006; Hirschman, 2007) and may therefore be considered as feasible. Results from varying *PR* up to 5% up- or downwards show that lower values of *PR* yield lower cumulative capacities for a specific target, with concomitant lower annual growth rates (Van Sark, 2008b). The 0.8 €/Wp target in 2013 for 1 to 5% larger values of *PR* yields unrealistically large annual growth rates. Overall, the 2013 targets constitute a large challenge for the industry to reach.

Lessons for policy makers

The Photex (Schaeffer, 2004a, Schaeffer, 2004b) and the NEEDS (Neij, 2007) study provide a comprehensive overview of PV experience curves. Nemet (2006) has added some more issues. Main policy lessons are listed as:

1. Experience-curve based projections better than bottom-up engineering studies
   By comparing historical bottom-up engineering price projections with historical data, and by comparing these with simple experience-curve based extrapolations, it has been seen that the price projections derived from experience curves were as good or bad or better than from bottom-up engineering studies.
2. Use scenarios for price projections
   Since progress ratios are not an intrinsic property of a technology, but can change over time, also the future progress ratio is unknown, as well as the future growth rate. Therefore different scenarios, consisting of different combinations of progress ratios and growth rates should be used to make a valuable set of price projections.
   Note that this conclusion was based on an apparent decrease in PR for PV technology. Presently, PR seems to increase, however. Taking an average PR, based on a long time period, in combination with proper variations, is a viable approach in scenario development. Growth rates are probably more uncertain than PR values.
3. Support at least medium-term price projections with bottom-up studies
   That bottom-up engineering studies are sometimes over-optimistic about the time schedule of the realisation of cost reduction does not reduce their value in indicating how certain cost reductions can be achieved. Price projections based on experience curves can only be made credible if they are underpinned by engineering studies showing that there are sufficient possibilities to realise the mid-term (5 to 10 years) projections. For longer-term projections this becomes of course more difficult since it is unknown what kind of results and research directions can be expected in the longer-term. Experience curves therefore are useful for the long-term.

Regarding investing in learning and learning investments the following is stated:

1. To find a proper balance between RTD actions, directly aimed at technology development (a 'technology push' effect) and stimulation of market penetration (a 'demand pull' effect) is very difficult. What is clear from the literature is that both learning investment (market support) and investment in learning (policy programs aiming at improving the progress ratio) are important. Effective learning only takes place when both go hand in hand. However, qualitative and quantitative analysis can help to see what the possible gains are of putting more emphasis on the one or the other compared to a business-as-usual scenario.
2. Many obstacles are met in projects aimed at getting sufficient and reliable data. Therefore, a proper data collection and monitoring of progress ratios of desired technologies (such as PV) should be set-up EU-wide as a continuous task or the EU has to support organisations to do so. Moreover, if it is combined with monitoring of data regarding investments in learning, this monitoring could lead to a better understanding of the qualitative relationship between investing in learning and the progress ratio. Until now data that could lead to an idea about the relation between investing in learning and the progress ratio resulting from that, are very scarce.
3. If substantial additional investments in learning processes lead to an improvement of the progress ratio of PV from 80% to 75%, there will be several benefits. The break-even year will come 5 tot 10 years closer. The market share of PV electricity needed to get to break-even will remain below the point where substantial additional cost will have to be made to account for the intermittent character of PV (e.g. storage, back-up power or improved demand response by ICT-solutions). The global learning investments needed to get to break-even will be reduced by several hundred billion Euros/dollars.
4. The latter point means that as long as the additional investments in learning (provided it leads indeed to a progress ratio of 75%) stay below the savings on learning investments, society wins also in financial respect.
5. Substantial reductions of learning investments are possible if high-value markets are developed first. The success of an approach targeting at high-value markets first is shown by the Japanese PV program. According to the PV Status report 2003 (Jäger-Waldau, 2003) the annual subsidy budget for PV is stable since 2001, while the number of systems

subsidised has tripled. With a subsidy of about 1 Euro/Wp the high-value residential market is developed successfully.

A final lesson cannot be stated clearer than Albrecht (2007) did: “Our portfolio analysis showed that PV, next to wind energy, offers the ability to reduce the risk from fossil-fuel dependence while the cost consequences of an energy system transformation are modest. Hence, we conclude that not investing in PV is much riskier than promoting the diffusion of PV.”

General discussion

Production costs vs. prices - the recent price increases

Since 2003, global market prices for photovoltaic modules have been increasing slightly, as opposed to the expected decrease following the experience curve. Present (2006) average module price is about 7% higher than the price in 2003, while the present price is 50% higher than expected, i.e., when extrapolating the experience curve. This price increase and the discrepancy with expected price development are thought to be caused by the following reasons:

- *Insufficient availability of purified silicon feedstock.* The strong increase in cell production capacity has put a strong demand on silicon feedstock, with a concomitant price increase of the feedstock. Spot market prices of silicon feedstock of 200 US$ are not uncommon, constituting a factor of 8-10 price increase with respect to earlier years. Investments in silicon feedstock facilities have been lagging behind, and as construction time of such facilities are 1-2 years, it will take until 2010 for feedstock capacity to be inline with feedstock demand. At that point in time, the amount of silicon needed for the PV industry will surpass the needs of the semiconductor industry.
- *Increasing prices for all power technologies.* Maltepe (2007) pointed out, that the prices of many conventional technologies have increased also, even more strongly (claimed up to 50%) for e.g. gas turbines, steam turbines etc., due to increasing steel prices and increasing general demand for electricity world-wide. As the PV technology chain requires a considerable amount of energy, price increases are partly due to this.
- *Profit margins.* Some cell manufacturing companies seem to have used the silicon feedstock problem as driver for price increases to add an additional amount to increase (or take) their profit margins. Companies having long-term contracts with feedstock suppliers will have lower cell production cost than others that do not have these contracts.
- *Strongly increasing demand for photovoltaic energy.* Probably the most important development is the strongly increasing demand for photovoltaic modules all over the world (with annual growth rates of 40% over the past 10 years) because of all the national policy support measures (e.g. EEG scheme in Germany). Currently existing manufacturing capacity is not able to keep up with this demand. It can be expected, that on the longer term (>2010) a healthy balance between demand and supply can be reached, after a possible shake-out phase within the PV industry.

As PV has not been ‘riding down the experience curve’ for some years now, it is tentative to conclude that learning has not taken place. Of course, this is not the case. Due to the high silicon feedstock price, technological developments in reducing the amount of silicon needed have been faster than anticipated. It is therefore expected that when the silicon feedstock price decreases again, PV module prices will drop faster than only accounting for the silicon price.

Use of national vs. global experience curves

The market of PV modules is a global one, with market players from all over the world, although manufacturers from Japan and Germany are dominating, however, it is a highly dynamical market. The global progress ratio of 79.3% was found to be higher when considering national system boundaries, as reported by Schaeffer (2004) for the case of Germany, but most probably this can be generalized. BOS learning can be fast on a national level, if a favourable support scheme is in place, also shown by Schaeffer (2004). In this respect, developments in inverter manufacturing are increasingly on a global level, while support structures and installation labour will probably remain subject to local learning.

Qualitative technical developments / technology trends, outlook for future costs
The EU, USA, and Japan have developed similar roadmaps for future technological developments, see e.g, the PV Status Report 2007 (Jäger-Waldau, 2007). To maintain the high annual growth rates of PV technology, RD&D is focused on

1. reduction of material consumption per silicon solar cell and Wp by means of reaching higher conversion efficiencies, thinner silicon wafers, higher yields in the whole production chain
2. introduction of thin film solar cell technologies in the market at higher growth rates than is the case for silicon wafer-based technology
3. drastic increase of solar grade silicon feedstock facilities
4. very large scale manufacturing facilities reaching 1 GW_p annual production
5. intensive R&D on next-generation PV devices and materials to reach >50% efficiency at cost level below 1 €/Wp

3.1.4 Concentrating solar thermal electricity technology

Introduction
Concentrating Solar Power (CSP) is a term for a group of Solar Thermal Electricity (STE) technologies that employ tracking reflective surfaces systems for concentrating solar irradiation on an absorber. The working principle is similar to that of a magnifying glass (De Laquil, 1993). The absorber contains a medium which is heated to high temperatures between 600 and 1200 ºC, depending on the technology. Thermodynamic energy conversion efficiencies are therefore high. Carnot efficiencies are theoretically about 66 % and 80 % for these two temperatures. For thermodynamic conversion a Rankine cycle with organic or water based liquid as working fluid in the primary closed circuit is often used. The process fluid in the secondary closed system is required to be in the liquid state at the high operating temperatures. This liquid runs through the solar receiver tubes and transfers the heat to the primary circuit of the thermal engine. Molten salts and thermal oils meet with these conditions. As a heat sink, the surrounding air is used in a cooling tower. Typical installation sizes are between 30 and 200 MW. First installations have been operational since the 1980s in the US, and amount to 355 MW. The deployment of CSP technology has been standing still for a long time; renewed interest in the past few years has led to various studies and plans for new installations. This rebirth is taking place in Spain, which aims to install 500 MW by 2010. Interestingly, mainly German companies are involved in CSP development. Future scenarios always include STE, albeit in a small role, for example contributing 1% to global energy supply in 2040 (EREC, 2004).

Although many variants exist, CSP technology can be divided in the following main types, to show the variety in technologies that have been proposed and tested nowadays:

- The layout of *parabolic trough* technology is dominated by the use of parabolic mirrors that focus the solar rays on a tube (Mills, 2000; WEC, 2004; Wenslawski, 2003). Typical generated temperatures are about 400 ºC with thermal oil as working fluid (Pitz-Paal, 2004);
- In *parabolic dish* technology the concentrator has the shape of a parabolic dish. Typical temperatures in the receiver are about 800 ºC, with molten salts or thermal oils as working media (Pitz-Paal, 2004);
- *Central receiver* technology deploys a tank (receiver) wherein the medium is heated. Many flat mirrors (heliostats) reflect solar rays on the receiver. Typical temperatures in the receiver are 600 to 1200 ºC, with molten salts as working media (Pitz-Paal, 2004; Wenslawski, 2003).
- *Solar updraft tower* in which turbines are employed that are driven by rising air that is heated in a large greenhouse structure surrounding the tower

Present costs of new plants range from 3500 €/kW_{el} for a solar updraft tower, via 5000 €/kW_{el} for a parabolic through plant to 10000 €/kW_{el} for a central receiver plant (Neij, 2007). This translates into cost of electricity around 15 €c/kWh (Pitz-Paal, 2004).

Experience curves and concentrating solar thermal electricity
Although solar thermal power plants are in existence since the 1980s, due to the limited amount of installations, only a few studies have been performed using experience curves primarily to analyse future cost reduction trends. A study by Enermodal (Enermodal, 1999) has used data of installed capital costs for the solar electricity generation (SEGS) plants in California (SEGS I to SEGS IX). From their experience curve, as shown in Figure 3.12, a progress ratio of 88% can be derived. Future technology development is estimated to have a range of progress ratios of 85-92 % for parabolic trough as well as for central receiver technology, due to the similarity between these systems. According to this study cost of either system would be around or lower than 2000 US$(1996)/$kW_{el}$ at a cumulative installed capacity of 10 GW_{el}.

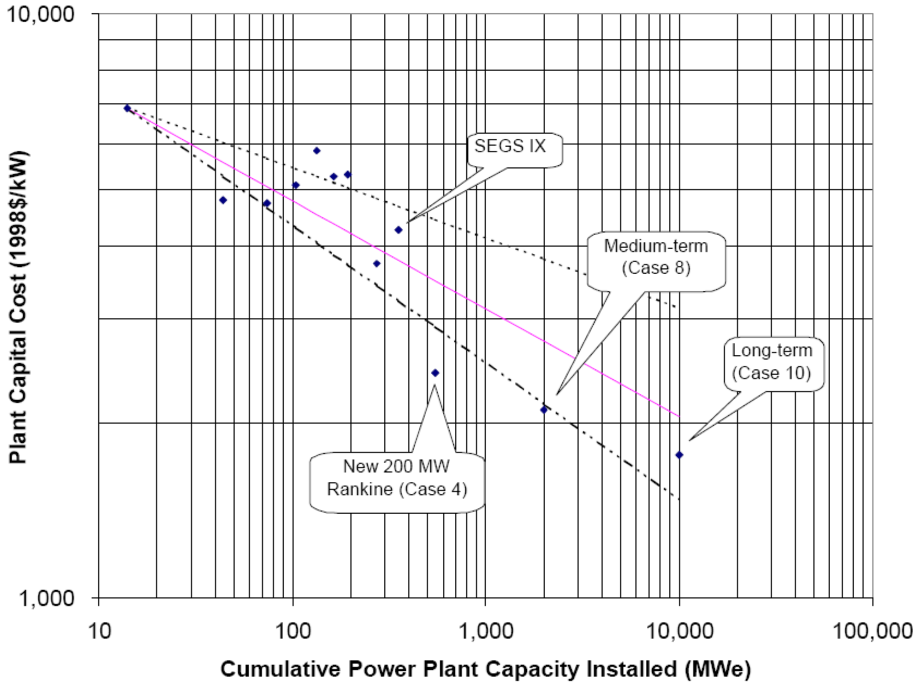

Figure 3.12 The extrapolated experience curve of parabolic trough technology (data from Enermodal, 1999).

From other studies, that rather present future estimated experience curves, assumed progress ratios are used, of the order of 80%. DLR (2003) has developed a model, and even used the experience curve approach to subsystems. In their ATHENE model the progress ratios are 90%, 88%, and 94%, for collectors, storage systems, and the power generator, respectively. Analysis of the Spanish plans, as reported by Neij (2008), leads to derived progress ratio of 80%.

Economics
The costs of CSP systems has decreased to the present cost of around 5 €/W_{el}. This can be translated, using realistic assumptions for irradiance, system performance, depreciation time, and interest rate into an electricity price of about 0.2 €/kWh in the sun-belt area (Pitz-Paal, 2004; Sargent & Lundy LLC Consulting Group, 2003).

Expected future developments indicate possible cost reductions leading to cost of electricity in a narrow range around 0.07 €/kWh. (Pitz-Paal, 2004; Sargent & Lundy LLC Consulting Group, 2003; Cohen, et al., 1999; Trieb, 2000; Trieb, 2005).

Policy measures
It is often stated that present R&D support measures are insufficient for a proper development of CSP technology. Nevertheless, some demonstration plants have been deployed and partly financed. As CSP technology may become important in countries where the CDM mechanism would apply, policy measures in that direction are of interest for large-scale market deployment.

Reasons behind the cost reductions / bottom-up assessments

As the present experience curves are based on only few historical data that have been extrapolated for future estimates, the reasons behind cost reduction are also estimates. For example, the ECOSTAR study provides many incremental reasons, one being the increase of unit size of the power generator (Pitz-Paal, 2004). Besides that, general effects such as volume production, will also take place. In the various studies a steady 25% annual market increase is used, which would allow for a cost reduction of 55-65%.

General discussion

In summary, experience curves for STE are primarily used for cost estimation in the mid and long term, with a progress ratio of 80%. Potential cost reductions will lead to cost of electricity that would be competitive in 2020 with conventional electricity generation (coal, gas, nuclear). It goes without saying that monitoring of real cost data is recommended to construct a reliable STE experience curve.

3.1.5 Biomass for electricity, heat & biofuels and experience curves

Introduction

Renewable energy sources[28] accounted for 12.6% (62 EJ) of the world's total primary energy demand in 2005. Biomass[29] is by far the largest source of renewable energy. Due to its widespread non-commercial use in developing countries, solid biomass is by far the largest renewable energy source, representing 9.6% of the worlds totalprimary energy supply (TPES), or 75.6% of global renewables supply. After wind energy, the non-solid biomass combustible renewables and waste (such as renewable municipal waste, biogas and liquid biomass) displayed the second highest growth rate, growing on average at 8.2% annually since 1990. Solid biomass (which is the largest contributor to renewable energy in the world) has experienced the slowest growth among the renewable energy sources, growing only 1.5% per year. The bulk of solid biomass (86.6%) is produced and consumed in non-OECD regions, where developing countries, situated mainly in South Asia and sub-Saharan Africa, use non-commercial biomass for residential cooking and heating. Africa, which consumed about 5.3% of world TPES in 2005, produced 26.2% of the world's solid biomass supply. Energy diversification and a more efficient use of solid biomass are expected to provide mitigation opportunities to sustainability issues regarding the use of biomass in some non-OECD regions (OECD/IEA, 2007).

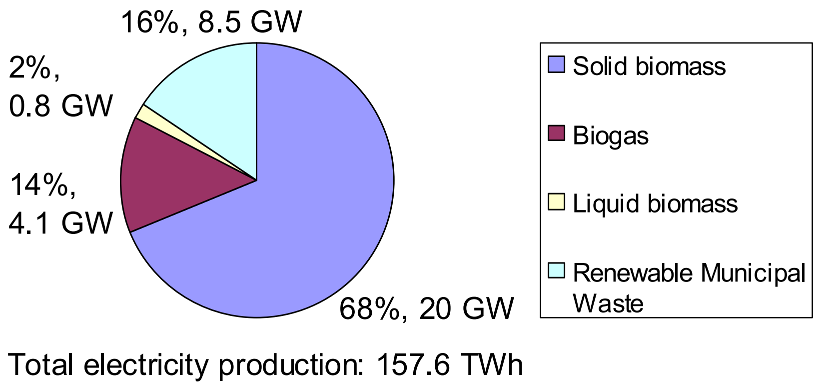

Figure 3.13 Electricity production from biomass and renewable municipal waste in OECD countries in 2005, and corresponding installed capacities (data source: OECD/IEA, 2007).

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[28] Refers to renewable non-fossil sources of energy (wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogas).

[29] Refers to the biodegradable fraction of products, wastes and residues from agriculture (including vegetal and animal substances) and forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste.

Biomass fuels cover approximately 1% of global *electricity production*, and are often used in combined heat and power production (CHP) (OECD/IEA, 2007). The current global biomass power generation capacity is approximately 44 GW_e (REN21, 2006), of which about 33.4 is situated in OECD countries (OECD/IEA, 2007, see Figure 3.13). Electricity production in OECD countries amounted to about 158 TWh in 2005. More than two thirds of this is based on solid biomass, the remainder on biogas, renewable municipal waste and (marginally) liquid biofuels. The largest producing countries are the US, Japan, Germany, Canada, Finland and Sweden.

Generally, biomass has been a marginal source of *energy in industry and district heating*. However, in countries such as Sweden, Finland and Austria, which have a large forestry sector, forest-based biomass has a remarkable importance. For example, in Finland, renewable energy sources cover 25% of the total primary energy consumption, and over 80% of renewable energy was derived from wood. In total, global thermal biomass capacity was estimated at 220 GW_{th} (REN21, 2006).

The global consumption of *liquid biofuels for transportation* was 0.33 EJ in 2002, of which Brazil accounted for 70% and the United States for 23%. The share of biofuels in total global transport consumption was only 0.4%.

While fossil fuels still account for more than 95 percent of the global transportation fuel market, production of *liquid biofuels for transportation* is growing roughly 15 percent per year, a rate over ten times that of oil (Davis, 2007). Ethanol production more than doubled between 2000 and 2005, reaching 27 million metric tonnes in 2005 (about 710 PJ). Biodiesel production, which started from a smaller base, quadrupled, reaching about 3.1 million metric tonnes in 2005 (including some pure vegetable oil), equivalent to about 115 PJ (Davis, 2007, Biofuels Barometer, 2007). Ethanol and biodiesel combined contribute about 1% to the global transportation fuel consumption in 2005. Corn-based U.S. ethanol and sugarcane-based Brazilian ethanol currently account for almost 90% of global biofuels production. However, other countries all over the globe are rapidly expanding output using a variety of sugar crops and cereals. Europe is currently the leading producer of biodiesel, which is processed from vegetable oils that are derived from rapeseed, sunflower seeds, soy beans and oil palm, among other crops, but again many countries in South East Asia and Latin America are also rapidly developing biodiesel production.

Biomass energy and experience curves

Modular renewable energy technologies have been described in numerous studies in the literature. In contrast, relatively few studies have been published that apply the experience curve approach to bioenergy systems. There are probably several reasons for this (see also the general disccion part of this section. Most obviously, biomass energy systems differ from most other renewable energy technologies, as they require fuel. This adds another cost component to the total production costs. It can also influence investment costs and O&M costs[30]. Thus, for biomass-fuelled power plants, the total learning system can principally be split up in three parts (see Figure 3.13). For each of these parts, a separate learning system can be defined. This approach of investigating compound learning systems has been described by Wene (IEA/OECD, 2000), and is recommended especially when the production costs development of electricity is investigated. Splitting the entire learning system in several subsystems may provide insights in the various learning mechanisms.

[30] For example, meeting emission levels may require additional investment and O&M costs, and difficult fuels may affect reliability and maintenance cost.

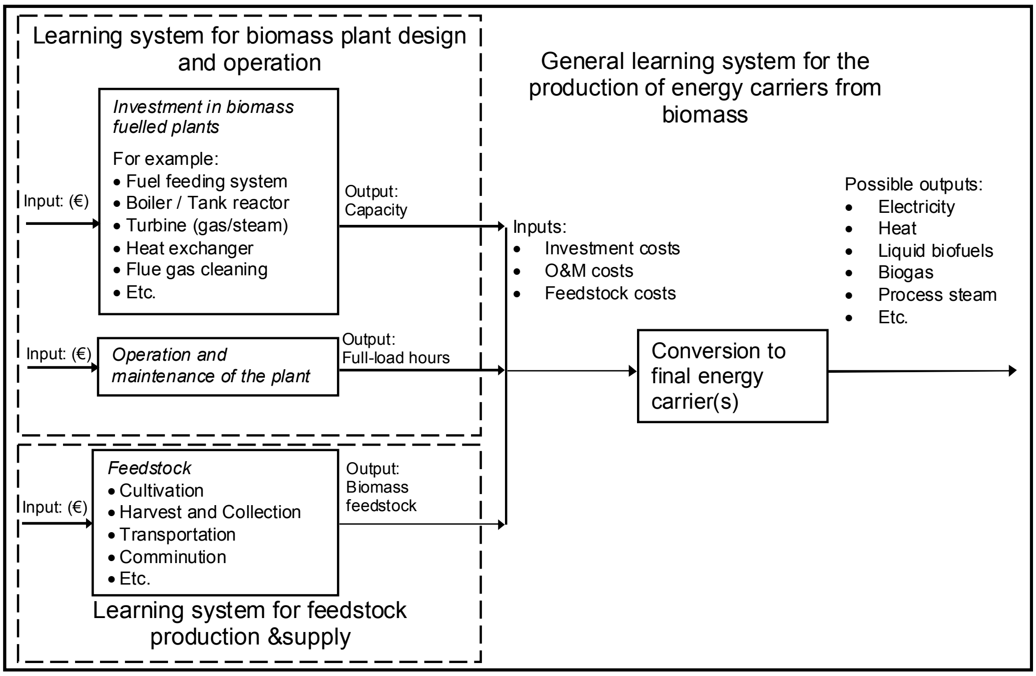


Figure 3.14 General structure of biomass energy learning systems

Table 3.6 Overview of experience curves for biomass energy technologies / energy carriers

Learning system	PR (%)	Time frame	Region	n	R^2	Data qual.	Comment
Feedstock production							
Sugarcane (tonnes sugarcane) Van den Wall Bake et al.; 2008	68±3	1975-2003	Brazil	2.9	0.81	II	
Corn (tonnes corn) Hettinga, 2007	55±0.02	1975-2005	USA	1.6	0.87	II	
Logistic chains							
Forest wood chips (Sweden) Junginger et al., 2005	85-88	1975-2003	Sweden / Finland	9	0.87-0.93	II	
Investment & O&M costs							
CHP plants (€/kW$_e$) Junginger et al., 2005	75-91	1983-2002	Sweden	2.3	0.17-0.18	II	
Biogas plants (€/m^3 biogas/day) Junginger et al., 2005	88	1984-1998		6	0.69	II	
Ethanol production from sugarcane Van den Wall Bake et al.; 2008	81±2	1975-2003	Brazil	4.6	0.80	II	(annual capital charges & O&M cost combined)
Ethanol production from corn (only O&M costs) Hettinga, 2007	87±1	1983-2005	USA	6.4	0.88	II	
Final energy carriers							
Ethanol from sugarcane Goldemberg et al., 2004	93 / 71	1980-1985	Brazil	~6.1	n.a.	II	
Ethanol from sugarcane Van den Wall Bake et al.; 2008	80±2	1975-2003	Brazil	4.6	0.84	II	
Ethanol from corn Hettinga et al, 2007	82±1	1983-2005	USA	6.4	0.96	II	
Electricity from biomass CHP Junginger et al., 2005	91-92	1990-2002	Sweden	~9	0.85-0.88	II	
Electricity from biomass OECD/IEA (2000)	85	Unknown	EU (?)	n.a.	n.a.	n.a.	
Biogas Junginger et al., 2005	85- 100	1984-2001	Denmark	~10	0.97	II	

n Number of doublings of cumulative production on x-axis.
I cost/price data provided (and/or confirmed) by the producers covered
II cost/ price data collected from various sources (books, journals, press releases, interviews)
III cost/price data (or progress ratio) being assumed by authors, i.e. not based on empirical data

In Table 3.6 an overview is given for all studies presenting experience curves for the various components of biomass energy systems.

Starting with the analysis of dedicated feedstock production, sugarcane production in Brazil (van den Wall Bake et al., 2007, see Figure 3.15) and corn production in the US (Hettinga et al. 2008) show remarkably low (i.e. benign) PRs of 68% and 55%[31] respectively. The experience curve by Junginger (2005) describes cost reduction in the logistic wood-fuel supply chain, or primary forest fuel (PFF). The experience curve, with a progress ratio of 85%, is based on production cost data of different types of supply chains (terrain, roadside and terminal). For investment and/or O&M costs, experience curves for plants producing electricity and heat, biogas and ethanol have been devised (see Table 3.6). For the studies with a satisfactory correlation coefficient, progress ratios between 81-88% were found.

Regarding the production of electricity from biomass, only two studies with experience curves were found. Junginger (2005) presents a progress ratio for biomass CHP electricity generation of 91-92% (see Figure 3.16). The figures used were based on actual electricity production per plant, O&M cost based on literature and expert opinions, average wood-fuel prices from literature, and the allocation of electricity and heat based on the annual economic value of both products. Second, in OECD/IEA (2000) an experience curve for electricity from biomass is presented - based on data from the EU-ATLAS project. The progress ratio of the experience curves is estimated at approximately 85%. However, it is not clear what type of data has been used. Furthermore, it is not clear what type of biomass sources and technologies are included.

In a first publication on experience curves and ethanol production costs, Goldemberg et al. (2004) find a PR of 93% between 1980-1985, and PR of 71% between 1985-2002. This trend is explained by an initial mediocre price drop due to slow gains in agroindustrial yields, while the sharp decrease of prices after 1985 is attributed to increasing economies of scale and political pressure to reduce prices. In van den Wall Bake et al., a constant PR of 80% is determined over the entire period 1975-2005. It is observed that Goldemberg et al. (2004) only assume a very modest initial cumulative ethanol production before 1980, approximately 3 million m^3. Van den Wall Bake et al.(2008) took into account the cumulative ethanol production from 1941 onwards, and determine a cumulative ethanol production of 25 million m^3 in 1980.

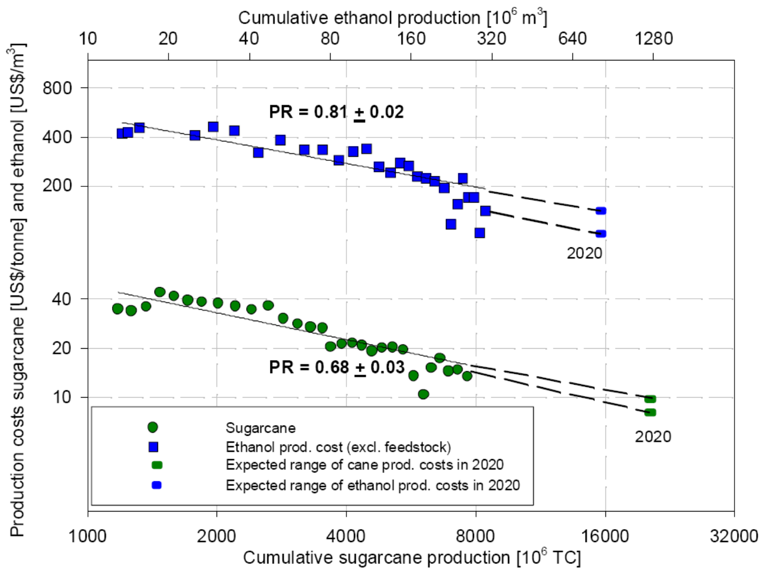


Figure 3.15 Experience curves for sugarcane production costs and ethanol production costs in Brazil between 1975-2005, and extrapolation to 2020.

[31] These PRs are exceptionally low compared to an average PR of 80%. However, as there are no reference experience curves for crops are known, it remains unclear whether these two values are exceptional or typical for agricultural products.

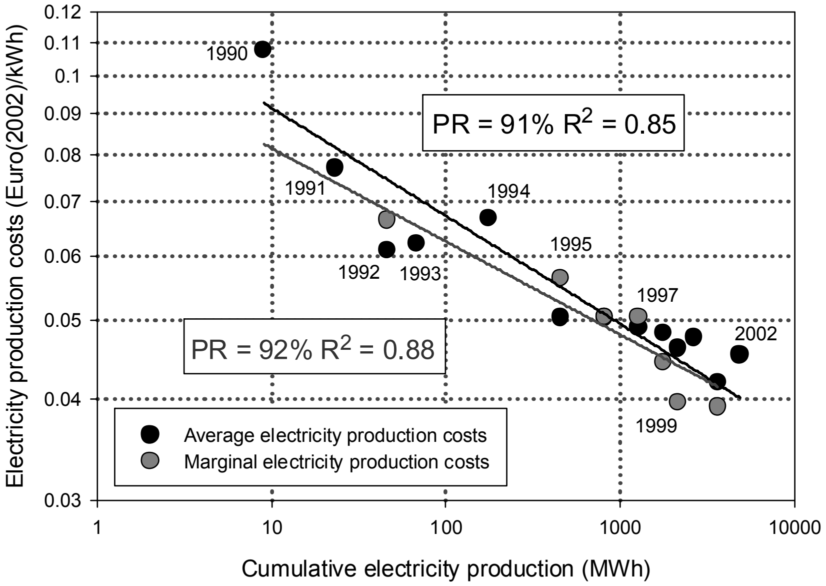


Figure 3.16 Experience curve for the average and marginal production cost of electricity from Swedish biofuelled CHP plants from 1990-2002 (Junginger, 2005). The allocation of production costs to electricity and heat was done based on market value.

Economics

Costs for biomass energy technologies vary widely, due to the very large range in conversion technologies (e.g. stand-alone combustion, co-combustion with fossil fuels, gasification, pyrolysis, anaerobic fermentation etc.), a large-range of feedstock costs (ranging from 'waste streams' with negative costs to dedicated energy crops with relatively high costs) and large differences in scale (from < 1 kW_{th}-sized farm scaled biomass digesters and residential heating systems to >100 MW_e stand-alone and co-combustion power plants). A broad overview of turnkey investment costs and energy cost ranges is presented in Table 3.7.

Table 3.7 Overview of cost ranges of biomass energy technologies (van Tilburg et al., 2007)

Electricity technologies	Capital costs in 2006 [€/kW_e]	Electrical efficiency [%]
Existing coal - co-firing of wood pellets	590	35-40
Small scale wood combustion <10 MW_e	4000	20
Wood combustion 10-50 MW_e	2900	30 (20-40)
Co-digestion	2500	27
Waste incineration	2375	23

Policy support

Since the two oil crises in the 1970s, the development of modern biomass has received serious attention in many different countries. Examples are biomass use for district heating (often combined with electricity production in CHP plants) in Scandinavian countries and Austria, ethanol production as substitute for gasoline in Brazil and the US, and electricity and heat production from manure in Denmark and Germany. In many industrialized countries, these developments have been supported by *market pull* instruments, such as investment subsidies, feed-in tariffs (often differentiated by type of biomass fuel, and type and size of the conversion plant), and in some cases quotas. The latter has been especially used in the last decade in various EU countries to stimulate the use of biomass transportation fuels, and is now used in the EU. For a comprehensive overview of European market-pull biomass support policies, see e.g. Thornley and Cooper (2007). Regarding *technology-push* programmes (i.e. public R&D support) also numerous national efforts have been made in many (mainly industrialized) countries. Within the European Union, biomass has received continuous attention in the seven framework programmes. Also, in the US, NREL (and other research centres) have carried out

R&D since the early 1980's. Most of this research is directed at increasing the efficiency of feedstock production, improving biomass conversion processes (mainly combustion, gasification, pyrolysis for electricity and biofuels production), and in general lowering production costs. Specifically regarding the production of biofuels for transportation, both the US and the EU mainly focus on the development of so-called second generation biofuels, i.e. producing ethanol from lignocellulosic biomass and various biofuels (such as hydrogen, methanol and Fischer-Tropsch diesel) through a gasification route.

Reasons behind the cost reductions / bottom-up assessments
As discussed above, biomass energy systems are differing strongly in terms of feedstock, conversion technology and scale and final energy carrier. Yet, there are a number of general drivers that can be identified:

For the production of sugar crops (sugarcane) and starch crops (corn[32]) (as feedstock for ethanol production), increasing yields have been the main driving force behind cost reductions.

Specifically for sugarcane, also increasing strength of different varieties of sugarcane (developed through R&D efforts by research institutes), prolongation of the ratoon systems, increasingly efficient manual harvesting and the use of larger trucks for transportation reduced feedstock costs (van den Wall Bake et al. 2008). For the production of corn, highest cost decline occurred in costs for capital, land and fertilizer. Main drivers behind cost reductions are higher corn yields by introducing better corn hybrids and the upscaling of farms (Hettinga, 2007). While it is difficult to quantify the effects of each of these factors, it seems clear that both R&D efforts (realizing better plant varieties) and learning-by-doing (e.g. more efficient harvesting) played important roles.

Industrial production costs for ethanol production from both sugarcane and corn mainly decreased because of increasing scales of the ethanol plants. Cost breakdowns of the sugarcane production process showed reductions of around 60 percent within all sub processes. Ethanol production costs (excluding feedstock costs) declined by a factor of three between 1975 and 2005 (in real terms, i.e. corrected for inflation). Investment and operation and maintenance costs declined mainly due to economies of scale. Other fixed costs, such as administrative costs and taxes did not fall dramatically, but cost reduction can be ascribed to application of automated administration systems. Declined costs can mainly be ascribed to increased scales and load factors.

For ethanol from corn, ethanol processing costs (without costs for corn and capital) declined by 45% from 240$$_{2005}$ per m^3 in the early 1980's to 130$$_{2005}$ per m^3 in 2005. Costs for energy, labour and enzymes contributed in particular to the overall decline in costs. Key drivers behind these reductions are higher ethanol yields, the introduction of specific and automated technologies that require less energy and labour and lastly the upscaling of average dry grind plants.

Future scenarios and cost reduction potentials
Only for the production of ethanol from sugarcane and corn, future production cost scenarios based on direct experience curve analysis were found in the literature:

For ethanol from sugarcane (van den Wall Bake et al, 2007), total production costs at present are approximately 340 US$/m^3 ethanol (16 US$/GJ). Based on the experience curves for feedstock and industrial costs, total ethanol production costs in 2020 are estimated between US$ 200-260/m^3 (9.4-3 12.2 US$/GJ).

For ethanol from corn (Hettinga et al, 2008), production costs of corn are estimated to amount to 75US$$_{2005}$ per tonne by 2020 and ethanol processing costs could reach 60 - 77 US$/m^3 in 2020. Overall ethanol production costs could decline from currently 310 US$/m^3 to 248 US$/m^3 in 2020. This estimate excludes the effect of probably higher corn prices in the future.

32 Corn is also referred to as maize.

Lessons for policy makers
For most technologies considered, policy support played a major part in the successful development and market diffusion. Clear examples are the Swedish and Brazilian policy support measures. In Sweden, amongst others taxes on fossil fuels for heating and investment cost subsidies, which enabled the sustained development of woody biomass use for district heating. The Brazilian ProAlcool programme included R&D support, investment support and various other market support measures.

Most importantly, it seems that in both cases, support measures were in place for an extended period of time (a decade or longer), which enabled investors to continuously improve feedstock production and supply chains, and develop processing technologies. While in the Brazilian case, clearly R&D programmes contributed to both cost reductions of feedstock and industrial processing, in the Swedish case the technological learning of forest fuel supply chains occurred basically with no major targeted R&D efforts.

General discussion
Biomass energy systems in general are complex, and cover many types of combinations of conversion technologies and fuel supply chains. Experience curves so far have only been developed for a few systems and these curves have been based on a broad set of data. The bio energy systems, - however, not always the individual technologies - are immature and it is difficult to assess future technology development. For this reason, future cost development is uncertain. Below, in our discussion we distinguish between experience curves for investment costs of bioenergy plants, experience curves for the biomass feedstock costs, and experience curves for the overall energy carriers.

Analyzing investment costs of bioenergy systems using experience curves
When analyzing the **investment costs** of biomass power plants, there are several issues that complicate the application of the experience curve concept compared to other (modular) renewable energy technologies.

First, as plants are normally large-scale technologies, in general far less ‘plants’ are produced compared to modular technology such as solar PV or wind to generate a certain amount of electricity. To give an indication of differences in volumes compared on basis of annual electricity production, a single biomass plant of 30 MW_e will annually produce approximately as much electricity as 50 wind turbines of 1.5 MW_e or 1.5 million solar panels of 100 Wp. To devise experience curves, large amounts of data are required to be able to calculate average investment costs in a statistically significant way for biomass plant technologies. These data are generally available in small amounts only.

Second, (biomass) power plant investment costs generally depend on local conditions. In many cases, plants are custom-designed to meet specific conditions and requirements in terms of heat and electricity demand and load, available building space, biomass storage space, existing infrastructure etc. The fuel type also has an important influence on investment costs. A wide variety of biomass fuels exists, with often very different properties such as moisture content, ash content, alkali content and size. In addition, biomass may be co-fired with other fuels such as coal and municipal solid waste. If a plant is designed to handle a multitude of different fuels instead of a single one, investment costs are generally higher. Furthermore, the investment costs are determined by local factors such as environmental regulations and the cost of labor. The impact of these factors on the analysis of PRs may possibly be circumvented by focusing on one fuel, one geographical region, a minimum emission standard and one, narrowly defined, type of power plant.

Third, scale effects strongly influence costs per unit of capacity (specific costs). It has often been shown that in general the specific costs decrease with upscaling the capacity of the plant or component (such as the boilers or turbines). This difference can be adjusted by using scaling functions (Remer and Chai, 1990). For power plants, sclae factores of around 0.7 are quite commonly used (Joskow and Rose, 1985; Faaij et al., 1998). Applying a scaling function and converting all plants to a reference size may make the data more suitable for use in an experience curve. However, as upscaling is one of the underlying mechanisms of cost reductions, this will probably also flatten the experience curve (assuming that average plant size increases with the development of the technology).

Fourth, biomass energy systems often have more than one output. Most common is the production of electricity and heat using combined heat and power (CHP) plants, but also poly-generating systems with biomass transportation fuels (Hamelinck, 2004) or biomass-based polymers (Dornburg, 2004) as additional outputs can be an option. In these cases, allocation of the production costs is required, based e.g. on the market or exergy value of the products.

Fifth, in most experience curves for renewable energy technologies, data about marginal production costs are used, especially for modular technologies such as wind turbines and PV modules. For these technologies, the investment cost largely determines the overall electricity production costs. Also, once installed, the electricity production costs for these technologies tend to remain constant (or even rise with increasing O&M costs at the end of the economical lifetime). However, for plants producing a certain commodity (such as biomass plants producing electricity), there is also significant learning-by-using occurring during the operation of the plant. Typically, a plant achieves a rather low load factor in its first year of operation, and only achieves the design load factor after several years, when all start-up problems have been solved. In addition, electricity costs are also more influenced by fuel and O&M costs; these costs may change over the entire lifetime of a plant. For example, fuel costs may decline as an effect of more efficient supply chains. O&M costs may decline because of automation and efficiency gains on one hand, but increase due to aging on the other hand. Therefore, it is also interesting to analyze the development of the average production costs. Empirically, it was shown that the experience curve approach can also be applied to describe average costs developments. For example, average costs data have been used in experience curves describing the development of different chemical commodities, the American electricity sector (BCG, 1968) or the carbon intensity of the global economy (IEA/OECD, 2000).

From the case studies described by Junginger et al. (2005) it can be concluded that it is very difficult to devise empirical experience curves for the investment costs of biomass fuelled power plants. To some extent, this is due to lack of (detailed) data. Mainly, it is caused by varying plant costs due to scale, fuel type, plant layout, region etc.

Analyzing feedstock production costs of bioenergy systems using experience curves
Even though only based on two studies (Van den Wall Bake, 2008 & Hettinga et al, 2008), it appears that feedstock production costs can quite adequately be described using the experience curve concept, and that the Progress Ratios found are very benign (55-68%), implicating rapid decrease of production costs with cumulative production. These reductions are mainly driven by yield increases. This raises the question, whether cost reduction can continue indefinitely, or whether it is curtailed by limits to the uptake of CO_2 by plants.

Analyzing overall production costs of bioenergy systems using experience curves
Compared to fitting empirical investment costs, the experience curve approach seems to deliver better results, when the production costs of the final energy carrier (e.g. electricity or biogas) are analyzed. PRs of 91-92% for electricity from biofuelled CHP plants and 85-100% for biogas production costs were found with satisfactory coefficient of determination values (R^2). One simple explanation is the larger amounts of principally available data, and thus the possibility of averaging plant data. Other explanations are that investment costs only contribute a minor share to the cost of the final energy carrier. In both the Swedish CHP case and the Danish biogas case, the other cost components (fuel costs and O&M costs) and also the annual load change in a gradual, structural fashion, which makes the data more suitable for use in experience curves. Unfortunately, calculating total production costs is even more data intensive. Therefore, this was only possible in the case of CHP plants in Sweden and biogas plants in Denmark. The experience curve approach also seems to be suitable for measuring the cost development of complex fuel supply chains. Further research is however recommended to investigate, whether this holds also for other (biomass) supply chains.

Use of experience curves in (biomass) energy models

Modelling cost reduction of biomass technologies in scenarios and energy models has so far largely been hampered by the lack of empirical data and studies. One new approach is presented in the Refuel project (Londo et al., 2008), in which production cost development of 2nd generation biomass fuels is modelled using a hybrid approach of bottom-up engineering studies and experience curves. For example, in Figure 3.17, the feedstock cost developments of Fischer-Tropsch diesel are shown. Note that processing costs decline over time, but these are to some extent cancelled out by increasing feedstock costs (as more and more less suitable soils within the EU-27 are used). Again, this implicates that the experience curve approach does not incorporate feedstock limitations.

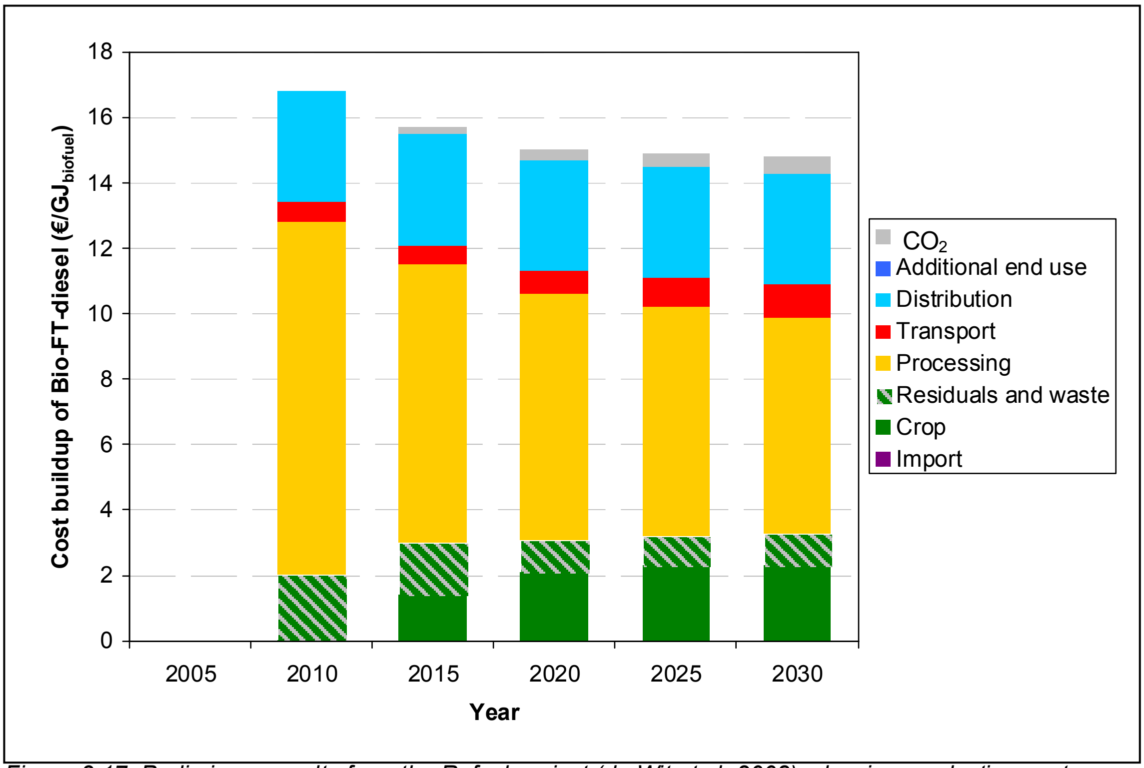


Figure 3.17 Preliminary results from the Refuel project (de Wit et al. 2008), showing production cost development of Fischer-Tropsch fuels.

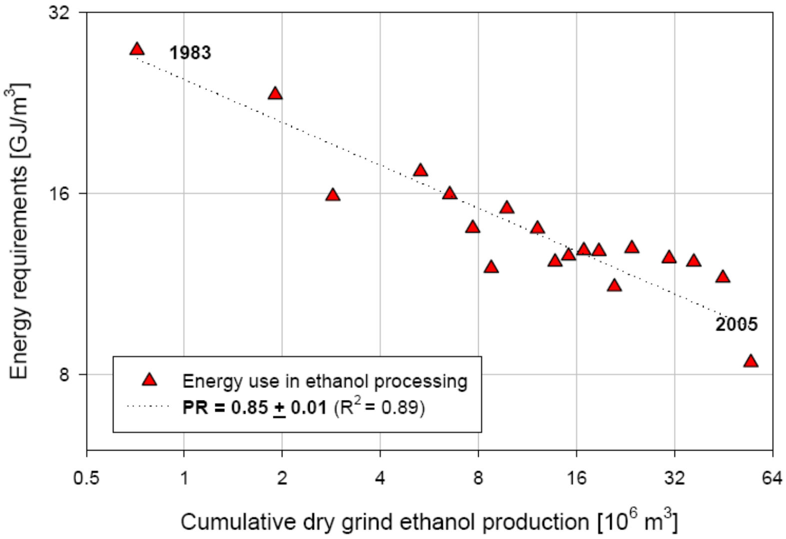


Figure 3.18 Experience curve for energy requirements during corn processing to ethanol (Hettinga, 2007)

In the literature, so far the experience curve approach has mainly been used to quantify production costs reductions. However, similar to energy demand technologies, it may also be possible to measure energy efficiency improvements using the experience curve approach, as shown in Figure 3.18 for ethanol production from corn in the US (Hettinga, 2007). While insufficient data availability prevents any hard conclusions on the validity of the application of the experience curve approach on energy efficiency improvements, and the possibly underlying mechanism needs to be explained in more detail, it is an observation deserving further research.

3.2 (Clean) fossil and nuclear energy technologies

3.2.1 Gas Combined Cycle plants

Technology description

The gas-fired Combined Cycle (CC) plant is a combination of a gas turbine, a steam turbine, and a Heat Recovery Steam Generator (HRSG), which makes use of the latent heat of the exhaust gas of the gas turbine to raise steam for the steam turbine. The first Combined Cycle plants were constructed in the 1970s. Before this time, gas-fired power plants were based solely on the steam cycle. The technology provides several advantages compared to coal-fired power or nuclear power plants. These include (Claeson Colpier et al, 2002):

- high thermal efficiency, currently up to 60%;
- low emissions of NO_x, SO_2, etc.
- relatively low specific investment costs;
- short construction schedule (generally 3 years);
- low space requirement compared to, e.g., nuclear power plants;
- relatively moderate capacities, e.g., 400 MW;
- fast start-up capability of the gas turbine; the time needed for a cold start-up of the CC plant is about 3 hours, with a ‘ramp rate’ of 7%/minute (NPPC, 2002).

The economics of Combined Cycle power plants have profited much from technology development. One of the main improvements of the last few decades relates to the use of high-efficiency compressors and gas turbines with high inlet pressures and temperatures. Modern gas turbines for power generation applications generally utilise axial compressors with several stages of blades to compress air drawn in from the atmosphere to 15-19 times atmospheric pressure. These compressors have efficiencies of around 87%. A modern unit might have 10-12 sets of compressor blades or ‘stages’ (Internet Source 20).

Experience curves and gas Combined Cycle plants

Two studies describe learning effects for gas-fired power plants - conventional gas-fired steam plants (which have been replaced by Combined Cycle technology) - or Combined Cycle plants:

- Ostwald and Reisdorf (1979) show learning effects in the USA for three types of power plants: gas-fired power plants based on the steam cycle, coal-fired power plants, and nuclear power plants.
- Claeson Colpier et al. (2002) analyse contracts published for Combined Cycle power plants and derive learning effects based on the global cumulative installed capacity of gas-fired Combined Cycle plants for three stages: the ‘development stage’, the ‘commercialisation stage’ and the ‘stage of maturity’.

As the power generation technologies analysed in these studies are different, it is doubtful whether learning effects observed or derived may be compared. Ostwald and Reisdorf (1979) show significant learning effects for the gas-fired steam cycle plant: PRs of 85-89%. Taking into account the relatively large number of plants analysed for the USA and the concomitant high number of doublings of cumulative capacity, their results seem to be reasonably robust.

Claeson Colpier et al. (2002) make a selection of contracts published for Combined Cycle power plants. This selection is inevitably somewhat arbitrary. Therefore, the learning effects in this study are not very straightforward. The authors make a distinction between three phases:

- In the period 1981-1991, there is a 'negative' experience curve (PR >100%) which is attributed to the development stage, and weak competition. This seems rather convincing.
- In the period 1991-1997, learning (PR 75%) is attributed to a shakeout phase, and because upgraded gas turbine frames became available for the same equipment cost.
- After 1997, a phase of maturity is assumed to start with a PR of approximately 90%.

Table 3.8 shows a number of generic parameters of the experience curves in these studies. The data refer to prices of, e.g., Combined Cycle power plants built in several world regions. The distinction between the 'development stage' and the 'commercialisation stage' in (Claeson Colpier et al., 2002) seems to be convincing. However, it is quite possible that the stage of 'commercialisation' does not end in 1997 but is continued thereafter: a prolonged stage of commercialisation and maturity.

Table 3.8 Overview of experience curves for Combined Cycle plants and single-cycle plants a

Source	Phase	Progress Ratio	Period	Region	n	R^2	Data quality	Notes
Ostwald and Reisdorf, 1979		85-89%	1949-1968	USA	23	0.69-0.99	II	Refers to less efficient gas-fired steam cycle plant
Claeson Colpier et al, 2002				Global market				Selection criteria applied to ensure that data used were comparable
	'Development stage'	>100%	1981-1991		N/A	N/A	II	Until 1991, costs increase, due to the development phase and weak competition
	'Commercialisation stage'	75%	1991-1997		N/A	N/A	II	After that, a quick learning stage occurs, attributed to a shakeout phase
	'Stage of maturity'	90%	> 1997		N/A	N/A	II	Learning effects are assumed to decrease after 1997
	Total timeframe	>100% until 1991, 75% until 1997, after that 90%						Cumulative learning effects are (much) more moderate than in the commercialisation stage

a Ostwald and Reisdorf (1979) do not examine Combined Cycle power plants, but less efficient gas-fired plants based on the steam cycle (predecessor of Combined Cycle plant).
n number of doublings of cumulative capacity.
I Data based on prices of gas-fired power plants.
II Data based on limited number of gas-fired power plants (Ostwald and Reisdorf, 1979) or selection of published price data (Claeson Colpier et al., 2002).
III Data based on scarce evidence or assumption.
Sources: Ostwald and Reisdorf, 1979; Claeson Colpier et al, 2002.

The distinction between the 'development stage' and the 'commercialisation stage' seems to be convincing. However, it is quite possible that the stage of 'commercialisation' does not end in 1997 but is continued thereafter: a prolonged stage of commercialisation and maturity.

Economics

In the USA, the market for Combined Cycle plants has been volatile. There was a dramatic change in the U.S. electricity generation market conditions from the mid 1990's to the present. In the period 1990-2000, the drive to replace old base load generation, such as coal-fired plants, with clean and efficient Combined Cycle plants was quite dominant. Purchasing decisions were being made by studying economic data, generating capacity, and dispatch curves. The decisions to buy new generation plant were made in an open market environment. Most merchant plant owners made similar decisions without being able to foresee the overcapacity and fuel price scenario that would develop. The result was that the total electric capacity growth since 1997 has exceeded peak growth demand by three times. Combined Cycle plants supplied 65% of this new capacity. This resulted in a decreasing overall capacity factor (Bancalari, 2005). This is because coal-fired plants and nuclear plants do not suffer similar cost increases in terms of €/MWh for their fuels (coal and uranium, respectively) as Combined Cycle power plants.

One of the difficulties in characterising learning effects for Combined Cycle power plants is that the specific investment cost strongly depends on the plant capacity, as shown by (Internet Source 21) - see Figure 3.19 (the data are levelised to 1996 constant dollars and a 1.0 labour factor). It has been noted that Claeson Colpier et al. (2002) made a selection of contracts for CC plants. Figure 3.1 shows that selection of 'representative' specific investment costs is not easy.

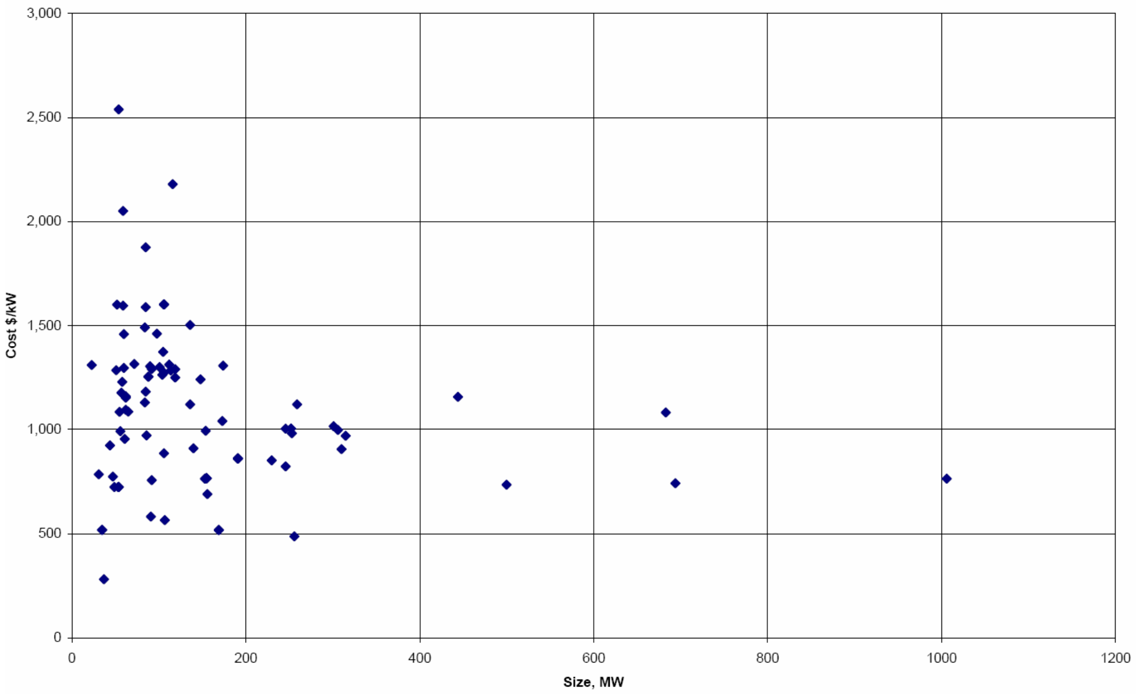


Figure 3.19 Specific investment cost Combined Cycle plant as a function of capacity (MWe) Source:Internet Source 21.

Figure 3.20 shows a graph of investment cost by date of construction. Specific investment costs appear to increase towards 1994, and to decline after that. Thus, market conditions may have changed in the period analysed by Claeson Colpier and Cornland (2002), or as (Internet Source 21) states: 'The timeframe in which the plant was built could have a significant impact on the capital cost'.

(Internet Source 21) gives an explanation for the variation in specific investment costs observed in the timeframe 1990-1997 for the USA. Plant costs are dependent on technology, timeframe, and site (in the USA). Increasing environmental regulations cause plants to add more equipment (e.g., steam injection for suppression of NO_x emission and possibly Selective Catalytic Reduction (SCR) systems), lose potential capacity, and lose efficiency. Advanced technologies may have a higher capital cost, and be incorporated into the facility.

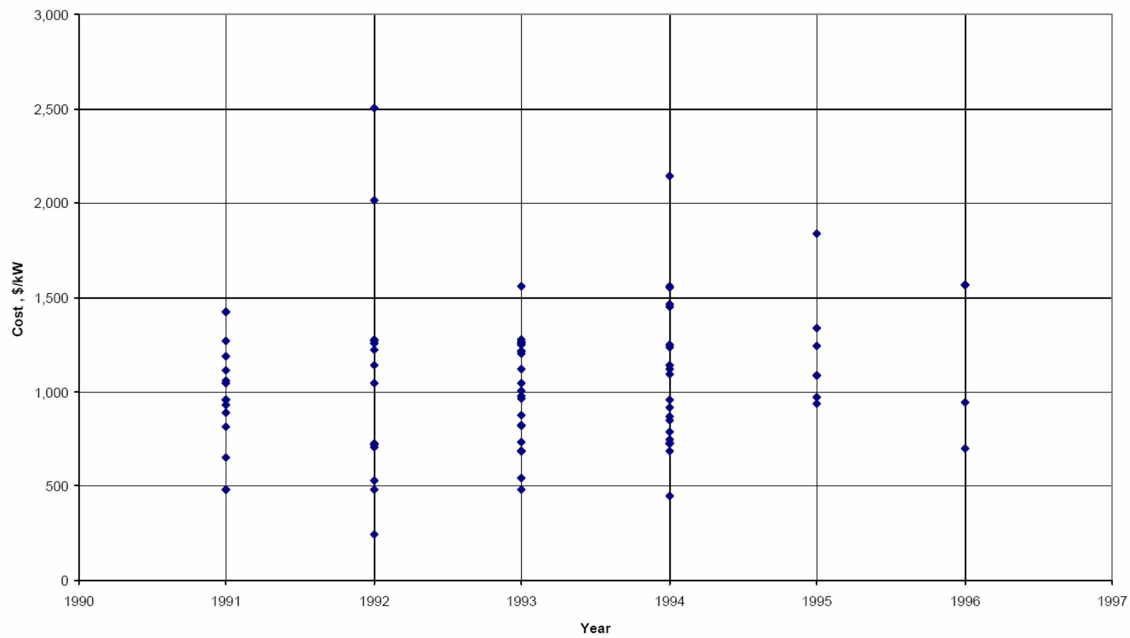


Figure 3.20 Specific investment cost Combined Cycle plant as a function of year built. Source: Internet Source 21.

Higher specific investment cost do not necessarily imply higher production costs (in terms of €/MWh). New technologies may reduce operating costs, thereby reducing production costs; however, the data presented by (Internet Source 21) are solely a presentation of capital costs. The specific investment cost of a large Combined Cycle plant - the 1,650 MW CC plant constructed by RWE at Staythorpe, UK - is approximately € 545/kW (RWE, 2007a).

Policy measures

The Combined Cycle power plant has become a mature technology, which is developed more or less incrementally. This is highlighted by the 220 plants built by one supplier in the timeframe 1954-2007 (Internet Source 22). The CC plant is predominant among these power plants, but also (single cycle) gas turbines, re-powering projects, Combined Heat and Power (CHP) plants, and Integrated Gasification Combined Cycle (IGCC) plants (based on residual oil) are listed. The maturity of the Combined Cycle power generation technology is also reflected in the slowly increasing energy efficiency of these plants, hovering around 60% today.

In several EU countries, e.g., Germany and France, Combined Cycle plants are built. With full deregulation of the French electricity market in July 2007, there is increasing demand for combined cycle power plants to meet peak- and intermediate-load needs, according to Siemens (Internet Source 23). In Brazil, Combined Cycle power plants, next to energy efficiency improvement and in conjunction with hydro power, may contribute to greenhouse gas emission reduction, as the Pew Centre observes (Internet Source 24). In a liberalised electricity market, there is no room for governmental policies with regard to Combined Cycle power plants.

Reasons for cost reductions / bottom-up assessments

It has been noted that CC power plants profited much from use of high-efficiency compressors and gas turbines with high inlet pressures and temperatures, enabling efficiencies of approximately 60%. This is much higher than the generating efficiency of a pulverised coal-fired power plant, which is approximately 45%. The efficiency of coal-fired power plants may be raised, but really high efficiencies would probably require a switch to IGCC technology (based on coal). These IGCC plants also utilise Combined Cycle technology. There seems to be still room for technology improvement, although incrementally and based on a diversified fuel portfolio.

Future scenarios and cost reduction potentials
There are no specific scenarios for Combined Cycle power plants, except for the aforementioned IGCC as an alternative to pulverised coal-fired power. However, as IGCC plants will gradually capture the market because they promise higher generating efficiencies and lower emissions of NO_x and SO_2, this does influence the Combined Cycle power plant technology substantially in the next decades. Thus, moderate cost reductions seem to be most likely.

Lessons for policy makers
Policies with regard to R&D and market penetration for Combined Cycle power plants are nowadays generally absent, as the technology is mature and improvements are incremental and based on further R&D performed by the main suppliers (General Electric, Siemens, Alstom, etc.). It is acknowledged that the technology may also be applied to other fuels like residual oil and coal. The latter fuel is particularly important as the worldwide coal resources are very large and a switch from gas to coal is observed in the last few years. In several countries IGCC projects based on coal have been developed (*inter alia* in the Netherlands, Spain, and the USA) in the past 15 years, and number of other IGCC plants based on coal is firmly planned in the USA and Europe, e.g., in Germany (Internet Source 25). Some projects are envisioned with CO_2 (Carbon) Capture and Storage (CCS).

General discussion
The Combined Cycle technology has been commercially applied for over 25 years and has become mature. This does not rule out further technology improvement, incurring still higher efficiencies and - possibly, as higher efficiencies may require costly investments - cost reductions. The main emphasis for the next few decades will be on diversifying the portfolio of fuels, ranging from natural gas and residual oil (which is also more or less ‘state-of-the-art’) to coal - IGCC, a novel technology which requires a lot of technology development and probably suitable for CCS - and biomass.

3.2.2 Pulverised coal-fired power plant

Technology description
Coal-fired steam-electric power plants - in this Chapter denoted as ‘Pulverised Coal-fired power, PC’ - are a mature technology, in use for over a century. The basic components of a pulverised coal-fired power plant include coal storage, handling and preparation section, a boiler, and a steam turbine-generator set. Coal is ground to fine particles, blown into the boiler, and the heat generated by burning the fine coal particles is used to drive the steam turbine-generator. Ancillary equipment and systems include flue gas treatment equipment and stack, an ash handling system, a condenser cooling system, and a switchyard and transmission interconnection. Environmental control has become increasingly important and since the 1980s, PC plants are typically equipped with low-NO_x burners, Flue Gas Desulphurisation (FGD), filters for particulate removal - generally Electrostatic Precipitators - and closed-cycle cooling systems. Selective Catalytic Reduction of NO_x (SCR) is becoming increasingly common.

Beginning in the late 1980s, the economic and environmental advantages of gas-fired Combined Cycle (CC) power plants resulted in that technology eclipsing pulverised coal-fired power technology for new resource development in North America and European countries. In the last few years, however, there is a switch back from gas-fired plants to new coal-fired power plants.

Experience curves and coal-fired power plants
Three studies describe learning effects for pulverised coal-fired power plants or coal-fired boilers:
- Ostwald and Reisdorf (1979) analyse learning effects for a relatively large number of coal-fired power plants in the USA, from 1957 to 1976.
- Joskow and Rose (1985) analyse the technological, regulatory, and organisational factors that have influenced the cost of building pulverised coal-fired power plants over a 25-year period.

- Yeh and Rubin (2007) review the history of PC power plants, with a specific focus on the technological progress of PC boiler technology over the last century.

The first study, Ostwald and Reisdorf (1979), focuses on 25 coal-fired plants in the USA with a cumulative capacity of approximately 10 GW. The authors report a Progress Ratio of 92-93% for the specific investment cost of these power plants for the entire period of the analysis, viz. 1957-1976. They note that environmental regulation since 1973 has incurred significant costs, in particular due to desulphurisation equipment. If these additional costs are assumed to occur from 1973 onwards, the aforementioned PR of 92-93% may be disentangled in a PR of 87-93% in the period 1957-1973 and a PR of 99-113% for the period after 1973.

Joskow and Rose (1985) make an analysis of the specific investment costs of approximately 400 coal-fired power plants in the USA in the period 1950-1982. They distinguish technological change on the one hand and economies of scale on the other hand. For economies of scale, a PR of 82% is determined, but the authors note that the exploitation of scale economies requires a switch from (moderate-scale) sub-critical PC plants to large supercritical PC plants. This technological change in itself has a cost penalty (PR>100%).

Table 3.9 Overview of experience curves for Pulverised Coal-fired power plants/boilers

Source	Cost factor analysed	PR	Period	Region	N [a]	R^2	Data qual.	Notes
Ostwald and Reisdorf, 1979	Specific investment cost	92-93%	1957-1976	USA	~ 7	0.35-0.90	I	Focused on specific investment cost of 25 PC units with a cumulative capacity of approx. 10 GW
Joskow and Rose, 1985	Specific investment cost, scale economies	82%	1950-1982	USA	N/A	N/A	II	An attempt is made to distinguish between technological change and, e.g., scale economies; PR 82% for scale economies, is technology specific
	Specific investment cost, technological change	>100%	1950-1982	USA	N/A	N/A	II	For large coal-fired plants, supercritical PC becomes state-of-the-art; the aforementioned PR of 82% can only be achieved by switching from sub-critical to supercritical PC, resulting initially in a cost penalty (PR>100%)
Yeh and Rubin, 2007; Rubin et al, 2007	Specific investment cost of sub-critical PC boiler	94%	1942-1988		~ 9	0.71	I	Higher-efficiency supercritical coal units have not been built in large numbers in the USA
	Operation and maintenance cost of PC plants	92%	1929-1997	USA	~ 15	N/A	I	Operation and maintenance cost adjusted for changes in GDP (GDP price deflator), real wages (wage and salary for utilities employees, and plant utilisation

a N = number of doublings of cumulative capacity.
I Data based on prices of coal-fired boilers for a long period of time.
II Data based on disentanglement of different factors governing cost reduction (Joskow and Rose, 1985).
III Data based on scarce evidence or assumption.
Sources: Ostwald and Reisdorf, 1979; Joskow and Rose, 1985; Yeh and Rubin, 2007.

Yeh and Rubin (2007) note that other studies with regard to learning for PC power sometimes lack sufficiently long timeframes. They analyse *inter alia* learning effects with regard to the specific investment cost of sub-critical pulverised utility boilers in the timeframe 1942-1988, and find a PR of 94% (Figure 3.21). They also determine a Progress Ratio of 92% for the operation and maintenance costs of PC plants in the period 1929-1997 (Figure 3.22). Table 3.9 shows a number of generic parameters of the experience curves in these studies. The data refer to prices of, e.g., pulverised coal-fired power plants or coal-fired boilers built in the USA.

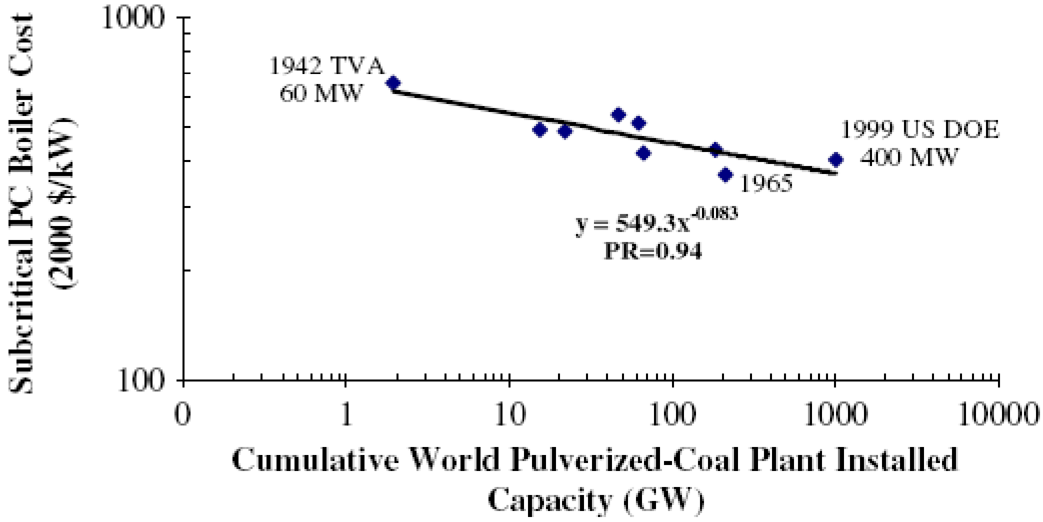


Figure 3.21 Experience curve for sub-critical pulverised coal-fired boiler. s Source: Yeh and Rubin, 2006.

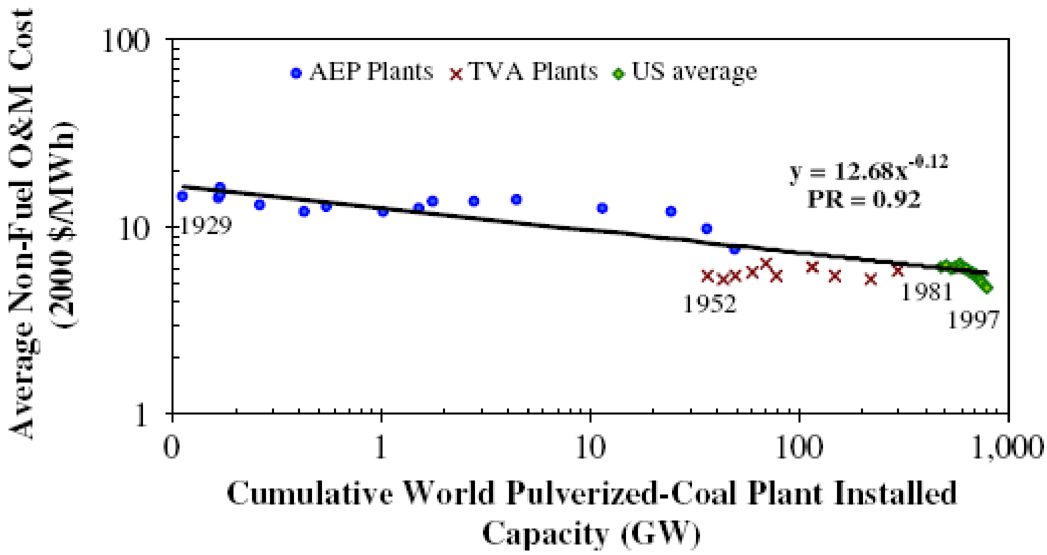


Figure 3.22 Experience curve for operation and maintenance cost of PC power plants. Source: Yeh and Rubin, 2006

Yeh and Rubin (2007) also determine a PR of 103.8% for the generating efficiency of PC plants, based on the U.S. plants from 1920 to 1985, supplemented by data of PC plants in the rest of the world. Finally, Rubin et al. (2007) present *inter alia* experience curves for the specific investment cost of Flue Gas Desulphurisation (FGD) and Selective Catalytic (NO_x) Reduction (SCR).

Economics
In a balanced energy generation portfolio comprising nuclear, coal, gas and renewables, coal has a number of attractive features (Internet Source 26):

- Coal is easy to store and transport and can be sourced from diverse stable suppliers worldwide;
- Pulverised coal-fired power stations offer unique load carrying flexibility, particularly useful in meeting peak demand, and in compensating for the intermittency of renewables;
- Coal fired generation (including emission control equipment to the latest stringent standards) is one of the lowest cost options for electricity generation.

According to DoE (1999), plant costs are dependent on technology, time frame, and site. Increasing environmental regulations cause plants to add more equipment (e.g., FGD systems), lose potential capacity, and lose efficiency. Advanced technologies may have a higher capital cost, but may reduce operating costs, thereby reducing production cost. The specific investment cost of a large pulverised coal-fired power plant - the twin-unit 1,560 MW pulverised coal-fired power plant constructed by RWE at the Eemshaven, Netherlands- is approximately € 1,410/kW (RWE, 2007b). According to RWE, the global boom in coal-fired generation equipment orders, rising material costs and margin improvement by suppliers have forced new-build power station costs up by as much as 30% since 2005 (RWE, 2007c).

Policy measures
Pulverised coal-fired power technology is among the most mature power generation technologies (Jamasb, 2007). In IEA countries, public R&D budgets are available for further research and development with regard to coal-fired power. However, public funds are generally used to further novel technologies like Integrated Gasification Combined Cycle (IGCC) plants, rather than pulverised coal-fired power. IGCC plants offer prospects for CO_2 (Carbon) Capture and Storage (CCS), as the fuel gas is available at a higher pressure and hardly diluted by nitrogen compared to flue gas of a PC plant. Therefore, IGCC technology receives incentives from R&D funds in various countries.

Reasons for cost reductions / bottom-up assessments
In the past, cost reduction for PC power plants was generally related to technological changes and scale economies, viz. larger capacities. Technological changes in the past have significantly contributed to higher generating efficiencies, which currently amount to approximately 45%. Whereas technological development used to be limited to national boundaries in the period until the 1950s, after that improvement of the pulverised coal-fired power technology became more and more a global phenomenon. Nowadays, so-called Ultra Supercritical Coal-fired (USC) power plants are not only built in Europe, but also in other industrialised countries and China.

Future scenarios and cost reduction potentials
There are a few options for further technological development, e.g.:

- Ultra-supercritical steam parameters for PC boilers and steam turbines, as investigated in the framework of the so-called EU project ‘AD 700’ (Internet Source 27). One of the objectives of the project is a generating efficiency in the range of 52-55% (Figure 3.23).
- Pressurised pulverised coal combustion, an innovative long-term option (Förster, 2007).

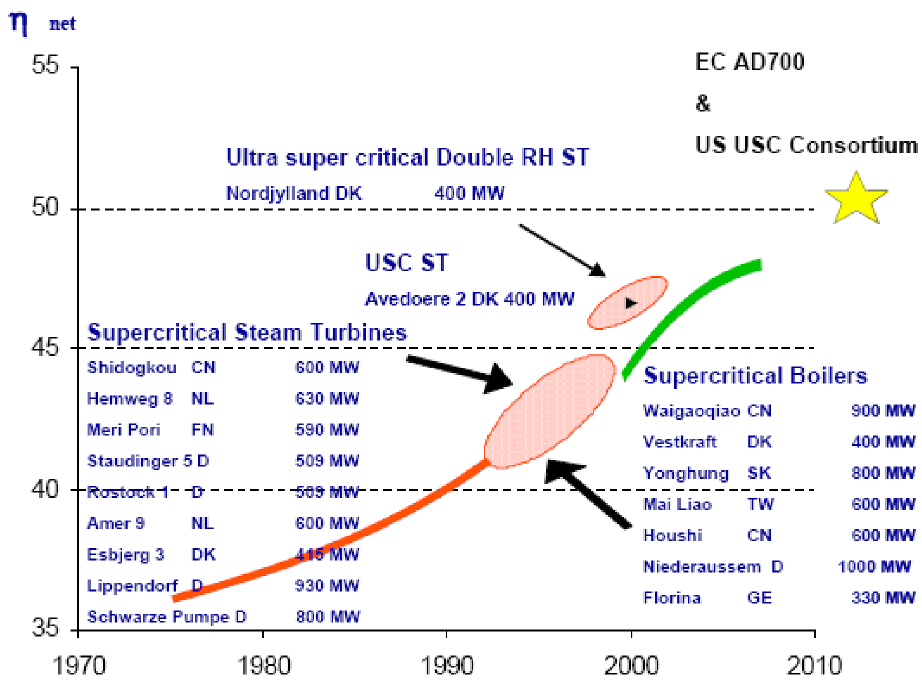


Figure 3.23 Efficiency improvements of pulverised coal power plants, 1975-2000. Sources: Otter, 2002; Lako, 2004.

Cost reduction of pulverised coal-fired power plants will almost certainly be incremental. Only in case of a change of technological concept, e.g., a switch to IGCC or pressurised pulverised coal combustion, more substantial learning effects may occur, be it from an initially elevated level of specific investment costs (compared to the mature PC technology).

There are only few dedicated scenarios for the deployment of pulverised coal-fired power technology in the next decades (DoE, 2002), as it is one of most widely utilised power generation technologies. Alternative technology like IGCC may deserve attention with regard to learning effects and cost reduction potential. In some cases, countries analyse the effects of R&D policies with regard to advanced power generation technologies, among which USC power plant.

Lessons for policy makers

Pulverised coal-fired power generation is a mature technology that will show incremental technological improvement. There are a few options for breakthroughs, e.g., IGCC and pressurised pulverised coal combustion. Also, combination with Carbon Capture and Storage (CCS) is closely related to technological development of coal-based power generation. Therefore, publicly financed R&D will remain important in order to achieve targets with regard to greenhouse gas emissions reduction, partly based on these innovative technologies.

General discussion

It has been noted that pulverised coal-fired power stations offer load carrying flexibility, particularly useful in meeting peak demand, and in compensating for the intermittency of renewables. This means that coal-fired power plants, based on pulverised coal technology or IGCC and without or with CCS, will remain important for many industrialised and developing countries. Coal-based power generation still offers a lot of scope for technological innovation, which is why this kind of technology may also be included in international agreements on greenhouse gas emissions reduction: technological innovation and technology transfer (Jansen and Bakker, 2006).

3.2.3 Carbon dioxide capture and storage (CCS) technologies

Introduction[33]

In the last decades, increasing attention has been paid to the concept op carbon dioxide (CO_2) capture and storage (CCS) as a potential climate change mitigation option, i.e. to allow a more continued sustainable use of fossil fuels. CCS is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. Especially the emission reduction by CCS based on large CO_2 point sources such as power plants is most promising, since these plants account for the largest part of GHG emissions. The CO_2 is then compressed and transported for storage in geological formations, in the ocean, in mineral carbonates, or for use in industrial processes. Large point sources of CO_2 include large fossil fuel or biomass energy facilities, major CO_2-emitting industries, natural gas production, synthetic fuel plants and fossil fuel-based hydrogen production plants. Potential technical storage methods are: geological storage (in geological formations, such as oil and gas fields, unminable coal beds and deep saline formations), ocean storage (direct release into the ocean water column or onto the deep seafloor) and industrial fixation of CO_2 into inorganic carbonates.

Metz et al (2005) consider CCS as an option in the portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations. The widespread application of CCS would depend on technical maturity, costs, overall potential, diffusion and transfer of the technology to developing countries and their capacity to apply the technology, regulatory aspects, environmental issues and public perception.

Experience curves and CCS

As there are no significant numbers of fossil fuel power plants equipped with CCS technology, it is impossible to devise historical experience curves. However, similar to the approach followed by Junginger (2005) for offshore wind turbines, potential cost reductions of the various components can be estimated based on progress ratios from similar technologies, e.g. from flue gas desulphurisation (FGD) by wet scrubbers, see Figure 3.24; and selective catalytic reduction (SCR) of NO_x, see Figure 3.25. Using this method, a comprehensive study of the future trends in the cost of carbon capture technologies was published by Rubin et al. (2006), which is based on and followed up by several other studies (e.g. Riahi et al, 2004; Rubin et al, 2004a; Rubin et al, 2004b; Rubin et al., 2005; Rubin et al., 2007; Yeh et al., 2005; Yeh et al., 2006). Based on the historical progress ratios of various technologies (see Table 3.10) and comprehensive cost models for various CCS options, Rubin et al (2006; 2007) calculated progress ratios for various power plant technologies equipped with CO_2 capture technology (see Table 3.11)

These studies only treat the 'capture' part of CCS. Technological learning for CO_2 transport and storage has barely been investigated so far, and no experience curves have been devised. Given the unique properties of each reservoir, it is also highly unlikely that the concept of experience curves can ever be used for the storage component.

[33] The introduction and economics sections are largely based on Metz et al. (2005).

Table 3.10 Summary of "best estimate" progress ratios for capital and O&M costs from historical case studies, and whether a cost increase was observed during the early stages of commercialization (Rubin et al. 2007)

	PR Capital cost (%)	PR O&M cost (%)	Time frame	N	R^2	Data qual.	Remarks: Initial cost increase
Flue gas desulfurization (FGD)	89	78	1976-1995	2 (±)	0.79	II	Yes
Selective catalytic reduction (SCR)	88	87	1983-2000	4.2 (±).	0.75	II	Yes
Gas turbine combined cycle (GTCC)	90	94	1981-1997	n.a.	n.a.	II	Yes
Pulverized coal (PC) boilers	95	82		n.a.	0.71	II	n/a
LNG production	86	88		n.a.	0.52	II	Yes
Oxygen production	90	95	1980-2003	n.a.	0.43	II	n/a
Hydrogen production (SMR)	73	73		n.a.	0.65	II	n/a

n/a: not available.
I cost/price data provided (and/or confirmed) by the producers covered
II cost/ price data collected from various sources (books, journals, press releases, interviews)
III cost/price data (or progress ratio) being assumed by authors, i.e. not based on empirical

Table 3.11 Calculated Progress ratios for various power plant technologies equipped with CO_2 capture technology (maximum ranges from sensitivity analysis) (Rubin et al. 2007)

	PR Capital costs (%)	R^2	PR O&M costs (%)	R^2	PR Cost of electricity (%)	R^2
NGCC plant	97.8 (96.4-98.8)	0.96	96.1 (94.5-99.6)	1.00	96.7 (95.2-99.4)	1.00
PC plant	97.9(96.5-98.9)	0.97	94.3 (91.7 - 98.0)	0.99	96.5 (94.6- 98.5)	0.98
IGCC plant	95.0 (92.4 - 97.5)	0.99	95.2 (92.7 - 98.8)	1.00	95.1 (92.5 - 97.9)	0.99
Oxyfuel plant	97.2 (95.6-98.6)	0.97	96.5 (95.0-99.3)	0.99	97 (95.1 - 98.8)	0.98

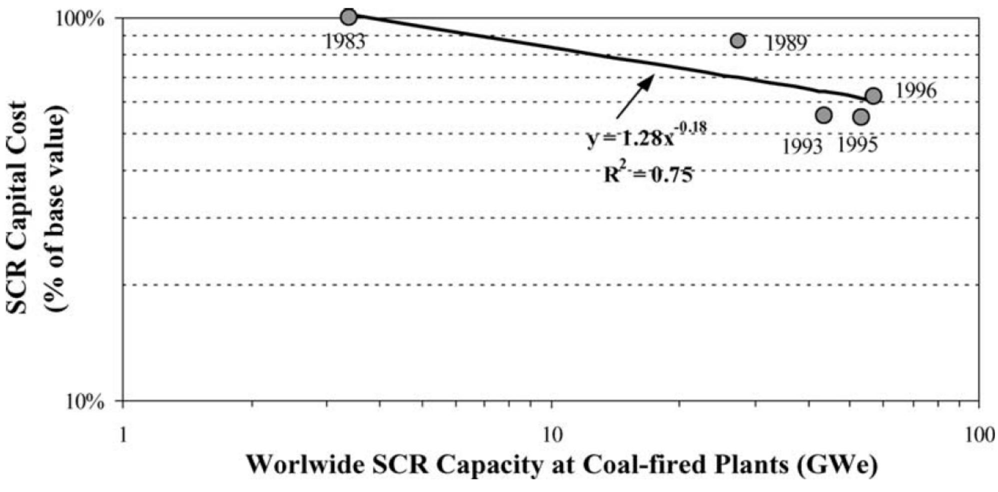


Figure 3.24 FGD capital costs for a standardized coal-fired plant (500 MW, 3.5% S coal, 90% SO2 removal) vs. cumulative installed FGD capacity worldwide. All data points normalized on an initial (1976) value of US$ 254/kW in constant 1997$. (Rubin et al, 2004a).

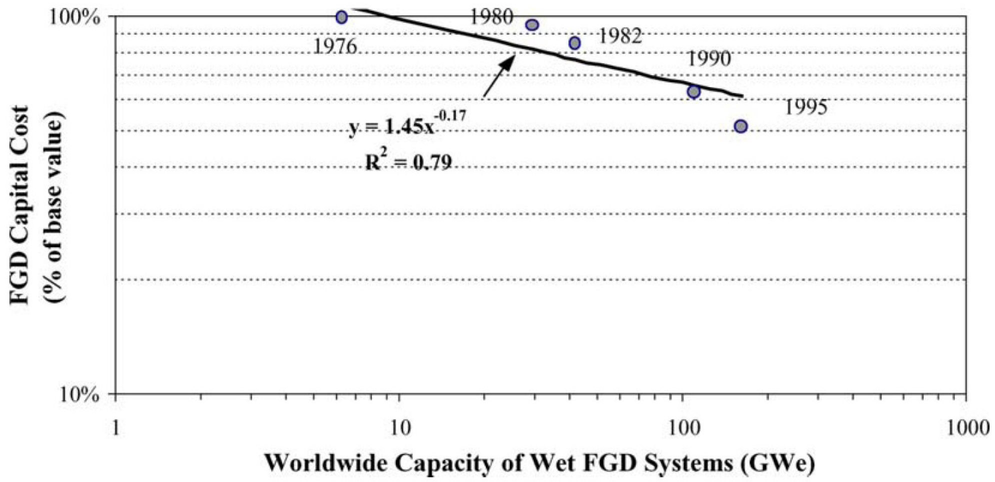


Figure 3.25 SCR capital costs for a standardized coal-fired power plant (500 MW, 80% NOx removal) vs. cumulative installed capacity worldwide. All data points normalized on an initial (1983) value of US$ 105/kW in constant 1997$ (Rubin et al, 2004b).

Economics[33]

Application of CCS to electricity production, under 2002 conditions, is estimated to increase electricity generation costs by about 0.01-0.05 US dollars per kilowatt hour (US$/kWh), depending on the fuel, the specific technology, the location and the national circumstances. Rubin et al (2007) provide an overview of investment cost, O&M cost and the final cost of electricity for four different conversion technologies with CCS. They estimate that cost of electricity would vary between 59.1-78.9 US$ (2002) / MWh_e, excluding transport and storage costs.

Inclusion of the benefits of enhanced oil recovery (EOR) would reduce additional electricity production costs due to CCS by around 0.01- 0.02 US$/kWh. Increases in market prices of fuels used for power generation would generally tend to increase the cost of CCS. The quantitative impact of oil price on CCS is uncertain. However, revenue from EOR would generally be higher with higher oil prices. While applying CCS to biomass-based power production at the current small scale would add substantially to the electricity costs, cofiring of biomass in a larger coal-fired power plant with CCS would be more cost-effective.

Table 3.12 Cost estimates for current power plants with CO_2 capture (excluding transport and storage costs; see legend for reference plant costs without capture). Source: Rubin et al. (2007)

	Total plant costs ($ 2002)					
	Capital costs		Total O&M cost[a]		Total CoE[b,c]	
	$/kW	% Total	$/MWh	% Total	$/MWh	% Total
NGCC plant[d]	916	100	38.5	100	59.1	100
GTCC (power block)	660	72	2.2	6	17.1	29
CO_2 capture (amine system)	218	24	2.4	6	7.3	12
CO_2 compression	38	4	0.2	0	1	2
Fuel cost	0	0	33.6	87	33.6	57
PC plant[e]	1962	100	29.3	100	73.4	100
PC boiler/turbine-generator area	1282	65	5.7	19	34.5	47
AP controls (SCR, ESP, FGD)	241	12	4.1	14	9.5	13
CO_2 capture (amine system)	353	18	7.2	25	15.2	21
CO_2 compression	86	4	0.4	1	2.3	3
Fuel cost	0	0	11.9	41	11.9	16
IGCC plant[f]	1831	100	21.3	100	62.6	100
Air separation unit	323	18	1.7	8	8.9	14
Gasifier area	494	27	3.7	17	14.8	24
Sulfur removal/recovery	110	6	0.6	3	3.1	5
CO_2 capture (WGS/selexol)	246	13	1.6	7	7.1	11
CO_2 compression	42	2	0.3	1	1.2	2
GTCC (power block)	616	34	2	9	15.8	25
Fuel cost	0	0	11.6	54	11.6	19
Oxyfuel plant[g]	2417	100	24.4	100	78.9	100
Air separation unit	779	32	3.1	13	20.6	26
PC boiler/turbine-generator area	1280	53	5.6	23	34.4	44
AP controls (ESP, FGD)	132	5	2.7	11	5.7	7
CO_2 distillation	160	7	1.4	6	5	6
CO_2 compression	66	3	0.5	2	1.9	2
Fuel cost	0	0	11.2	46	11.2	14

Source: IECM version 5.0.2. The cost of reference plants with similar net output and no CO_2 capture are: NGCC = $ 563/kW, $ 43.3/MWh; PC = $ 1229/kW, $ 44.9/MWh; IGCC = $ 1327/kW, $ 46.8/MWh.

[a] Based on levelized capacity factor of 75% for all plants.
[b] CoE is the levelized cost of electricity.
[c] Based on fixed charge factor of 0.148 for all plants.
[d] NGCC plant = 432 MW (net); 517 MW (gross); two 7FA gas turbines; gas price = 4.0 $/GJ.
[e] PC plant = 500 MW (net); 719 MW (gross); supercritical boiler; Pittsburgh #8 coal; price = 1.0 $/GJ.
[f] IGCC plant = 490 MW (net); 594 MW (gross); three GE gasifiers + two 7FA gas turbines; Pgh #8 coal; price = 1.0 $/GJ.
[g] Oxyfuel plant = 500 MW (net); 709 MW (gross); supercritical boiler; Pittsburgh #8 coal; price = 1.0 $/GJ.

Policy support measures[34]

Although carbon capture and storage (CCS) was first proposed as a GHG mitigation option in the 1970's, government funding for R&D first appeared in the 1990's. At the European level, for instance, the Third Framework Programme FP (1990-1994) was the first to cover activities in CCS (a number of cycles with CO_2 capture, mainly closed or semi-closed cycles, were first studied and in 1993 a two year study was funded dealing with the possibilities of underground disposal of CO_2 as part of the Joule II Non-nuclear Energy Research Program). The importance of CCS increased with each framework program and under the Sixth FP (2002-2006), capture and sequestration of CO_2 associated with cleaner fossil fuels was considered by the Commission a priority in long term energy R&D, with a CCS portfolio of funded projects accounting for 61 million Euro (the total budget of the projects was 98 Million Euro). In the United States federal funding for R&D in CCS was first offered by the Department of Energy in 1997 through modest $50.000 grants to proposals that might have worthwhile ideas for carbon sequestration (12 grants were awarded). The US budget for R&D has increased significantly since then and for the fiscal year 2007 the requested budged amounted to $73 Million dollar.

[34] This section is based on Ramirez and Faaij (2007).

The United States is currently working with private sector partners on 65 carbon sequestration projects around the country.

The important role that CCS could play as CO_2 mitigation option has been translated into national support programs (many of them including public-private partnerships), international initiatives and private sector alliances. Among the national support programs are Coal21 (Australia), the Energy Carbon sequestration program (US-DoE), FutureGen (US), COORETEC (Germany), CATO (the Netherlands), the Cleaner Fossil Fuels Programme (UK), and the Clean Power Coalition (Canada). Examples of international initiatives are the Carbon Sequestration Leadership Forum (CSLF), the IEA Working Party on Fossil Fuels and the Asia-Pacific Partnership (6 countries). Finally, a number of private Sector Alliances are Statoil/Shell (CCS/EOR); General Electric/Bechtel (Integrated Gas Combined Cycle); BP/General Electric (Hydrogen Turbines) and ConocoPhillips/Fluor (Integrated Gas Combined Cycle).

Large-scale initiatives to ensure the clean use of fossil fuels and include them in carbon management strategies are appearing worldwide. Figure 3.26 shows sites where geological storage of CO_2 and CO_2 Enhanced gas and oil recovery takes place (or will take place in the short term).

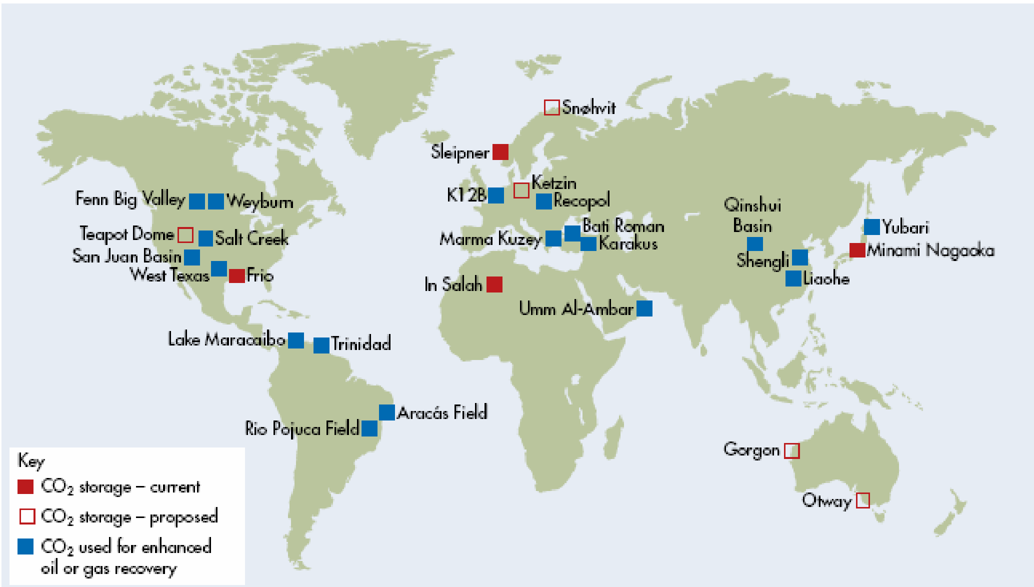


Figure 3.26 Location of sites where geological storage of CO2 and COE Enhanced gas and oil recovery takes place. Source: Metz et al., 2005.

Of particular note are

- The Weyburn project in Canada, which involves the injection of CO_2 into 17 oil wells in a mature oilfield in southern Saskatchewan (the CO_2 comes from the Great Plains Synfuels generating Plant in North Dakota and is transported from the USA to Canada via 330 km purpose-built pipeline);
- The Sleipner project in Norway which entails the injection of about 1 million tonnes CO_2 per year since 1996 into sands of the Utsira formation at the Sleipner field, a gas condensate producing field in the middle of the North Sea;
- The Stanwell Corporation in Australia is constructing a 190 MW IGCC power plant with carbon capture and storage near Rockhampton in Queensland, which will include piping the CO_2 200 km west to the Denison Trough.
- In Japan, RITE is investigating ocean storage of CO_2 using ocean-going ships. Liquid CO_2 is delivered by ships to sites several hundred kilometers offshore and is injected into the ocean at depths of 1500 - 2000m.

About 20 plans have been proposed for integrated CCS schemes, including CO_2 capture from power or industrial plants to be realized in the period 2009-2016 (Damen, 2007). The projects cover a wide range of fuels (bituminous coal, lignite, natural gas and petroleum coke) and capture technologies (post-combustion capture, precombustion capture and oxyfuel combustion). Most of these projects involve CO_2 removal during natural gas processing, because CO_2 needs to be separated anyway.

At the moment no countries have implemented large-scale market deployment measures, e.g. a feed-in tariff for 'clean' fossil electricity or a quota.

Possible future cost reductions and bottom-up assessments
Riahi et al (2004) evaluate the effect of CCS market penetration under alternative assumptions for technological learning for a set of long-term energy-economic-environmental scenarios implemented in the MESSAGE model. Under assumed technological learning in parallel with the massive introduction of CCS technologies on the global scale, costs of the emissions reduction for CCS technologies drop rapidly, up to a factor of four within one century: natural gas-based costs drop from currently 37 to about 10 US$/tonne CO_2 by the year 2100, and coal-based CCS technologies from currently 53 to 11-17 US$ /tonne CO_2 by the year 2100. Compared to scenarios based on static cost assumptions for CCS technologies, the contribution of carbon sequestration is about 50% higher in the case of learning, resulting in cumulative sequestration of CO_2 ranging from 150 to 250 billion tons of carbon during the 21st century. Also, carbon values (carbon tax) across scenarios (corresponding to the 550 ppmv carbon concentration constraint) are between 2% and 10% lower in the case of learning for CCS technologies by 2100 (Riahi et al., 2004).

Rubin et al. (2006) show that major factors which contribute to process technology cost reductions include, but are not limited to, improvements in technology design, materials, product standardisation, system integration or optimisation, economies of scale and reductions in input prices. Analysis of various process technologies indicates that in most cases capital costs have reduced by 10-15% for each doubling of installed capacity. The corresponding reduction in operating and maintenance costs is 5-30%. Based on progress ratios data for analogous process technologies, the cost of electricity from power plants with CO_2 capture is predicted to decline by 10-18% after 100 GW_e of capacity has been installed (about 200 CCS plants). Much of the cost of a power plant with CO_2 capture is for equipment which is already widely used, such as pulverised coal boilers and gas turbine combined cycles. Reductions in the incremental costs of CO_2 capture are predicted to be 13-40%, i.e. greater than the reductions in the overall cost of electricity. Key factors determining the estimated cost reductions include the point at which learning (cost reductions) begin, the current capacity of each plant sub-system, and the magnitude of non-CCS applications contributing to future cost reductions. In general, combustion-based power plants, whose total cost is dominated by relatively mature components, showed worse overall progress ratios than gasification-based plants. For similar reasons, the cost of CO_2 capture technologies is projected to decline faster than the cost of the overall power plant. Results presented in this study can help to bound estimates of future CCS costs based on observed rates of change for other technologies.

In comparison, Peeters et al. (2007) have carried our a comprehensive bottom-up analysis of natural gas combined cycles with CCS, and find CoE of 5.6 €ct/kWh on the short-term (2010), declining to 4.5 €ct/kWh on the long-term (2030), corresponding to 45 €/tonne CO_2 in 2010 and 28 €/tonne CO_2 in 2030.

However, so far no meaningful large-scale CO_2 capture facilities have been implemented, neither for natural gas Combined Cycle, Pulverized Coal nor Integrated Gasification Combined Cycle system. Thus, it is not possible to verify from empirical data whether the projected cost reductions of either top-down experience curve or bottom-up engineering studies will occur.

In general, it can be stated that expected costs vary considerably in both absolute and relative terms from country to country. In the future, the costs of CCS could be reduced by research and technological development and economies of scale. Economies of scale could also considerably bring down the cost of biomass-based CCS systems over time. The application of CCS to biomass-fuelled or co-fired conversion facilities would lead to lower or negative CO_2 emissions, which could reduce the costs for this option, depending on the market value of CO_2 emission reductions. Retrofitting existing plants with CO_2 capture is expected to lead to higher costs and significantly reduced overall efficiencies than for newly built power plants with capture. The cost disadvantages of retrofitting may be reduced in the case of some relatively new and highly efficient existing plants or where a plant is substantially upgraded or rebuilt. The costs of retrofitting CCS to existing installations vary. Industrial sources of CO_2 can more easily be retrofitted with CO_2 separation, while integrated power plant systems would need more profound adjustment. In order to reduce future retrofit costs, new plant designs could take future CCS application into account. In most CCS systems, the cost of capture (including compression) is the largest cost component. Costs for the various components of a CCS system vary widely, depending on the reference plant and the wide range in CO_2 source, transport and storage situations. Metz et al. (2005) estimate that over the next decade, the cost of capture could be reduced by 20-30%, and more should be achievable by new technologies that are still in the research or demonstration phase. The costs of transport and storage of CO_2 could decrease slowly as the technology matures further and the scale increases.

Lessons for policy makers
In none of the literature studies reviewed, explicit lessons regarding the use of experience curves and CCS for policy makers were mentioned. This is probably largely due to the fact that CCS is still in an early phase of development and (especially) market deployment, and thus there are neither many existing experience curves nor policy measures to evaluate.

Riahi et al (2004) evaluated the effect of CCS market penetration under alternative assumptions for technological learning for a set of long-term energy-economic-environmental scenarios implemented in the MESSAGE model. As quoted above, they find rapidly declining costs for CCS (of up to a factor of four in one century). Regarding policies, they recommend that climate policies need to be extended to include technology policies, in order to make the diffusion of environmentally sound technologies operational in the long run (as shown by the stabilization scenarios). This calls for early action to accomplish the required cost and performance improvements in the long term, including the creation of niche markets, the development of small-scale demonstration plants, and targeted R&D.

General discussion
Given the early stages of CCS technology development, it is impossible to devise historical experience curves. The top-down experience curve approach yields PRs ranging between 92.4-98.8% (for investment costs), and similar PRs for CoE of 93.5-99.5%. Thus, they fall in the typical range of large-scale power plant technologies.

One specific observation made by Rubin et al. (2006; 2007) that for all historical technologies investigated, the first commercial plants show substantially higher investment/CoE costs than anticipated by pre-assessment engineering studies, and that previously estimated cost levels only are reached after several doublings of cumulative capacity (which in the case of FDG occurred after more than 20 years, and in the case of SCR about 6 years).

3.2.4 Nuclear power

Technology description
Most nuclear power plants in operation today are based on fission of enriched uranium, with water as coolant and moderator. The term ‘moderator’ denotes that only part of the energy potential of uranium is used, viz. without using the potential of ‘fast’ neutrons. Development of an advanced fission reactor based on ‘fast’ neutrons needs more R&D, and may result in a reactor (‘Generation IV’) becoming available around 2030. The most widely used nuclear power plant is the Light Water Reactor (LWR) - as opposed to a Canadian type of reactor (Candu) which uses natural uranium (without uranium enrichment) and heavy water as coolant and

moderator. The LWR is a family of two types of reactors which are predominant around the world:

- The Pressurised Water Reactor (PWR), a representative of which is the 1,590 MW_e European Pressurised Reactor (EPR) of the company AREVA - a so-called 'Generation III' reactor. Two EPRs are currently under construction in Finland and France;
- The Boiling Water Reactor (BWR), an example of which is the 1,350 MW_e Advanced Boiling Water Reactor (ABWR) of GE Energy. Four ABWR units are in operation in Japan, and three units are under construction in Taiwan and Japan (Internet Source 28).

Experience curves nuclear power

Four studies describe nuclear power in the past few decades and possible learning effects:

- Ostwald and Reisdorf (1979) analyse learning effects for 32 nuclear power plants built in the USA in the period 1960-1973.
- Zimmerman (1982) analyses 41 nuclear power plants in the USA completed between 1968 and 1980 for which completed cost figures were available.
- Cowan (1990) reviews the history of nuclear power, shedding light on the dominance of currently used reactor types mentioned above (PWR and BWR).
- The University of Chicago (2004) carried out an in-depth study of the economic future of nuclear power, reviewing learning effects reported by other authors and showing evidence for progress ratios for nuclear power today.

Ostwald and Reisdorf (1979) focus on learning for 32 nuclear power plants built in the US in the period 1960-1973, with a cumulative capacity of approximately 20 GW. The authors report a Progress Ratio of 0.78-0.81 for the specific investment cost of these power plants. They acknowledge that specific investment costs of nuclear power plants in the US increased around 1973, probably due to more stringent safety regulations and corresponding capital costs.

Zimmerman (1982) analyses learning effects for 41 nuclear power plants (some with multiple reactors) in the US, completed between 1968 and 1980. Learning-by-doing - generally resulting in cheaper construction - is assumed to be partially internalised by the construction company and partially accruing to the industry as a whole. A construction firm with a great deal of experience can capture rents. Such a firm can change the price of its competitors and realise the lower cost as profit. Zimmerman (1982) indicates that completion of the first plant reduces the cost of the next plant by 11.8% (PR 88%), and that completing the second plant reduces cost by 4% (PR 96%). According to the University of Chicago (2004), this experience curve might be approximated by a constant average progress ratio of 95%.

Cowan (1990) indicates that the technology of choice in the early 1960s in the USA, the LWR, was based on learning effects from the US program focused on small pressurised water reactors for naval propulsion. This may be a situation in which potential superior technologies can disappear from the market. Because the superior technology is not being used, it cannot prove its superiority or advance along its experience curve. Theory suggests that events early in the process can be crucial in determining the long-term outcome, according to Cowan (1990).

The University of Chicago (2004) reviews learning effects reported by other authors like Zimmerman (1982) and other studies on learning for nuclear power in the US from 1988 to 1996, as well as other evidence on learning 'overseas'. Besides, they mention factors other than experience that researchers found to be significantly correlated with nuclear plant capital costs:

- Regulation;
- In-house management, viz. the difference in costs between projects managed by construction firms and projects managed in-house by the utilities themselves;
- Multiple-unit sites;
- Economies of scale and construction-time effects; and
- Regional effects: input costs and inflation rates differ from region to region (US).

Table 3.13 shows a number of generic parameters of the experience curves in these studies. The data refer to prices of nuclear power plants. It is noted that the (positive) learning effects observed do not rule out cost increases due to increased safety requirements, as will be explained.

Table 3.13 Overview of experience curves for nuclear power plants

Source	Cost factor analysed	PR (%)	Period	Region	n [a]	R^2	Data qual.	Notes
Ostwald and Reisdorf, 1979	Specific investment cost	78-81	1960-1973	USA	~ 7	N/A	I	After 1973, specific investment costs of U.S. nuclear power plants increased
Zimmerman, 1982	Specific investment cost	~95	1968-1980	USA	N/A	N/A	I	Form of experience variable results in decreasing percent reductions at each doubling of experience, equivalent to a PR of approximately 0.95 (University of Chicago, 2004)
University of Chicago, 2004	Specific investment cost		Up to 2003	Global	N/A	N/A		Based on the literature with its mixed results and own considerations
	'Conservative'	97					III	Scenario in which regional demand for new capacity may be met by single new 1,000 MW reactors at a facility
	'Medium learning'	95					III	More or less continuous construction, but little cases of multiple-unit sites
	'Aggressive learning'	90					III	Continuous stream of orders, more instances of multiple-unit sites

n number of doublings of cumulative capacity.
I Data based on prices of nuclear power plants in a period with stable regulatory environment.
II Data based on prices of nuclear power plants in a period of changing regulatory environment.
III Data assumed, based on different scenarios for regulatory environment (University of Chicago, 2004).
Sources: Ostwald and Reisdorf, 1979; Zimmerman, 1982; University of Chicago, 2004.

Economics

Nuclear power is used since 50 years for base-load power generation. By the end of 2005, 443 nuclear reactors were in operation with a combined capacity of approximately 370 GW (IAEA, 2006a), and a cumulative experience of over 12,000 reactor years (Internet Source 29). Nuclear power contributes to worldwide electricity generation for approximately 16% (Figure 3.27).

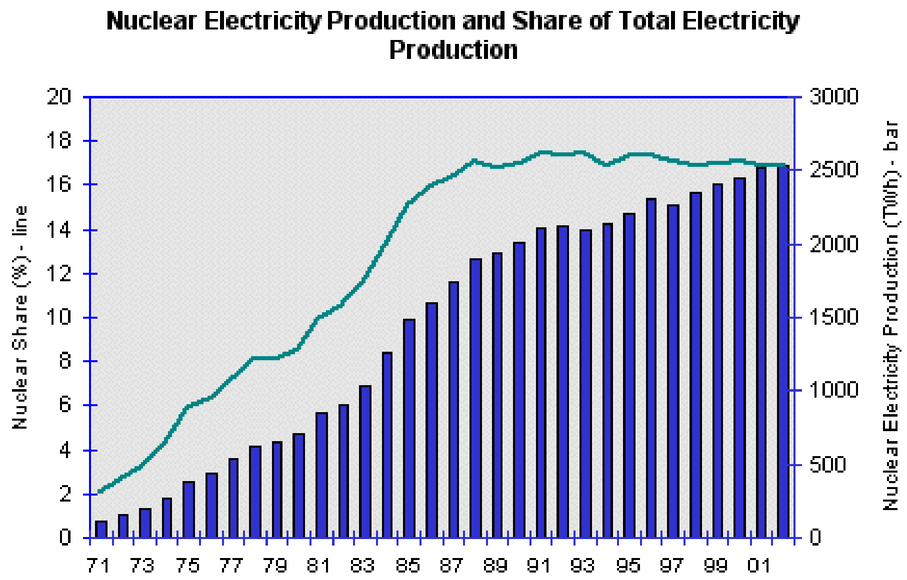


Figure 3.27 Nuclear power generation and share of total electricity generation. Source: Internet. Source 26

In the period 1965-1990, the specific investment cost of nuclear reactors built in Germany increased by a factor two, as exhibited by Figure 3.28 (Kim, 1991; Lako, 2006).

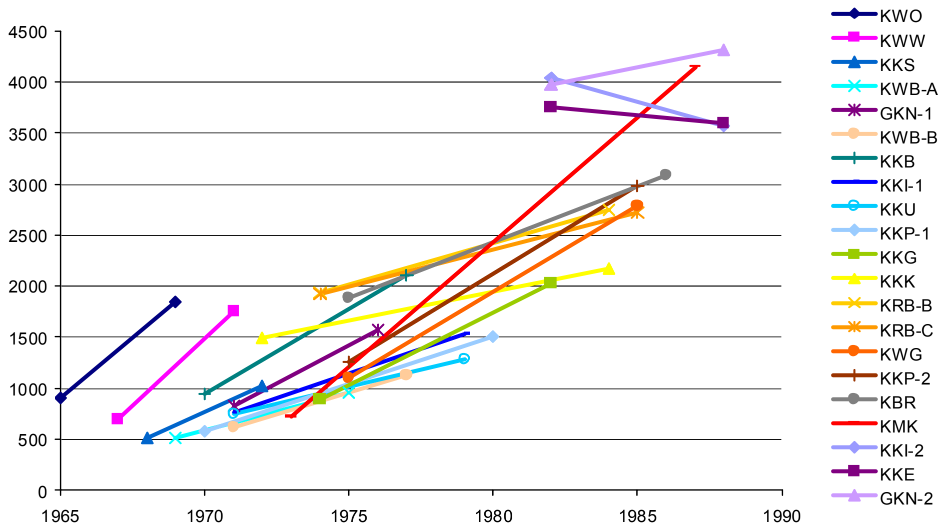


Figure 3.28 Specific investment cost (DM1991/kW) of nuclear reactors built in Germany

Note: 1 € ≈ 2 DM.
Sources: Kim, 1991; Lako, 2006.

The cost escalation is essentially due to increased safety requirements, although problems with operating licenses and construction delays also contributed to cost escalations. Or, as (Zaleski, 2005) puts it for the US: 'The second reason was the legal, regulatory and public opinion environment in the US - an unstable regulatory environment, changing rules during plant construction…' (the main reason for cost escalation in the USA being too many players, vendors, utilities, architect-engineers, resulting in no standardisation). Figure 3.28 shows, that at the end, three 'Konvoi' Pressurised Water Reactors (Siemens) were built on schedule and within budget.

Williams (2003) presents a similar picture for the cost escalation of nuclear reactors built in France (Figure 3.29). The cost escalation due to increased safety requirements described by Williams (2003) is acknowledged by Teller of AREVA, in a recent presentation (Teller, 2007).

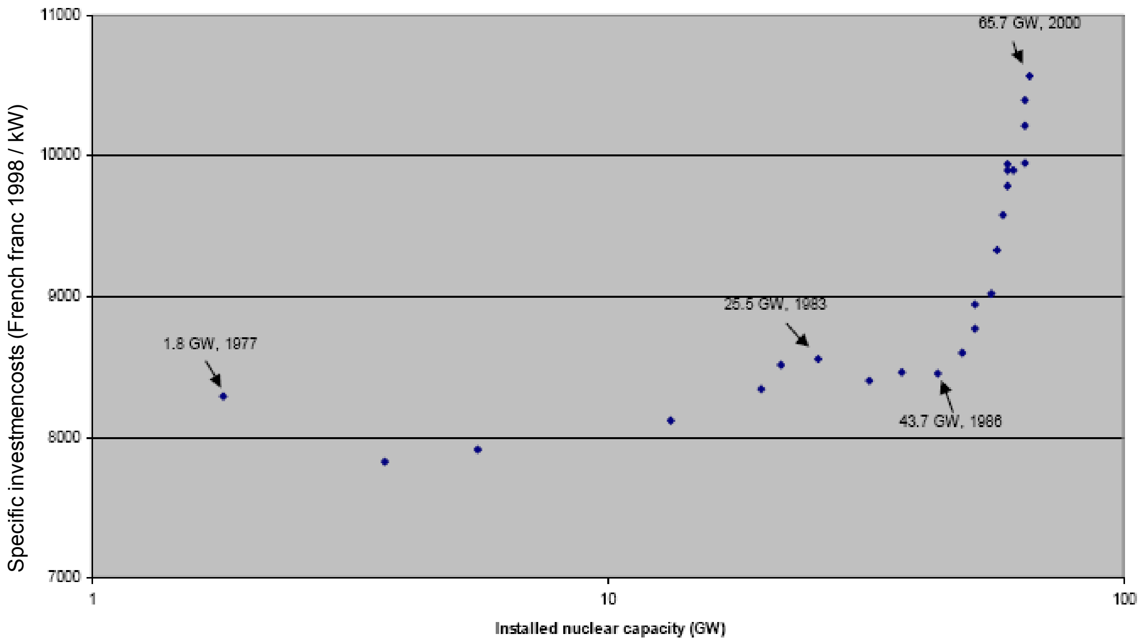


Figure 3.29 Specific investment cost (FF1998/kW) of nuclear reactors built in France.Note: Specific investment costs for nuclear power rose to $1,920/kW (US$2002) Source: Williams, 2003.

The economics of nuclear power may be explained based on AREVA's European Pressurised Reactor (EPR). The following is reported on construction of two EPRs in Finland and France:

- Construction of the first EPR at Olkiluoto, Finland, started in February 2005. In October 2006, AREVA's nuclear division experienced a substantial operating loss in the first half year of 2006 to the tune of € 266 million, due to a delay in the construction in Finland (NEI, 2006a). The loss attributed to the construction delay is estimated at € 300 million. As the original price tag for the EPR amounted to € 3 billion, the cost increase is 10%. As the EPR at Olkiluoto is a turnkey project, the price escalation is at the own expense of AREVA (AREVA, 2005). In November 2006, it was expected that construction would be completed by 2010 (NEI, 2006b). In August 2007, start of commercial operation was expected in 2011. De facto, the construction period will be 6 years, which is equal to the worldwide average construction time (Internet Source 30).
- In the first half of 2007, the Electricité de France (EdF) board of directors awarded AREVA the supply of the nuclear steam supply system for the planned EPR at Flamanville in France, with an estimated total investment cost of € 3.3 billion (€ 2,075/kW in $€_{2005}$). Construction of the second EPR (at Flamanville) is due to start in 2007, and completion is expected in early 2012.
- AREVA also signed a memorandum of understanding in China for the construction of two EPRs in partnership with China Guangdong Nuclear Power Company and the supply of fuel cycle services. The total investment of the EPR reactors is put at € 8 billion (€ 2,500/kW in $€_{2007}$), including the first core (NEI, 2007; ATW, 2007).

Based on this overview and other publications, the main characteristics of a nuclear power plant (based on the EPR design) are summarised in Table 3.14. Taking into account (WEC, 2007), the current generation cost of an EPR is estimated at € 48-53.5/MWh ($€_{2007}$). The CO_2 avoidance cost of a new nuclear power plant compared to an old lignite-fired power plant is put at € 8-10/ton CO_2 (RWE, 2007d).

Table 3.14 Main characteristics of nuclear power plant to be constructed in Europe

Reference plant		EPR Flamanville 3, France	
Category	Unit	Typical value	Notes/Source
Technical characteristics			
Thermal capacity	[MW_{th}]	4,300	(Goreaud, 2004)
Net generating capacity	[MW_e]	1,600	
Electrical efficiency	[%]	37	
Service lifetime	[year]	60	
Burnup	[GWd/tHM]	60	
Start of construction		Middle of 2007	
Start of operation		End of 2012	
Construction schedule	[year]	~ 5.5	Finland: ~ 6 years; France: ~ 5.5 years
Economic characteristics			
Investment cost	[$€_{2007}$]	4 billion	(ATW, 2007)
Specific investment cost	[$€_{2007}$/kW]	2,500	
Availability	[%]	90	(Internet Source 31)
Generation cost			Mostly based on (WEC, 2007)
Typical capital cost	[$€_{2007}$/MWh]	35	
Typical O&M cost	[$€_{2007}$/MWh]	6-9	
Typical front-end fuel cost	[$€_{2007}$/MWh]	3.5-4.5	
Typical back-end fuel cost	[$€_{2007}$/MWh]	3-4	(WEC, 2007) applies a range of 1-4
Decommissioning cost	[$€_{2007}$/MWh]	0.5-1	
Total generation cost	[$€_{2007}$/MWh]	48-53.5	46 €/MWh according to (Dupraz, 2007)
Environmental characteristics			
CO_2 avoidance cost of nuclear power plant	[€/t CO_2]	8-10	Calculation of costs (RWE, 2007d): - Compared to old lignite-fired units - Allocation of CO_2 certificates not taken into account

Sources : Goreaud, 2004 ; ATW, 2007 ; WEC, 2007 ; RWE, 2007d ; Dupraz, 2007 ; Internet Source 31.

Policy measures

As nuclear power plants (LWR type reactors) are commercially available, governments do not need to further their development. However, nuclear power is important for European countries and the EU from the perspective of reduction of greenhouse gas emissions and security of supply - uranium is relatively widely available, also in countries like Canada and Australia. Figure 3.30 shows that the total nuclear R&D expenditures in IEA countries are declining in real terms, but still very substantial.

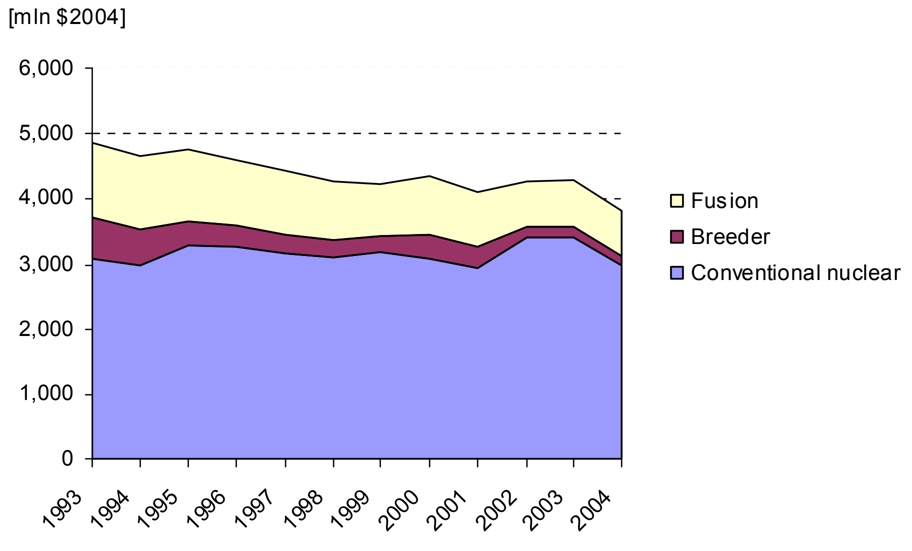


Figure3.30 Trend of IEA R&D expenditures on conventional nuclear, breeder and fusion Source: IEA, 2005.

Several EU countries are engaged in nuclear options ranging from the High Temperature Reactor (HTR) to 'Generation IV' reactors. The long-term (2050) option of fusion power is a typical example of R&D to which the EU has committed itself - the International Thermonuclear Experimental Reactor (ITER), under construction at Cadarache, France, for R&D purposes. The EU is also committed to develop a common framework for safety standards and for repositories for (long-living) nuclear waste. Nevertheless, a number of other EU countries have committed themselves to abstain from nuclear power in the medium term (e.g., Germany).

Reasons for cost reductions / bottom-up assessments
In the past few decades, cost reductions were based on economies of scale (large generating capacities), series production, automation of operation and inspection, and increased availability. These effects resulted in competitive designs of LWRs around 1985-1995 in Germany and France, which were built in multiple units and were characterised by enhanced safety measures and generating capacities of 1,300-1,400 MW_e.

Further cost reductions may be achieved by series production - AREVA is going to build at least four EPRs, two in Europe and two in China, and possibly more in the UK and the USA - and multiple unit sites, if applicable. The extent to which cost reductions may be achieved depends on the regulatory framework. If additional safety requirements or requirements with regard to, e.g., reduction of the amount of long-living nuclear waste would be imposed on the nuclear power generators, cost reductions might prove to be difficult if not impossible to achieve.

Future scenarios and cost reduction potentials
There are several future scenarios for nuclear power in various world regions. An example of a scenario for nuclear power on a global scale is (IAEA, 2006b), see Figure 3.31.

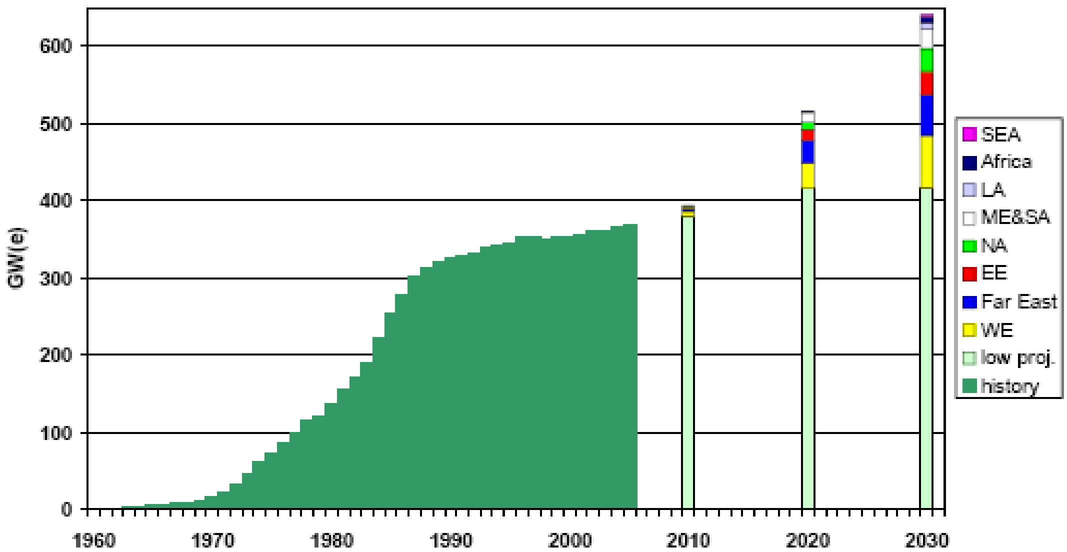


Figure 3.31 Installed nuclear power generating capacity worldwide and projection to 2030. Notes:The dark green bars show historical growth from 1960 through 2005. The light green bars show the Agency's latest low projection for 2010, 2020 and 2030. The other colours show how much of the difference between the Agency's low and high projections is attributable to different regions of the world.SEA = South-East Asia; LA = Latin America; ME&SA = Middle East and South Asia; NA = North America; EE = Eastern Europe; WE = Western Europe. Source:IAEA, 2006b.

Future cost reductions depend on the extent to which series production may be achieved. Also the development of new reactor types, e.g., the aforementioned High Temperature Reactor (HTR) is important. A typical example is the 168 MW_e Pebble Bed Modular Reactor (PBMR) - a Generation III+ reactor - developed in South Africa. The design and safety review of a demonstration unit of the PBMR in South Africa has been completed and a licensing review is underway. Commercialisation is expected after 2010. It has been noted that the regulatory framework - safety, long-living nuclear waste - may determine whether cost reduction will occur.

Lessons for policy makers
A number of EU countries consider nuclear power as indispensable for achieving their ambitions to reduce global warming - the greenhouse gas emissions of the fuel cycle ('from cradle to grave') are comparable to those of renewable power generation options like wind energy. Also, nuclear power contributes to security of supply. Other European countries, however, have committed themselves to abstain from nuclear power in the medium term.

The investment costs of nuclear power plants increased in the 1970s and 1980s due to increased safety requirements. Around 1990, several evolutionary LWRs with advanced safety features and reliable operation characteristics were commercially available. Nowadays, a few advanced LWR designs are commercially available which have been built in multiple units (e.g., in Japan) or are under construction. Whether further cost reductions for nuclear power will materialise depends *inter alia* on the regulatory framework, e.g., with regard to safety or reduction of the amount of long-living nuclear waste.

General discussion
The studies referenced with regard to learning for nuclear power signal differences in learning due to increased safety requirements in the 1970s and 1980s. Nowadays, nuclear reactors seem to have evolved to a stage at which safety requirements may be met in a straightforward way, e.g., by demonstrating a very low probability of a core-melt accident and even then warranting zero or very low radioactive emissions. Thus, catastrophic accidents become more and more exceptional for advanced nuclear reactors that are currently constructed in Europe and Asia.

Starting with advanced nuclear reactors like the ABWR and the EPR, it would be interesting to analyse what the potential cost reduction (specific investment cost, generation cost) because of series production would be. Also, the development of new reactor types like the PBMR deserves attention, as this type of modular reactor offers a larger potential of economies of series production than, e.g., the EPR. Such analysis should take into account developments on regulatory requirements, e.g., with regard to safety or reduction of long-living nuclear waste.

3.3 Energy demand technologies

In this section, we analyse the results of experience curve studies for the following two groups of energy demand technologies: (i) energy demand technologies in the residential and commercial building sector and (ii) energy demand for the production in the refinery, chemical, and fertilizer industry.

3.3.1 Energy Demand Technologies in the Residential and Commercial Building Sector

We differentiate this group of energy demand technologies into three sub-categories, i.e., (i) household appliances, (ii) lighting, and (iii) space heating and cooling. Common to all of these technologies is (i) that they are consumer products, (ii) that their unit costs (i.e., prices per unit of product) are comparatively low, and (iii) that the market for these products (expressed in number of unit sales) is generally much larger than for energy supply technologies. The main characteristics of the analyzed energy technologies can be summarized as follows:

- Consumer decisions depend to a large extent on soft product criteria such as brand names, product design, consumer convenience, personal taste.
- The primary function of demand technologies is not to consume energy but to provide services to the consumer (e.g., laundry cleaning, room lighting, space heating).
- Energy consumption and energy efficiency are hence secondary product functions.

- Unlike for energy supply technologies, market prices (i.e., consumer investment costs) for energy demand technologies tend to be a more important criterion for the market success of products than life cycle costs. The cheaper energy demand technologies are, the less important are life cycle costs for consumer decisions (e.g., while consumers are generally aware of the expected life cycle costs when buying a gas boiler, they pay far less attention on that aspect when they buy a light bulb).
- Energy demand technologies are bought by a large and relatively heterogeneous group of consumers with different perceptions and levels of education. The awareness of consumers for product functions, product related costs, energy consumption, and energy efficiency might be lower than the awareness of investors deciding about the adoption of energy supply technologies.

In the following sections, we describe both technology characteristics and the results of the various experience curve analyses for (i) household appliances, (ii) lighting, and (iii) space heating and cooling separately.

3.3.1.1 Household Appliances

Introduction
In this section, we summarize the results from experience curve analyses for appliances, i.e., washing machines, laundry dryers, refrigerators, freezers, dishwashers, and television sets. Household appliances are mature products that are on the market for many decades. Commercial production of, e.g., electric washing machines dates back to 1908, the first electric laundry dryers appeared on the US market around 1915, and colour TVs were introduced in the 1940s. The product characteristics, i.e., technical components of all of the analyzed appliances changed in the decades since these products are sold at the market. Washing machines do no longer only wash clothes but they also centrifuge dry them. Today freezers and refrigerators are sold in all variations, combinations, and sizes. Due to their ozone depletion potentials, CFCs were removed as cooling fluids in refrigerators and freezers by the early 1990s and replaced by other chemicals such as butane or tetrafluoroethane. All studies on household appliances have therefore one characteristic in common, i.e., they analyze technological learning for a product that serves a certain function (i.e., cleaning and drying laundry, or cooling and freezing food products) but that varies at the same time greatly with regard to the technological solution it uses to serve these functions.

Household appliances are produced by numerous different manufacturers around the world. They are global mass products. Worldwide sales of appliances increased steadily during the last decades. In the year 2003, the worldwide market for washing machines reached roughly 65 million units sold, sales of laundry dryers are in the range of 11 million untis sold, and refrigerator sales amount to 80 million units sold. Producers of appliances have been typically located in Europe, North America, and Japan but falling trade barriers caused major shifts of production towards China, Eastern Europe and other low-wage regions.

Household appliances are major consumers of electricity, i.e., in 2003 they consumed roughly 30% of all electricity generated in OECD countries, thereby being responsible for 12 % of all energy related CO_2 emissions (Ellis et al., 2007). The electricity consumption of household appliances is even expected to grow by 25% until the year 2020. At the same time, considerable energy saving potentials have been identified for household appliances that are still largely untapped to date (Ellis, 2007)[35].

Experience curves for household appliances
We identified three studies that analyze price and cost developments of appliances based on the experience curve approach (Table 3.15). The results generally suggest a decline of prices/production costs albeit with considerable differences for individual appliances. Based on

[35] Ellis (2007) quantifies global electricity saving potentials for household appliances with 33% until the year 2030, yielding global GHG emission savings of at least 770 Mt CO_2.

price data, the average progress ratios for production costs are 88% for refrigerators, 84% for freezers, 74% for washing machines, 86% for laundry dryers, 85% for dishwashers, by 83% for black and white TVs, and 94% for colour TVs. The data in Table 3.15 indicate that the progress ratios for appliances as determined by Laitner and Sanstad (2004) are generally lower than the ones determined by Bass (1980) and Weiss et al. (2008).

Weiss et al. (2008) did not only construct experience curves for the price/cost development of appliances but also for the dynamics of energy efficiency. Similar to Ellis et al. (2007), Weiss et al. (2008) found a trend towards improved energy efficiency of household appliances (Figure 3.32). The empirical data indicate that energy efficiency policies (i.e., the introduction of energy labels in the EU in the mid 1990s) can affect the slope of the efficiency experience curve, e.g., accelerating energy efficiency improvements as it is indicated for the period between 1998 and 2001 (Figure 3.32). Further research is, however, recommended to verify and quantify these policy effects for a larger group of appliances and to develop a conceptual framework explaining and justifying the application of the experience curve concept for energy efficiency dynamics.

The results of the experience curve analyses are reliable but attached with considerable uncertainties. All analyzed studies estimate progress ratios based on price data that have been obtained from secondary literature sources. The errors that are caused by the use of secondary literature are minor relative to other sources of uncertainty (i.e., the estimation of production costs based on market prices or uncertainties related to the estimation of cumulative production). Only Weiss et al. (2008) quantify uncertainty intervals of their results. The uncertainty intervals range up to 20% of the final result but refer, however, only to deviations of individual data points from the fitted experience curve.

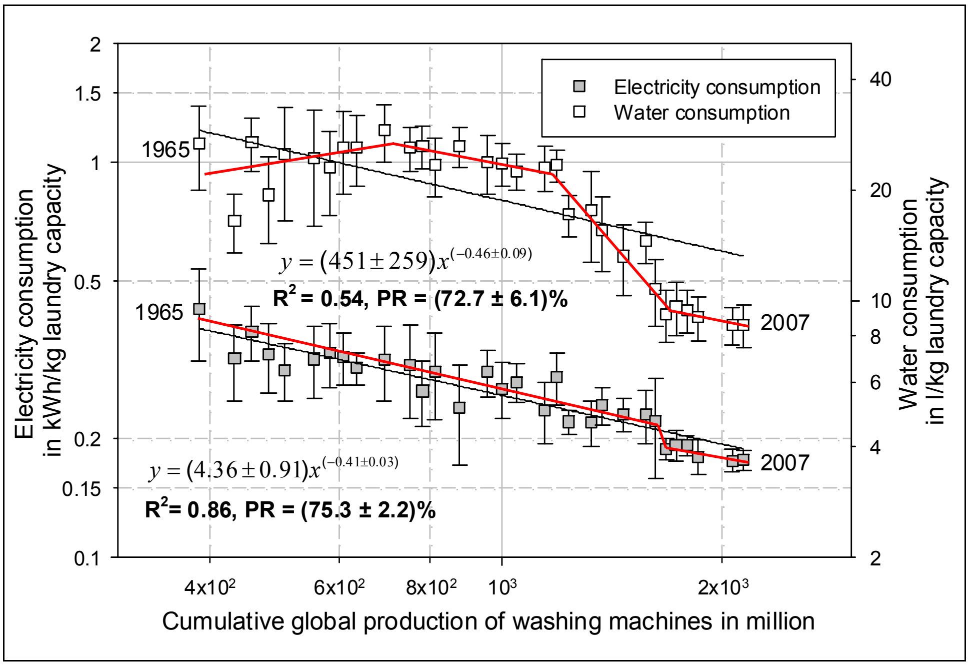


Figure 3.32 Learning in energy and water efficiency of washing machines in the Netherlands - the hypothetical effect of policies and consumer perception on energy and water efficiency (Weiss et al., 2008)

Table 3.15 Literature overview on experience curves for household appliances

Reference	Product	PR in %	R^2	Data quality[4]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Bass (1980)	Refrigerators	93	0.83	II	USA	Cumulative industry sales	Price	1922-1940	-	-
Laitner and Sanstad (2004)	Refrigerators	82	-	II	USA	Cumulative production	Price	1980-1998	5.1 million	126.3 million
Weiss et al. (2008)	Refrigerators	90 ± 2	0.32	II	The Netherlands	Cumulative worldwide production	Price per 100 l volume	1964-2007	43 million[2]	2.15 billion
Weiss et al. (2008)	Refrigerators	80 ± 2	0.73	II	The Netherlands	Cumulative worldwide production	Energy consumption [kWh] per 100 l volume	1964-2007	43 million[3]	2.15 billion
Laitner and Sanstad (2004)	Freezers	64	-	II	USA[1]	Cumulative production	Price	1980-1998	1.8 million	26.1 million
Weiss et al. (2008)	Freezers	103 ± 5	0.05	II	The Netherlands	Cumulative worldwide production	Price per l	1970-2003	88 million[2]	883 million
Weiss et al. (2008)	Freezers	97 ± 6	0.73	II	The Netherlands	Cumulative worldwide production	Energy consumption [kWh] per 100 l volume	1970-2003	88 million[2]	883 million
Laitner and Sanstad (2004)	Washing machines	80	-	II	USA[1]	Cumulative production	Price	1980-1998	4.4 million	104.7 million
Weiss et al. (2008)	Washing machines	68 ± 7	0.54	II	The Netherlands	Cumulative worldwide production	Price per kg clothes washing capacity	1965-2006	20 million[3]	1.69 billion

[1] *Data most likely refer to US market prices.*

[2] *Data refer to the cumulative worldwide production until the base year of the analysis.*

[3] *Data refer to the actual production in the base year of the analysis.*

[4] *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

Table 3.15 (cont.)Literature overview on experience curves for household appliances

Reference	Product	PR in %	R^2	Data quality[3]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Weiss et al. (2008)	Washing machines	75 ± 2	0.79	II	The Netherlands	Cumulative worldwide production	Energy consumption [kWh] per kg clothes washing capacity	1965-2006	20 million[2]	1.69 billion
Weiss et al. (2008)	Washing machines	73 ± 6	0.54	II	The Netherlands	Cumulative worldwide production	Water consumption [l] per kg clothes washing capacity	1965-2006	20 million[2]	1.69 billion
Bass (1980)	Laundry dryers (electric)	94	0.68	II	USA	Cumulative industry sales	Price	1950-1961	-	-
Bass (1980)	Laundry dryers (electric)	88	0.83	II	USA	Cumulative industry sales	Price	1950-1974	-	-
Laitner and Sanstad (2004)	Laundry dryers (electric)	82	-	II	USA[1]	Cumulative production	Price	1980-1998	2.5 million	61.0 million
Laitner and Sanstad (2004)	Laundry dryers (gas)	85	-	II	USA[1]	Cumulative production	Price	1980-1998	0.7 million	18.2 million

[1] Data most likely refer to US market prices.

[2] Data refer to the actual production in the base year of the analysis.

[3] Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.

Table 3.15 (cont.)Literature overview on experience curves for household appliances

Reference	Product	PR in %	R^2	Data quality[3]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Weiss et al. (2008)	Laundry dryers	83 ± 5	0.67	II	The Netherlands	Cumulative worldwide production	Price per kg clothes drying capacity	1969-2003	3 million[2]	222 million
Weiss et al. (2008)	Laundry dryers	80 ± 3	0.73	II	The Netherlands	Cumulative worldwide production	Energy consumption [kWh] per kg clothes drying capacity	1969-2003	3 million[2]	222 million
Bass (1980)	Dishwashers	90	0.75	II	USA	Cumulative industry sales	Price	1947-1968	-	-
Bass (1980)	Dishwashers	89	0.85	II	USA	Cumulative industry sales	Price	1947-1974	-	-
Laitner and Sanstad (2004)	Dishwashers	75	-	II	USA[1]	Cumulative production	Price	1980-1998	2.7 million	69.7 million
Bass (1980)	Black-and-white TV	87	0.78	II	USA	Cumulative industry sales	Price	1948-1960	-	-
Bass (1980)	Black-and-white TV	78	0.73	II	USA	Cumulative industry sales	Price	1948-1974	-	-
Bass (1980)	Colour TV	95	0.88	II	USA	Cumulative industry sales	Price	1961-1971	-	-
Bass (1980)	Colour TV	93	0.78	II	USA	Cumulative industry sales	Price	1961-1974	-	-

[1] *Data refer most likely to US market prices.*

[2] *Data refer to the actual production in the base year of the analysis.*

[3] *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

Economics

With shifts of household appliance production to low wage regions, major reductions of both production costs and consumer prices have been achieved in the past. In the Netherlands, for example the average price of washing machines decreases from around 1800 €$_{2006}$ in 1965 to 414 €$_{2006}$ in 2007. Similarly, the prices of refrigerators have decreased from 4.09 €$_{2006}$/l in 1964 to only 1.63 €$_{2006}$/l in 2007 (Weiss et al, 2008).

Dahlman (2007) emphasizes the importance of favourable market conditions for innovation and energy efficiency improvements in household appliances. Appliance manufacturers will only invest in product development, if projected sales are high enough to realize costs decline below market price levels after a reasonable time period (Diagram (a) in Figure 3.33). If, however, product sales are expected to remain low, production costs of the market leader might still remain well above market prices (Diagram (b) in Figure 3.33) and producers might decide against certain technology options. To support product development and market implementation of efficient appliances, governmental programs are regarded as important to stimulate markets.

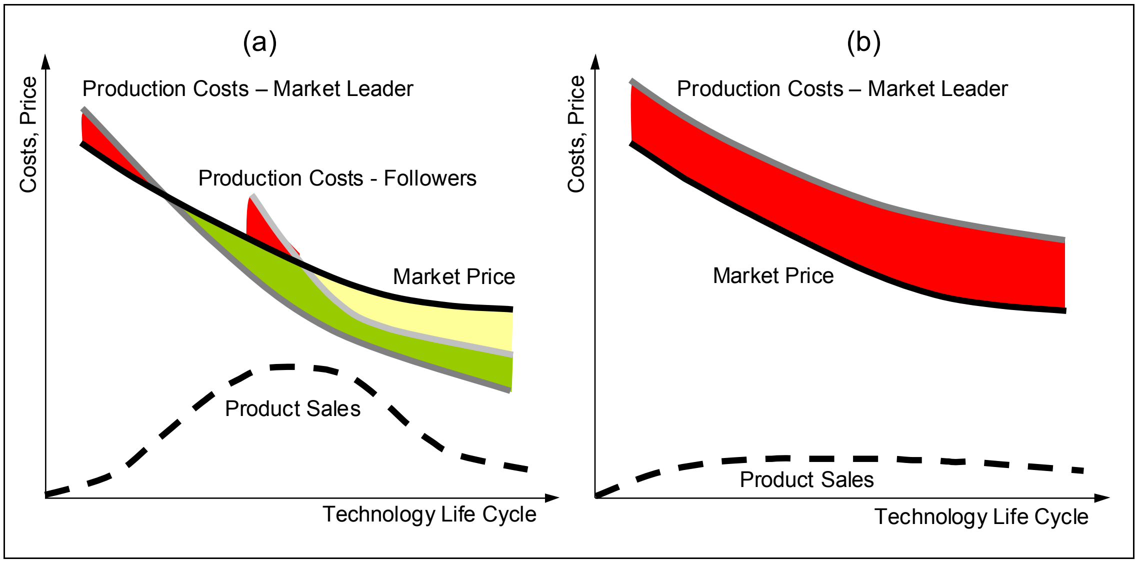


Figure 3.33 Stylized dynamics of production costs and market prices in a low and high sales scenario for household appliances (based on Dahlman, 2007)

The introduction of energy labels has spurred expectations of increasing consumer prices for household appliances. Ellis et al. (2007), however, identified increasing energy efficiencies of appliances and at the same time decreasing appliance prices. In Australia, the UK, the US, and Japan, the consumer price index has on average increased more than appliance prices in the past 10-15 years suggesting that the introduction of energy standards did not have adverse effects on appliance prices compared to the general basket of goods and services in these countries (Ellis et al., 2007).

Policy measures

Substantial policy efforts have been made in the past and are still made to increase the energy efficiency of household appliances. In the EU, energy labels were introduced in the mid 1990s (EU, 1995), rating the efficiency of appliances (i.e., washing machines, laundry dryers, refrigerators, freezers, dishwashers, and ovens) on a level from A to G (A being the most efficient). Minimum energy performance standards were introduced in the USA for refrigerators and freezers in 1990 and subsequently updated in 1993 and 2001. Australia and the UK introduced energy standards for appliances in 1999 with updates being made in Australia in the year 2005. Within IEA countries, a total of 82 minimum energy performance standards are currently in place, out of which 38 are also enforced in major developing countries (Ellis, 2007). Energy labelling and minimum energy performance standards lead to considerable decline in the specific energy consumption of appliances. In the US, average energy consumption of freezers and refrigerators declined by 60% between 1980 and 2001. Ellis et al. (2007) found considerable reductions in the specific energy consumption of refrigerators, freezers, and washing machines in Australia and in the UK.

Reasons behind the observed cost reductions

The observed price/cost reductions for appliances can be attributed to a variety of factors. Learning by doing and the starting of mass production might have been the most important one in the early years of appliance manufacturing. Technological innovation in other industries (e.g., information technology, electrical and electronics engineering) as well as automation of production processes has also contributed to price reductions for appliances in the 1970s and 1980s. After that, production costs were reduced by automation and streamlining of appliance manufacturing. The outsourcing of parts of component production to specialized companies, accompanied with price decline and technological developments regarding, e.g., time clocks and electronic controls contributed further to the overall reductions of production costs. Price declines in most recent years can be mainly attributed to reductions of manufacturing costs that has been realized by reducing labour costs and production shifts to low-income regions. Ellis (2007) concludes that changes in the market for appliance components have not only reduced production cost but also costs related to energy efficiency improvements.

Further improvements of energy efficiencies are likely to be achieved, as manufacturers met energy performance requirements so far at little or no additional costs (Ellis et al., 2007). This might, however, change, if future energy standards become more restrictive and if energy efficiency improvements can only be realized by product revolutions (e.g., such as it is the case for heat pump laundry dryers).

Future scenarios and cost reduction potentials

The global market for household appliances is expected to continue to grow in the future as well as the absolute energy consumption of household appliances. The implementation of mandatory energy efficiency programs has proven to be effective in reducing the specific energy consumption of appliances in the past. Energy labels and minimum energy performance standards have been and will continue to be the main instruments for improving the energy efficiency of appliances in the future. The success of energy labels and minimum energy performance standards will, however, rely on the periodic adaptation of threshold levels. Ellis (2007) recommends review cycles of 3-5 years that follow the cycles of product re-design to provide a clear signal to industry regarding anticipated target levels and to allow manufacturers and suppliers to prepare in advance.

Lessons for policy makers

There are several policy lessons to be learned from the analysis of appliances. First of all, experience curves are a suitable tool for assessing historic and future price/cost developments for appliances. They can supplement conventional engineering type of analyses to forecast price and cost developments of standard as well as novel and energy efficient models with considerably lower energy consumption as conventional appliances. Experience curves do often yield more reliable price and cost projections than engineering analyses (Ellis et al., 2007). The past price developments have shown that energy labels and minimum energy performance standards had so far no noticeable effect on prices/production costs of appliances but on the contrary have been very successful in improving the energy efficiency of appliances. For the effectiveness of energy labels, Ellis (2007) recommends regular adaptations of standards in close cooperation with appliance manufacturers. Further attention should be paid to improved international communication and harmonization of energy standards and labels.

General Discussion
Household appliances are among the major energy consumers in the residential sector. The future global market for household appliances is expected to continue to grow thereby leading to a considerable increase in appliance related energy consumption and CO_2 emissions. In our literature review, we found progress ratios of 75-103% for the cost dynamics of household appliances, indicating a general trend towards lower production costs and consumer prices. At the same time, the technology of appliances changed considerably leading to energy and water efficiency improvements at progress ratios of 73-96% in the analyzed time periods. The improvements of energy efficiency in the 1990s can be attributed to some extent to the introduction of minimum energy performance standards and energy labelling programs in most IEA, OECD, and EU countries. Further adaptations, improvements, and harmonisations of the various energy standards can help reducing the specific energy consumption of appliances in the future and can open the way for *efficiency revolutions* such as the heat pump laundry dryer.

3.3.1.2 Lighting

Introduction
Lighting accounts for 19% of global electricity consumption. In 2005, residential lighting consumed worldwide 811 TWh of electricity, being responsible for 31% of total electricity consumption for lighting and for roughly 18% of the residential sector's total electricity use (IEA, 2006). The Dutch company Philips is the international market leader in lighting technology with annual worldwide sales of € 4.5 billion in 2004 followed by Osram (€ 4.2 billion) and General Electric (sales of € 2 billion). The largest national producer of lighting equipment in the world (in monetary terms) is the EU with annual revenues of € 12 billion. China is the largest producer in physical terms generating revenue of € 9 billion (IEA, 2006).

To date, incandescent light bulbs are still the dominant lighting technology for residential lighting with estimated yearly sales of more than 13 billion units in 2003 (Figure 3.34), with minor shares for Linear Fluroescent Lamps (LFL) Compact Fluorescent Lamps (CFL) and Halogen lamps.

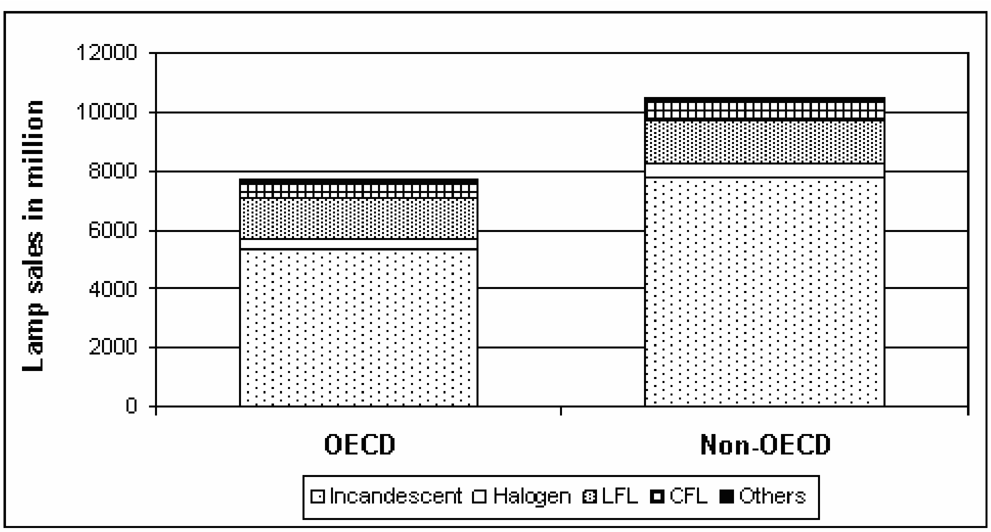


Figure 3.34 Global lamp sales in 2003 as estimated by IEA (2006).

Despite relatively short life spans and a low energy efficiencies, consumers still prefer incandescent light bulbs mainly because these offer a warm-coloured light, are available in an enormous range of styles and sizes, can be dimmed, and foremost because their unit prices are much lower than alternative (though more energy efficient) lighting technologies. However, as the discussions around CO_2 emissions mitigation and energy efficiency improvements intensify, the focus increasingly centres around CFLs as *THE* solution for more energy efficient lighting in the residential sector. CFLs have been first introduced to the market as early as in 1980 by Philips in the Netherlands and in the US but still constitute only a niche in today's lighting market. Due to drastically reduced prices and improved product quality (mainly related to size and light characteristics), CFLs gained market shares in the past years, reaching worldwide sales of 1.1 billion in 2003 (Figure 3.35).

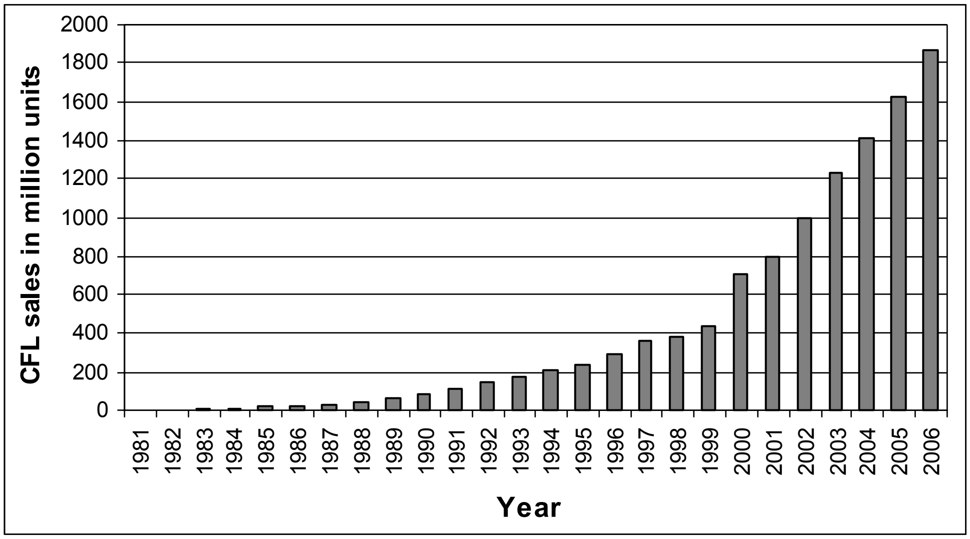


Figure 3.35 Global CFL sales (Source: Iwafune, 2000, IEA (2006a), Weiss et al., 2008)

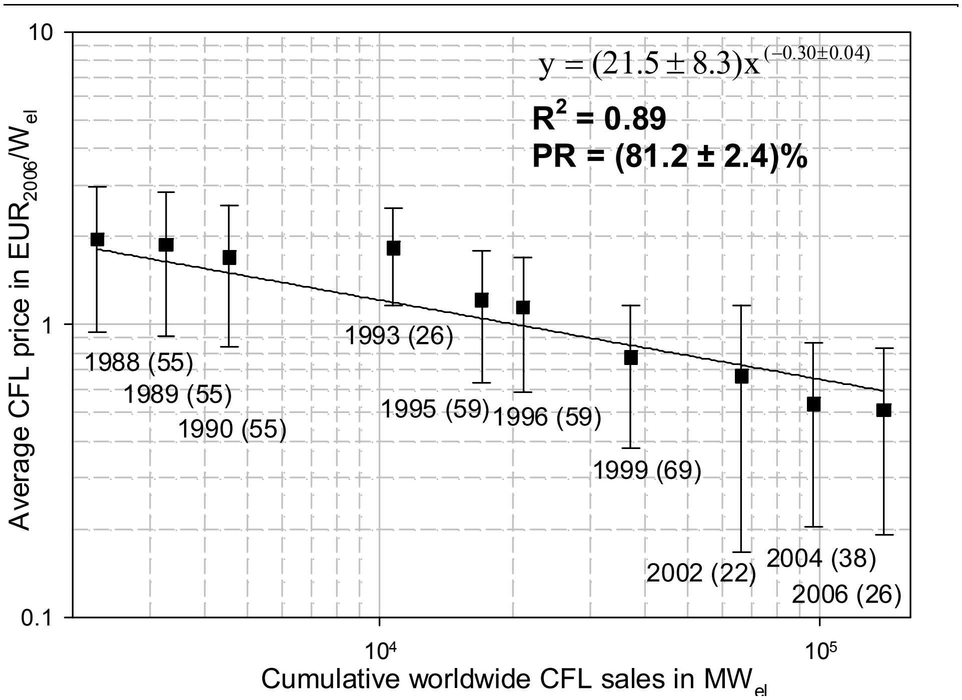
In the UK, for example, CFL ownership rose from 0.7 lamps per household in the late 1990s to 2 in the year 2005. Since the market introduction of CFLs, Europe has been the largest market and was only overtaken by China in 2001, reaching yearly sales of 355 million by 2003 (IEA, 2006). CFL sales compared to sales of incandescent light bulbs range from 2.5% (2004) in the USA to 10% in Europe, 14% in China, and 17% in Brazil. In Japan CFL sales even exceed the ones of conventional incandescent light bulbs (IEA, 2006).

Experience curves for lighting technologies

Experience curves for CFLs have been presented in several studies, with progress ratios ranging from 90% (Ellis et al., 2007) to 59% (Iwafune, 2000) (Table 3.16). Based on the literature overview presented in Table 3.16, we find average progress ratios for CFLs to be roughly 78% (see also Figure 3.35). Progress ratios for electronic and magnetic lamp ballasts are quantified on average with 86% and 80% respectively.

Iwafune (2000) differentiates two periods when calculating progress ratios for magnetic ballasts. The periods refer to the time before and after the enforcement of energy efficiency standards for ballast in the USA. The corresponding progress ratios suggest that technological learning in the manufacturing of magnetic ballasts has been accelerated after the standard was enforced (Table 3.16). This finding might, however, be attributed to reduced profit margins for producers rather than reduced actual production costs.

As is the case for household appliances, we regard the results of the experience curve analyses reliable but attached with considerable uncertainties. All analyzed studies estimate progress ratios based on price data that have been obtained from secondary literature. The errors that are caused by the use of secondary literature can be regarded as minor relative to other sources of uncertainty (i.e., the estimation of production costs based on market prices or uncertainties related to the estimation of cumulative production). Weiss et al. (2008) quantify uncertainty intervals of their results that again refer only to the deviation of individual data points from the fitted experience curve. Due to lack of more detailed insight, it is, however, impossible for us to assess the total uncertainties of the experience curve results presented in this chapter.



Economics

The largest handicap for the market success of CFLs is their high price (in early years, CFLs were more than 30 times more expensive than incandescent light bulbs). The first CFLs were sold at the Dutch market for nominal € 13.60, i.e., 25.76 $€_{2006}$ (18W and roughly 900 lumen). In 2006, a similar CFL was sold in the Netherlands for 4-10 $€_{2006}$ that is still considerably more expensive than conventional incandescent light bulbs. Potentials for future CFL price reductions (e.g., by further up-scaling of production) are hence seen as one key towards the *market break-through* for this technology. From the point of market introduction, life-cycle costs of CFLs were lower than the ones for conventional light bulbs due to higher efficiencies and a 5-8 times longer life-time (Figure 3.37). These advantages were, however only poorly acknowledged by most consumers.

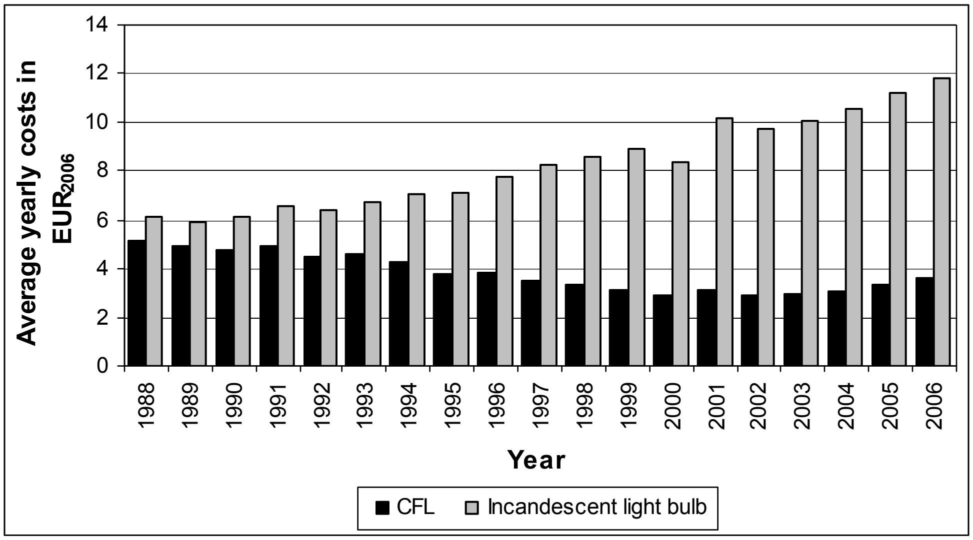


Figure 3.37 Yearly average nominal costs for light bulbs in the Netherlands (Weiss et al., 2008)

Policy measures

In all OECD countries as well as in many non-OECD countries, policies to promote energy efficient lighting exist. Policy measures differ in scope and ambition across countries comprising energy labels, minimum energy performance standards, market transformation programs, financial incentives, and promotion campaigns (IEA, 2006a). The European Union has introduced two mandatory regulations, (i) minimum energy performance standards for fluorescent lighting ballasts, and (ii) energy labelling for household lamps based on a division of seven energy performance categories (i.e., A to G) (EU 1998, 2000). This labelling scheme is the only policy instrument to date, that applies a common grading scale across different lamp types. In other countries, lamp labelling is applied individually for various lamp categories. In Japan, for example, energy efficiency standards particularly for fluorescent lamps were introduced in 1993 with the aim of achieving efficiency improvements of 3-7% compared to base level efficiencies in 1992.

Table 3.16 Literature overview on experience curves for energy-efficient lighting technologies

Source	Product	PR in %	R^2	Data quality[6]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Iwafune (2000)	Modular-electronic CFLs	80	0.56	II	USA	Cumulative worldwide production	Price per lumen	1992-1998	~110 million[1]	~500 million
Iwafune (2000)	Integral-electronic CLFs	84	0.66	II	USA	Cumulative worldwide production	Price per lumen	1992-1998	~160 million[1]	~1050 million
Iwafune (2000)	Modular-magnetic CFLs	59	0.90	II	USA	Cumulative worldwide production	Price per lumen	1992-1998	~110 million[1]	~500 million
Iwafune (2000)	Modular and integral CFLs - weighted average	79[2]	0.90	II	USA	Cumulative worldwide production	Price per lumen	1992-1998	<430 million[1]	~2000 million
Ellis et al. (2007)[3]	CFLs	90	-	II	USA	Cumulative worldwide production	Unit price[5]	1990-2004	-	-
Weiss et al. (2008)	CFLs	81 ± 3	0.89	II	The Netherlands, Germany	Cumulative worldwide production	Price per lumen in the Netherlands and Germany	1988-2006	142 million[4]	11,3 billion
Lipman and Sperling (2000)	Sony laser diodes	77	0.95	II	Production by the company Sony	Cumulative amount of units produced	Unit production costs	1982-1994	<100	10 million

1 These numbers refer to the first data point used for constructing experience curves. The numbers most likely refer to the cumulative worldwide production from 1986 to 1992.
2 Values range from PR=71 to PR=82 calculated based on the 95% confidence interval for possible progress ratios.
3 Based on data from Calwell et al. (2002) and EcoNorthwest (2002, 2004).
4 Data refer to the cumulative worldwide sales until the base year of the analysis.
5 Data most likely refer to US market prices.
6 *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

Table 3.16 (cont.) Overview of literature on experience curves for energy-efficient lighting technologies

Source	Product	PR in %	R^2	Data quality[3]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Duke and Kammen (1999)	Electronic ballasts for FLs	89	-	II	USA	Cumulative production	Unit price	1986-1997	-	0.2 million
Laitner and Sanstad (2004)	Electronic ballasts for FLs	82	-	II	USA[2]	Cumulative production	Production costs	1986-2001	43,000	350 million
Iwafune (2000)	Electronic ballasts for FL's	87	0.98	II	USA	Cumulative production in the USA	Price per unit	1986-1998	<1 million	~180 million
Iwafune (2000)[1]	Magnetic ballasts for FLs	84	0.80	II	USA	Cumulative production in the USA	Price per unit	1981-1988	~10 million	~150 million
Iwafune (2000)[1]	Magnetic ballasts for FLs	59	0.97	II	USA	Cumulative production in the USA	Price per unit	1990-1993	~160 million	~200 million
Laitner and Sanstad (2004)	Magnetic ballasts for FLs	96	-	II	USA[2]	Cumulative production	Production costs	1977-1993	29.4 million	629.3 million

[1] Iwafune (2000) differentiates two periods when calculating progress ratios for magnetic ballasts, (i) the period 1981-1989 and (ii) the period 1990-1993.
[2] Data refer to the US market.
[3] *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

In the US, minimum energy performance standards and labels for lamps were introduced at the federal level with the Energy Policy Act of 1992. It is estimated that the total of all energy efficiency measures that are related to lighting and that are in place already today, will potentially contribute to savings of 3.7% of the US electricity consumption by 2020 (IEA, 2006).

Reasons behind the cost reductions

Reductions of market prices for CFLs are caused by two factors, (i) decreasing production costs and (ii) decreasing profit margins for producers. As indicated in Table 3.16, the reduction of ballast prices contributed considerably to the overall price decrease of CFLs. For both, ballasts and entire CFLs, economies of scale as well as automation and streamlining of production processes play an important role for cost reductions in the early phase of market introduction. Progress in electronics, miniaturization of components but foremost the shifting of production from Europe or the USA to low-wage regions like China, reduced production costs considerably. Profit margins for producers decreased since the year 2000 due to mass production of CFLs in China by independent companies or joint ventures that flooded the market with cheap but often qualitatively less advanced CFLs causing fierce price competition among producers.

Technological trends regarding CFL developments in the past include the replacement of magnetic ballasts by electronic ones, and the change from single U-shaped tube design to duplet or triplet tube light bulbs. Manufacturers started the production of advanced CFLs enclosed by glass envelopes around the year 2000, adapting the appearance of a CFL to the widely accepted shape of incandescent light bulbs.

Future scenarios and cost reductions

Future technological developments of CFL will result in more diverse lighting products from both a technical and a design perspective. These developments include the miniaturization of CFLs, adaptations of chromaticity towards more yellow and red light colours, and the market introduction of dimmable CFLs in 2008.

Promising alternatives for CFLs are Light Emitting Diodes (LED). Their application currently experiences a boom in the automotive sector. LEDs can be thought of in various different lighting solutions. They can be produced in a wide variety of sizes[36] and might be embedded within structural elements of houses and furniture. LEDs can be combined to light bulbs, tube- or areal-arrangements. They offer an efficient light source for off-grid households. LED's are non-toxic, i.e., unlike fluorescent light bulbs they do not contain mercury. The market success of this emerging technology will, however, depend on future cost reductions. LEDs are currently too costly to allow their widespread application for household lighting (IEA, 2006a).

Lessons for policy makers

Policy measures in support of energy efficient lighting are generally very cost-effective and contribute to CO_2 savings at *net* negative costs. The IEA (2006a) concludes that future global lighting energy use could potentially be reduced by 38% in a cost-effective way. The development of market shares for CFLs shows, however, that this technology is still in a stage of infancy. Subsidies and other governmental measures might need a long 'breath' to achieve a market breakthrough of CFLs. The fact that CFLs are cost effective on a life cycle basis but that they are still a factor 5-10 more expensive than conventional incandescent light bulbs suggests that consumer education programs as well as leasing or rebate programs from utility companies might be an effective measures for pushing CFL markets.

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[36] One obstacle for the market success of CFLs was especially in the early years after their market introduction the relatively large size being caused by the dimensions of ballasts and tubes. This problem does not exist for LED's as these can be produced in various sizes ranging from millimeters to several centimeters.

General discussion

Compared to household appliances, energy efficient lighting technologies like CFLs are relatively novel. CFLs have been introduced to the market in 1980. Since then, technology has been far less subject to modifications and improvements than, e.g., the technology for household appliances. This makes CFLs particularly suitable for experience curve analyses. The reviewed studies find progress ratios of on average 85% for CFLs with integrated magnetic and electronic ballasts. The achieved price and cost reductions can be attributed to economies of scale, automation and stream lining of production processes and since the 1990s also to the shift of CFL production to low-wage regions like Eastern Europe and China. Despite low life cycle costs, CFLs constitute still relatively low shares in the total lighting market. This situation can be attributed to product characteristics (e.g., size, chromaticity of light) and to high sales prices. Policy support can increase the market share of CFLs. Special attention should be paid by researchers and policy makers to LEDs as a very efficient and novel lighting technology that might experience market breakthrough in the near future.

3.3.1.3 Space Heating and Cooling

Introduction

Space heating and cooling account together for more than half of the total primary energy consumption in the residential sector. In the Netherlands, for example, natural gas consumption for space heating and warm water production in households is responsible for 74% (315 PJ) of the total energy consumption (425 PJ) in households and accounts for 12% of the national total final energy consumption (2612 PJ) (CBS, 2005). Around 37% of natural gas for final consumption in the Netherlands (849 PJ) is consumed by space heating and warm water production in households only. Space heating and warm water production in households contribute 11% (19 Mt CO_2) to the total fossil CO_2 (carbon dioxide) emissions of the Netherlands (UNFCCC, 2006).

Ürge-Vorsatz et al. (2007) identify in a literature review of national and regional studies that worldwide roughly one-third of the energy (in primary terms) consumed in buildings can be saved in a cost-effective way by 2020, if the energy efficiency of energy functions is improved. Space heating but also space cooling in the residential sector offer great and largely untapped potentials for energy and CO_2 emissions savings. The extent to which these savings potentials can be utilized will, however, depend on the magnitude of cost savings that can be realized for energy efficient heating and cooling technologies.

Experience curves for space heating and cooling

Table 3.17 gives an overview of experience curve studies for household heating and cooling technologies. The overall average progress ratio for all technologies is 87%. Prices/costs of air conditioners decrease at a rate of 12% (PR = 88%) with each doubling of cumulative sales/production. Swiss heat pumps show a price reduction at a PR of 83%. Condensing gas boilers in the Netherlands show progress ratios of 86-93% (Weiss et al., 2008; see Figure 3.38). These numbers are somewhat lower than the ones estimated by Martinus et al. (2005) and Haug et al. (1998) but they are considerably higher than the estimates for gas water heaters in the USA, i.e., 75% as calculated by Newell (2000). Jakob and Madlener (2004) identify progress ratios of 82-85% for facades insulation. The overall results of our literature review suggest considerable reductions of production costs for residential heating and cooling technologies.

We regard the results of the experience curve analyses reliable but attached with uncertainties. Most of the analyzed studies estimate progress ratios based on price data that have been obtained from secondary literature sources. The errors that are caused by the use of secondary literature can be regarded as minor relative to other sources of uncertainty (i.e., the estimation of production costs based on market prices or uncertainties related to the estimation of cumulative production). Jakob and Madlener (2004) refer to data estimated in their detailed research report (Jakob et al. 2002).

These data can be regarded relative accurate because they base on detailed information given directly by various Swiss producers and installation companies. Weiss et al. (2008) quantify uncertainty intervals of their results that again refer only to the deviation of individual data points from the fitted experience curve.

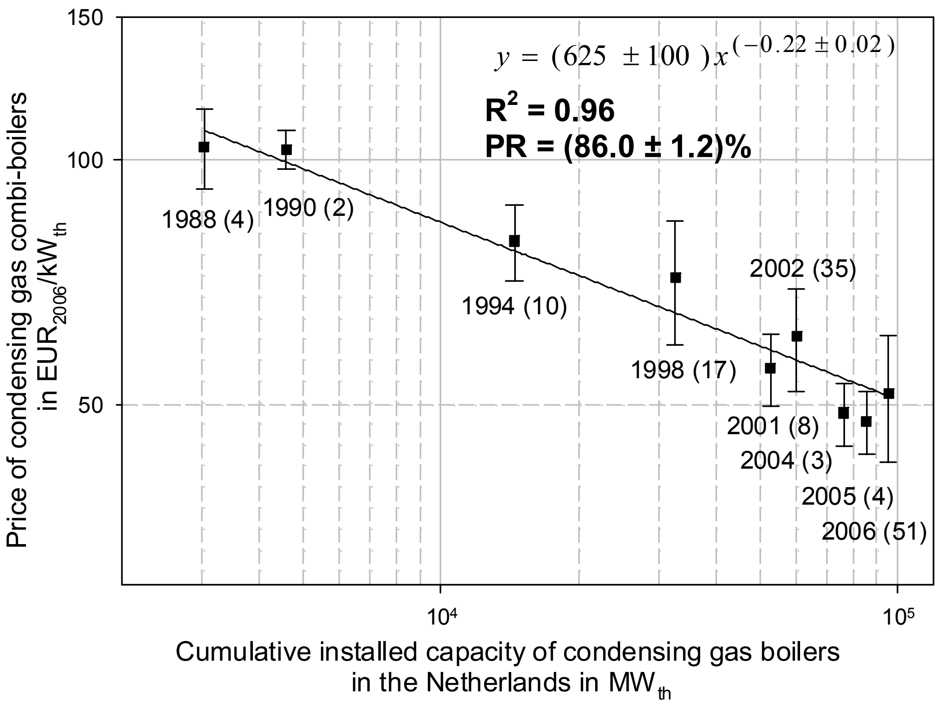

Figure 3.38 Experience curve for condensing gas combi-boilers in the Netherlands (Weiss et al., 2008); in brackets number of data for the respective year analyzed

Table 3.17 Overview of literature on experience curves for building insulation and space heating and cooling technologies

Source	Product	PR in %	R^2	Data quality[4]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production in the first year	Cumulative production
Bass (1980)	Room air conditioners	92	0.89	II	USA	Cumulative industry sales	Price	1946-1961	-	-
Bass (1980)	Room air conditioners	88	0.87	II	USA	Cumulative industry sales	Price	1946-1974	-	-
Newell (2000)	Room air conditioners	87	0.95	II	USA	-	-	1958-1993	-	-
Laitner and Sanstad (2004)	Room air conditioners	87	-	II	USA[1]	Cumulative production	Production costs	1980-1998	2.4 million units	63.3 million units
Newell (2000)	Central air conditioners	86	0.83	II	USA	-	-	1967-1988	-	-
McDonald and Schrattenholzer (2001)[2]	Air conditioners	90	0.82	II	Japan	Unit sales	Unit sales price	1972-1997	~0.5 million units	-
Martinus et al. (2005)	Condensing boilers	96	-	II	Germany	Cumulative capacity	Investment costs	1992-1999	~2,000 MW_{th}	~25,000 MW_{th}
Haug et al. (1998)	Condensing gas boilers	96	-	-[3]	The Netherlands	Cumulative capacity	Investment costs	1983-1997	~1,000 MW_{th}	~30,000 MW_{th}
Weiss et al. (2008)	Condensing gas boilers (space heating only)	93.0 ± 0.9	0.89	I, II	The Netherlands	Cumulative unit sales	Price per kW boiler capacity	1983-2006	829 MW_{th}	95,448 MW_{th}
Weiss et al. (2008)	Condensing gas boilers (combi)	86.0 ± 1.2	0.96	I, II	The Netherlands	Cumulative unit sales	Price per kW boiler capacity	1988-2006	3,034 MW_{th}	95,448 MW_{th}
Weiss et al. (2008)	Heat pumps	83.2	0.96	II	Switzerland	Cumulative number of installations	Price in constant CHF	1980-2004	3,000 units	132,000 units

1 Data most likely refer to US market prices.
2 Based on unpublished data from Akisawa (2000).
3 No information available.
4 *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

Table 3.17 (cont.) Overview of literature on experience curves for insulation and space heating and cooling technologies

Source	Product	PR in %	R^2	Data quality[3]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production in the first yeas	Cumulative production
Newell (2000)	Gas water heaters	75	0.87	II	USA	-	-	1962-1993	-	-
Laitner and Sanstad (2004)	Selective window coatings	73	-	II	USA[2]	Cumulative production	Production costs	1992-2000	4.8 million m^2	157.4 million m^2
Jakob and Madlener (2004)	Building facades insulation 1.0 W/m^2K	85[2]	-	I	Switzerland	Cumulative energy conserved	Cost per conserved energy	1975-2001	-	-
Jakob and Madlener (2004)	Building facades insulation 1.25 W/m^2K	82[2]	-	I	Switzerland	Cumulative energy conserved	Cost per conserved energy	1975-2001	-	-

1 Data most likely refer to US market prices.

2 Progress ratios refer to the cost reduction per unit of conserved useful energy.

3 *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

Economics
Condensing gas boilers contributed substantially to energy efficiency improvements in household heating. In the Netherlands, condensing gas boilers were introduced to the market in 1981 and represent now the standard heating technology for household heating with market shares of over 90%. The prices for condensing gas (combi) boilers have been reduced from roughly 2000 $€_{2006}$ in 1988 to 1200 $€_{2006}$ in 2006. At the same time, prices of conventional non-condensing (combi) boilers declined only from 1300 $€_{2006}$ in 1988 to 1000 $€_{2006}$ in 2006 due to changes of boiler technology from open to closed boiler settings. These price dynamics lead together with a relative decrease of installation and maintenance costs and a considerable increase of natural gas prices to the situation that the payback times for condensing gas boilers reduced considerably (i.e., from more than 7-15 years in the early and mid 1980s to 2-3 years nowadays).

With regard to insulation and glazing, Jakob (2007) points out that most recent data confirms the trend towards overall decreasing costs for insulation as determined by Jakob and Madlener (2004). Roughly two thirds of the total costs for insulation materials can be attributed to labour. Increasing costs for energy and mineral resources might, however, lead to price increases for insulation elements in the future, if labour cost cannot be decreased further (e.g., via prefabricating of larger insulation elements).

Policy measures
There is a large variety of political programs to improve energy efficiency of heating/cooling in the residential sector. The EU issued directive 2002/55/EC (EU, 2002) in which the framework for determining the energy efficiency of buildings is defined. The directive defines efficiency requirements for newly constructed and refurbished buildings and regulates inspection intervals for boilers, air conditioners, and other heating systems. Individual EU member states (e.g., Germany, the Netherlands) have initiated numerous programs to facilitate energy efficiency improvements of household heating and cooling technologies. Measures centre around two aspects, (i) improving *passive* energy efficiency of buildings such as building insulation (wall insulation and windows) as well as building design (ii) improving *active* energy efficiency such as the efficiency of boilers, water heaters, air conditioners, and (iii) introducing novel energy technologies, e.g., solar heating, or heat pumps. Jakob (2007) emphasizes that ambitious building codes and standards can enable the rapid diffusion of coated double and triple glazing in various European countries.

Reasons behind the cost reductions
A major factor that contributes to cost reductions is (as for other products) economies of scale. Cost reductions in the Dutch boiler industry, for example, have been mainly realized by streamlining production processes and by achieving progress in boiler electronics, control units, and burner technology along with considerable size reductions of boiler components (e.g., heat exchangers). The manufacturing of heating boilers changed especially in the last 10 years, when European boiler manufacturers started to out-source the production of boiler components (e.g., heat exchangers, burners, pumps) to specialized manufacturers. Nowadays, boiler producers only assemble more or less standardized components supplied by external companies. This has caused a higher degree of specialization in the boiler manufacturing industry, leading to drastically reduced production costs.

Future scenarios and cost reduction potentials
Condensing gas boilers, for example, have been introduced to the market at the same time as CFLs, i.e., in 1981. They are nowadays the standard technology in countries where natural gas is used as primary fuel for household heating (e.g., in the Netherlands and in the UK). Due to both market saturation and the mature stage of the technology, only minor cost reductions in the manufacturing of condensing gas boilers can be expected in the future. Condensing gas boilers will always remain more expensive than conventional non-condensing boilers due to their more complex technology. Despite this fact, rising fuel prices might, however, increase the market shares of condensing gas boilers also in regions where sales are currently low (e.g., in Eastern Europe). In

the Netherlands, already follow-up technologies such as micro-CHP units and condensing gas boilers with integrated heat pump technology are introduced to the market.

Jakob and Madlener (2004) see large cost and energy efficiency potentials for future improvements of wall insulation and window glazing. To exploit these potentials, minimum energy performance standards should be updated and improved (see also next section).

Lessons for policy makers
The case of condensing boilers in the Netherlands has shown that governmental support might need a long breath until energy efficiency products become established at the market. Investments in energy efficiency measures for household heating are, however, very cost effective. Weiss et al. (2008) calculated that governmental subsidies of € 70 million together with additional € 1.6 billion consumer spending for purchase, installation, and maintenance of condensing gas boilers, enabled energy savings of € 2.7 billion in the period of 1981-2006. Per ton of CO_2 saved, Dutch consumers and government saved roughly € 75.

To fully exploit energy saving potentials, Jakob and Madlener (2004) argue that ambitious building codes and standards are important drivers for techno-economic progress with the experience curve giving valuable guidance for targeted and effective policy measures. In the case of building insulation and glazing, companies do generally not produce at the levels of best available technology (with respect to energy efficiency) but only at a level to meet national standards. Jakob and Madlener (2004) give the example of Austria and Switzerland where coated and inert gas filled glazing became standard technology during the early 1990s (due to governmental regulations) while the market share in Germany for that type of windows was only 10%. It is ultimately the combination of different policy measures that will lead to the adoption of energy efficient residential heating and cooling technologies.

General discussion
Household heating and cooling offers major and still largely untapped potentials for energy efficiency improvements. This refers to both, *active* technologies, i.e., air conditioners and heating boilers as well as passive technologies (i.e., wall insulation, passive sunlight utilization, and window glazing). The progress ratios in the reviewed studies range from 75% for gas water heaters in the US to 96% for condensing gas boilers in Europe. The findings indicate an overall trend toward reduced prices and production costs for household heating and cooling technologies. Energy efficiency improvements can be expected to be very cost effective as the example of the condensing gas boilers in the Netherlands shows. Efficiency technologies such as heat pumps and improved window and wall insulation might, however, need political support (either in form of improved mandatory energy standards or via direct subsidies) to be successful in the market. To that end, experience curve analyses can assist decision makers regarding the amount and scope of required policy support.

3.3.1.4 Summary of Energy Demand Technologies in the Residential and Commercial Building Sector

We presented and discussed the results of experience curve studies on energy demand technologies in the residential and commercial building sector, i.e., household appliances, lighting technologies, and technologies for active and passive space heating and cooling. The overall frequency of progress ratios found in the analyzed studies is depicted in Figure 3.39.

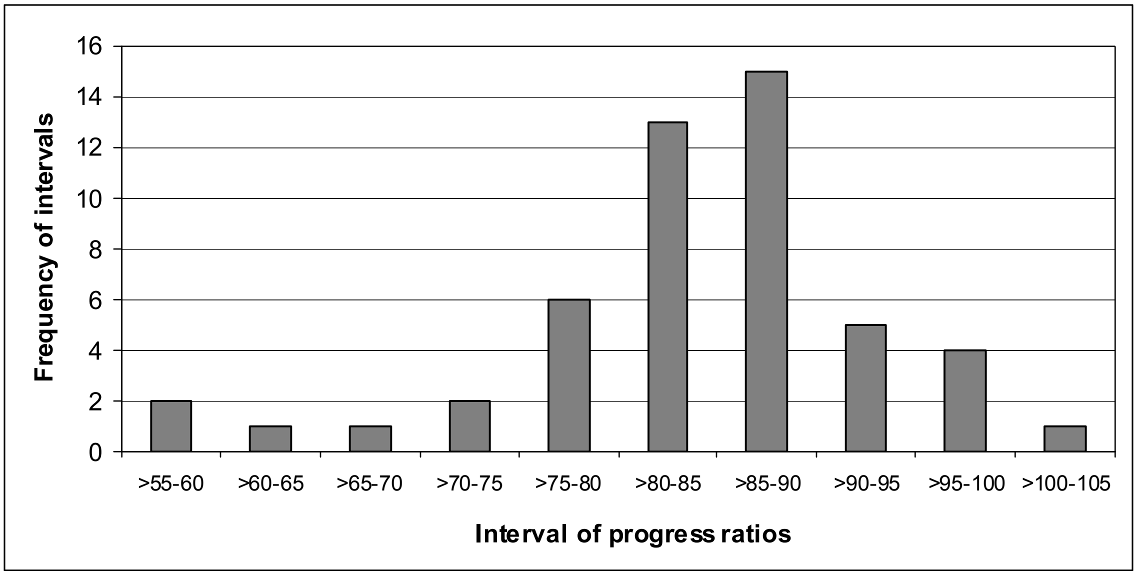

Figure 3.39 Frequency of progress ratios for energy demand technologies37

We find the majority of progress ratios to be in the interval between 80-95%. Our analysis confirms a general trend towards lower prices and production costs for energy demand technologies in the residential sector. Our findings support assumptions made in energy and CO_2 emission scenario models that typically use progress ratios of 80-90% to forecast cost dynamics for novel energy demand technologies. Our results, however, also show that progress ratios can deviate from this average for individual products.

The results presented in this section suggest that progress ratios are especially low for products, which are true technological revolutions (i.e., such as it is the case for CFLs). Products being novel but still relying on mature components (such as it is the case for condensing gas boilers compared to standard non-condensing boilers) can be expected to show cost reductions at lower rates as technologies and know-how related to, e.g., component manufacturing are mature and have already been subject to continuous improvements for several decades.

As mentioned previously, we regard the progress ratios estimated in the various studies as reliable but attached with uncertainties. We argue that major uncertainties result from two factors:

- The use of market prices as proxy for production cost. Price data are commonly used as basis of experience curve analyses because data on production costs are in most cases confidential. Price data introduce, however, considerable uncertainties into the final results because profit margins of producers are likely to vary substantially along the life cycle of products.
- Estimates for cumulative production are uncertain because it is often impossible to obtain reliable production data for early years after the market introduction of products and over long time periods. Errors in cumulative production data can introduce substantial uncertainties into the estimated progress ratios.

So far, a detailed and transparent uncertainty analysis for experience curve results is still missing. This is partly due to the fact that more detailed data at the level of higher disaggregation are generally not available. Further analysis to identify the magnitude of potential uncertainties is recommended.

[37] We include here both the progress ratios for costs and efficiencies of energy demand technologies for application in the residential and commercial building sector.

3.3.2 Learning in the Refinery Sector, in the Production of Bulk Chemicals, Fertilizers, and other Materials

Introduction

In this section, we present the results of our literature review on technological learning in the manufacturing of bulk chemicals, polymers, cellophane, fertilizers as well as fluid petroleum cracking in refineries.

The chemicals industry is a mature industry with its beginnings dating back to the late 19th and early 20th century. In the year 2003, the chemical industry accounts worldwide for roughly 10% of the total final energy consumption thereby being the second most important energy consuming industry after the iron and steel sector (IEA, 2005c). Polymers, as one of the most important chemical product category, have been produced in substantial quantities for more than 50-70 years. Polymers are considered newcomers among other bulk materials such as steel, cement, or paper but they can be regarded as mature products when compared to the other technologies analyzed in this report. By the end of the 1990s, plastics production alone accounted for 10% (in terms of mass) of the total bulk materials production in Europe. For several decades, the chemical industry has grown faster than any other bulk materials industry (i.e., EU plastics production grew by 4.4% per year between 1985 and 2000 (Crank et al., 2004)). It is expected that this trend will continue until and beyond the year 2020. Crank et al. (2004) forecast European polymers production to increase by 12.5 Mt and 25 Mtuntil 2010 and 2020 respectively.

Similar to polymers, fertilizer consumption has grown rapidly in the last 50 years (e.g., the consumption of synthetic nitrogen fertilizers has increased by roughly a factor of 10 since 1950). This development is closely connected to the agricultural revolution. In 2001, 137 Mt of fertilizer nutrients were applied in the agricultural sector worldwide.

Experience curves for the bulk chemical and refinery sector

Technological learning in the chemical industry and in the fertilizer and refinery industry has been studied in several publications (Table 3.18). The progress ratios for individual products and processes vary but indicate an overall trend towards a reduction of unit prices and production costs. The average progress ratio over all products and processes included in this research is 77%. The overall frequency of progress ratios as we found it for the included products and processes is shown in Figure 3.40.

Table 3.18 Overview of literature on experience curves for refineries and in the production of bulk chemicals and other materials

Source	Product / Activity	PR in %	R^2	Data quality[5]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Cunningham (1980)	Fluid petroleum cracking	80	-	II	USA	Installed design capacity of plant	Cost per unit capacity	1942-1958	-	-
Lieberman (1984)[1]	Inorganic and organic chemicals, metals[1]	72[3]		II	-	Cumulated industry output	Market price	1950s/1960s -1972[2]	-	-
Cowley (1985)	Cellophane	84	-	I	USA	Cumulative cellophane mass produced	Cellophane price	1924-1950	~60 t	~3.5 Mt
Cowley (1985)	Cellophane	86	-	I	USA	Cumulative cellophane mass produced	Production costs for cellophane	1925-1950	~1500 t	~3.5 Mt
Sallenave (1985)	Polyester	87	0.97	-[6]	One polyester manufacturer in North America	Polyester production	Polyester price	1973-1983	1 t[4]	34 t

[1] Lieberman (1984) covers in his analysis a total of 37 substances, i.e., acrylonitrile, aniline, bisphenol-A, caprolactam, carbon disulfide, cyclohexane, ethanolamines, ethyl alcohol, ethylene, ethylene glycol, formaldehyde, isopropyl alcohol, maleic anhydride, methanol, neoprene rubber, pentaerythritol, phenol, phthalic anhydride, LDPE, HDPE, sorbitol, styrene, 1,1,1-trichloroethane, urea, vinyl acetate, vinyl chloride, ammonia, carbon black, hydrofluoric acid, sodium, sodium chlorate, sodium hydrosulfite, titanium dioxide, acrylic fibers, aluminium, and magnesium.

[2] Depending on the chemical, time series data start in the period 1952-1964 and uniformly end in 1972.

[3] Average progress ratio refers to the weighed total of all 37 chemicals.

[4] Data refer to the actual polyester production in the first year of the analysis.

[5] Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.

[6] No information given.

Table 3.18 (cont.)Overview of literature on experience curves for refineries and in the production of bulk chemicals and other materials

Source	Product / Activity	PR in %	R^2	Data quality[5]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Sallenave (1985)	Polyester	88	0.83	-[6]	One polyester manufacturer in North America	Polyester production	Production costs for polyester	1973-1983	1 t[4]	34 t
Clair (1983)	Viscose rayon	~97	-	I	USA	Cumulative production	Unit price	1930-1966	-	900 t
Clair (1983)	PP	73[2]	-	I	USA	Cumulative production	Value added	-	-	~15 Mt
Crank et al. (2004)	PP	81	0.98	II	Germany	Cumulative German production	Relative PP price per t oil	1969-2002	~0.1 Mt PP[1]	~10 Mt PP
Clair (1983)	LDPE	64[3]	-	I	Western Europe	Cumulative world production	Value added per t produced	-	-	100 Mt
Clair (1983)	LDPE	64[2]	-	I	USA	Cumulative world production	Value added per t produced	-	-	100 Mt
Clair (1983)	HDPE	68[2]	-	I	USA	Cumulative production	Value added	-	-	~20 Mt
Clair (1983)	Ethylene/LDPE integrated	65[4]	-	I	Western Europe	Cumulative world production	Value added per t produced	-	-	~140 Mt
Clair (1983)	PS	80[2]	-	I	USA	Cumulative production	Value added	-	-	~20 Mt

[1] *Data refer to the cumulative production in Germany until the base year of the analysis.*

[2] *Based on cumulative worldwide production and value added data for the USA.*

[3] *Based on cumulative worldwide production and value added data for Western Europe.*

[4] *Referring to the cumulative worldwide production of LDPE and integrated value added data for ethylene and LDPE in Western Europe.*

[5] *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data*

[6] *No information given.*

Table 3.18 (cont.)Overview of literature on experience curves for refineries and in the production of bulk chemicals and other materials

Source	Product / Activity	PR in %	Uncertainty (R^2)	Data quality[4]	Geographical system boundary	Independent variable	Dependent variable	Period studied	Production of units in the first year	Cumulative production of units
Crank et al. (2000)	PE	71	0.92	II	Germany	Cumulative German production	Relative PE price per t oil	1969-2002	~1.2 Mt PE[1]	~54 Mt PE
Clair (1983)	PVC	66	-	I	USA	Cumulative production	Value added	-	-	~50 Mt
Crank et al. (2004)	PVC	86	0.86	II	Germany	Cumulative German production	Relative PVC price per t oil	1969-2002	~2.5 Mt PVC [1]	~44 Mt PVC
Ramírez and Worrell (2006)	Ammonia	71[3]	1.00	II	World	Cumulative worldwide production	SEC ammonia production	1913-2001	~3 million t N[2]	~3 billion t N
Ramírez and Worrell (2006)	Urea	89[3]	0.86	II	World	Cumulative worldwide production	SEC urea production	1961-2002	~1 million t N[2]	~900 million t N

[1] *Data refer to the cumulative production in Germany until the base year of the analysis.*

[2] *Data refer to the cumulative worldwide production until the base year of the analysis.*

[3] *The SEC data for ammonia and urea production refer to the level of best available technology.*

[4] *Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.*

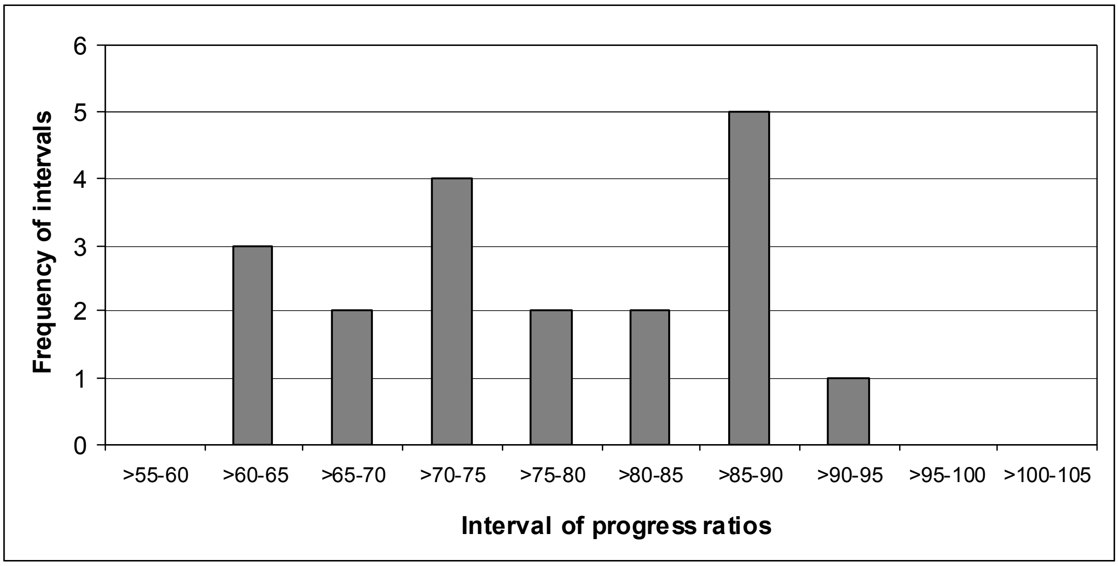

Figure 3.40 Frequency of progress ratios for the refinery sector and the production of bulk chemicals and other materials38

The progress ratios show a wider spectrum of values than the ones depicted in Figure 3.39. One explanation for this result is the fact that Clair (1983) does not analyze costs or prices but value added developments in the polymer industry of the USA and Western Europe. His analyses result in progress ratios (i.e., on average 69%) that are lower compared to the other studies shown in Table 3.18. The progress ratios based on price dynamics as identified by Crank et al. (2004) range from 86% for PVC to 71% for PE.

Ramirez and Worrell (2006) analyze the developments of specific energy consumption in the production of ammonia and urea. They justify the application of the experience curve concept with the fact that energy, i.e., natural gas consumption accounts for 70-90% and 70-75% of the total production costs for ammonia and urea, respectively. Ramirez and Worrell (2006) find reductions in the specific energy consumption (SEC) for ammonia and urea production by 29% and 11%, respectively with each doubling of cumulative production. The authors identify considerable potentials for further improvements of process-specific energy consumption. They argue that it will take 3.3 doublings of the cumulative production (which hypothetically might be reached in 2045) for the worldwide average SEC for ammonia production at current progress ratios to reach the best available technology levels of 2001.

We regard the results of the experience curve analyses for chemicals reliable. Most of the analyzed studies estimate progress ratios based on price data that have been obtained from secondary literature sources. The errors that are caused by the use of secondary literature can be regarded as minor relative to other sources of uncertainty (i.e., the estimation of production costs based on market prices or uncertainties related to the estimation of cumulative production). The data presented by Clair (1983) seem to be obtained from chemical companies or commercial business reports and can potentially be regarded as very reliable.

Economics

Studying polyester manufacturing, Sallenave (1985) argues that using prices as approximation for productions costs inherits the risk of over- and under-estimation of cost reduction, if profit margins do not remain constant in the period of study. Lieberman (1984) points to the same problem when stating that price behavior in the chemical industry is strongly linked to the market structure of particular chemicals. For products with numerous producers, prices tend to

[38] We include here the progress ratios as they were found by Ramirez and Worrell (2006) for the specific energy consumption for ammonia and urea production.

be flexible and rapidly responding to the appearance of new and more efficient plants. In contrast, price changes tend to be more gradual for products with only a few market players (i.e., less than five producers).

The price and cost dynamics for the manufacturing of polymers and other chemicals is correlated with price developments for crude oil. Changes in oil price have therefore a strong impact on the development of production costs of chemicals and often exceed learning effects such as learning by doing or up-scaling of production units.

Policy measures
Policies that address the chemical and refinery industry include governmental targets to improve energy efficiency within industry and the inclusion/exclusion of the refinery and the chemical industry in the Emission Trading Scheme of the European Union. Unlike renewable energies, chemicals production is not subject to governmental regulations that aim at particularly promoting the production of individual chemicals. In recent years, however, bio-degradable and bio-based polymers received growing attention and are indirectly supported via packaging directives or regulations referring to the agricultural sector.

Reasons behind the cost reductions
The results of the experience curve analyses for polymers (e.g., Crank et al., 2004) are to a large extent driven by the dynamics of the crude oil price. Crank et al. (2004) furthermore attribute differences in the progress ratios for individual polymers to specific product characteristics. In general, cost reductions in the chemical industry are achieved by up-scaling of production plants, technological innovation, improved material efficiency as well as automation requiring less man power for obtaining the same production output (Clair, 1983).

Future scenarios and cost reductions
Future developments in the chemical industry comprise the reduction of process-specific energy consumption. Neelis et al. (2007) identified theoretical energy-saving potentials for a total of 68 chemical processes in Western Europe with 1620 PJ of final energy and 1936 PJ of primary energy, resulting in total yearly emission reduction potentials of 127 Mt CO_2. Crank et al. (2004) state that a 50% price reduction for conventional polymers within the next 20 years does not seem impossible, if one considers that prices have declined by nearly a factor of 5 in the last 35 years. Depending on the period chosen, polymer prices have dropped by 1.2% to 3.6% per year. In view of the current increase in oil prices, it remains, however, open, whether reductions of prices and production cost for chemicals will also be observed in the future. Crank et al. (2004) highlight also potentials for the reduction of non-renewable energy consumption and GHG emissions due to the production of bio-based polymers. These potentials will, however, remain limited as bio-polymers are not expected to challenge the production of conventional petrochemical polymers within the next 10 to 15 years.

Lessons for policy makers
The results of our analysis show, that chemicals have become cheaper in the past. It remains, however, open whether this development can be continued in the future. Feedstock and energy prices are the main cost components in chemicals manufacturing. Rising oil and natural gas prices will, therefore, have a considerable effect on future production costs of chemicals. As the results of Neelis et al. (2007) and Ramirez and Worrell (2006) have shown, there exist large potentials for energy efficiency improvements within the chemical and fertilizer industry. Furthermore, bio-based chemicals offer additional potentials for both non-renewable energy and CO_2 emission savings. The manufacturing of bio-based polymers, furthermore, generates alternative income opportunities within the agricultural sector. Policy makers are therefore asked to re-evaluate the potentials of a bio-based chemistry under a high oil price scenario.

General discussion
For chemicals production, we find a relatively large spectrum of progress ratios (64-97%). The results indicate a general trend towards reduced prices and production costs. Ramirez and Worrell (2006) find progress ratios of 71% and 89% for the specific energy consumption in ammonia and urea manufacturing. Unlike for other products and energy technologies, feedstock

and energy costs are the major cost components for chemicals production. The production costs for chemicals depend therefore to a large extent on the dynamics of oil and natural gas prices. In view of this, it remains questionable, whether production costs and market prices of chemicals will continue to decrease in the future at same rates as it was observed for the past.

4 Synthesis and recommendations

4.1 Expected developments for selected technologies in terms of investment costs, production costs and avoided GHG emission costs

As was sketched in Chapter 3 of this report, numerous experience curves for various energy supply and demand technologies have been devised in the past years. In this section we attempt to combine several of these studies to illustrate the possibilities of experience curves to compare the past development of the different technologies and make estimate the future development of costs of capacity, cost of electricity, and the required learning investments for renewable energy technologies. Both may provide valuable insights for policy makers. As Chapter 3 provides a wealth of technologies, we made a selection to compare a few specific cases.

4.1.1 Energy supply technologies

Comparing developments of investment costs

Experience curves in general terms depict the speed with which a technology learns, i.e. cumulative production is a proxy variable for cumulative experience gained, whereas the (declining) costs of the technology can be seen as the increasing performance with cumulative experience. From the review of the various technologies, we are now able to compare the development of various technologies. Figure 4.1 shows the historical development of investment prices of three renewable and two fossil fuel power production technologies. We emphasize that the different investment costs cannot directly be used to compare the final costs of electricity (due to different load factors, fuel costs of fossil fuel technologies, etc.). We do however make some general observations:

- While all renewable energy technologies seem to follow experience curves, it is observed that the modular PV seems to follow the trend line very closely, while the large-scale plants (PC, NGCC and wind offshore) show large(r) fluctuations.
- All renewable energy technologies display increasing prices since 2002. The reasons (as discussed in various parts of Chapter 3) are likely a combination of rapidly increasing demand for these technologies, rising raw material prices, and rising prices of the fossil reference technologies as well[39] (see also Section 4.2). Note that both for NGCC and PC plants, the data series stop at 1997. However, in recent years, both the prices for NGCC and PC boilers and coal and natural gas have risen strongly. Thus, in the past 5 years, basically all power production technologies display rising prices.
- We observe that for example offshore wind clearly benefits from the experience gained earlier onshore. For example, at a cumulative installed capacity of 100 MW, offshore wind had much lower specific investment costs than onshore wind at the beginning of the 1980s (not shown in Figure 4.1).
- It would appear that with the increasing scale of a technology, the progress ratios become less benign. PV, a small-scale, modular technology displays a PR of about 80%. The same holds for CFL bulbs (PR of 81%) and tot a lesser extent for (natural gas boilers for space and heating (PR of 86%) (see Section 3.3). With increasing size of a plant, PRs seem to become less benign: onshore wind farms display PRs of 85-92%, offshore wind farms PRs of >=90%, and pulverized coal plants of 92%. This supports an earlier observation by Neij (1999) that modular technologies learn faster than large plant technologies.

[39] And for offshore wind plants, the shift to locations further away from shore and in deeper waters.

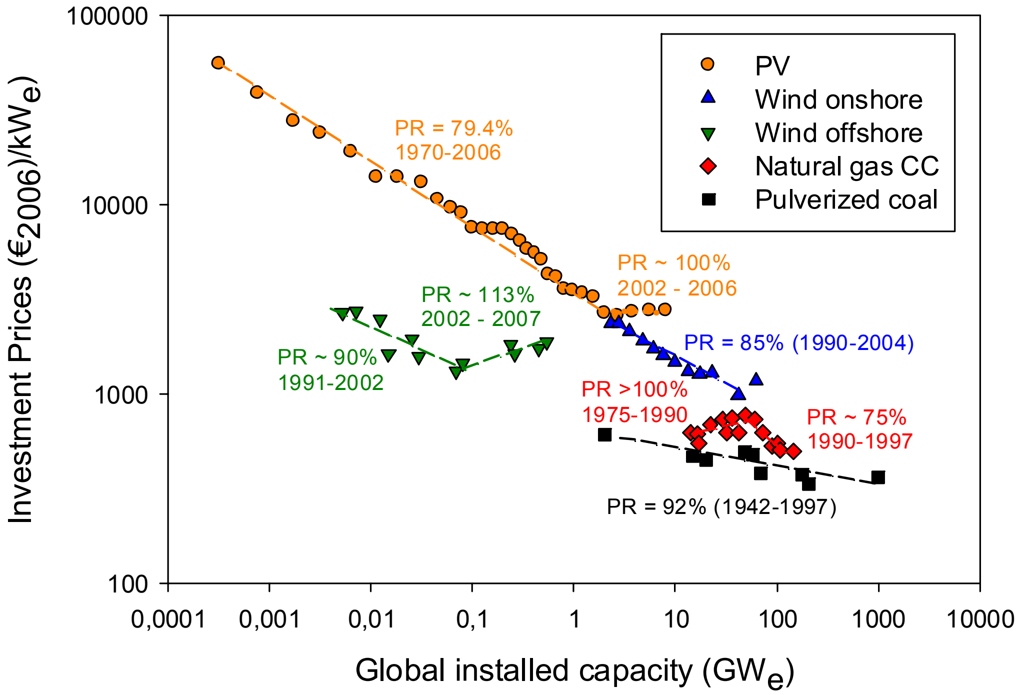

Figure 4.1 *Comparison of historic experience curves of energy supply technologies. Note that all (renewable) energy technologies investment prices are increasing, from 2002 onwards leading to PR>100%. This is likely to be caused by a combination of increasing demand for these technologies, rising raw material prices, and rising prices of fossil reference technologies. Data sources: Isles (2006), Van Sark (2008b), Junginger (2005) Claeson Colpier and Cornland (2002), Rubin et al. (2006), Milborrow (2007).*

In Figure 4.2, we make a comparison between the historic development of natural gas combined cycle (NGCC) plants, pulverized coal (PC) plants and the projected cost reduction of their equivalent CCS-equipped technologies[40], using optimistic, avergae ad pessimistc assumptions, for more details see Hoefnagels (2008).

[40] We emphasize that the calculations for all outlooks for various technologies in Section 4.1 are based on straight-forward assumptions, adapted as much as possible for the Dutch circumstances (see appendix D for details). The outlooks presented should be seen mainly as *illustration* rather than full-blown and well-supported scenarios (which would have exceeded the scope of this review study). Some additional data and a sensitivity analysis is presented in Appendix E.

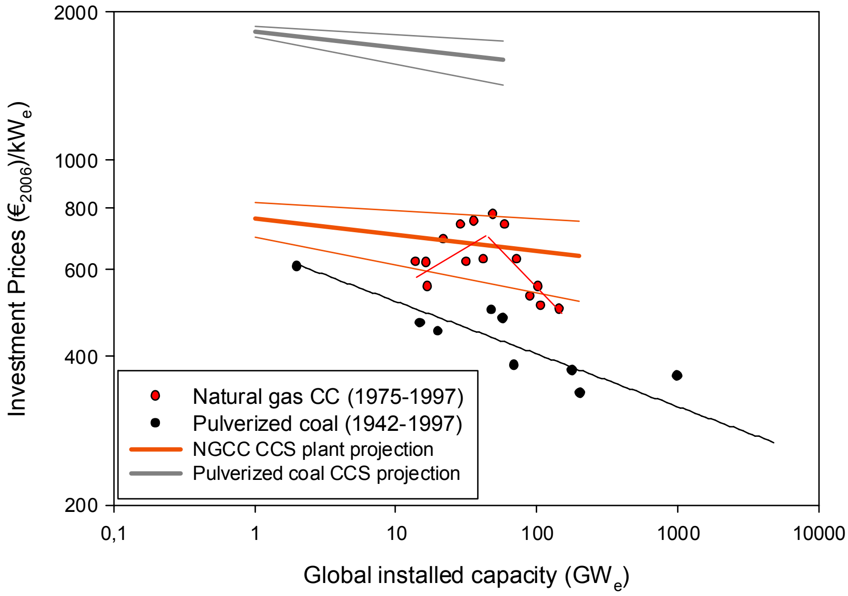

Figure 4.2 Development of historic fossil vs. projected CC and CCS plant investment costs. Note that in this Figure, costs of CO_2 transport and storage are excluded for CCS technologies. Based on data from Claeson Colpier and Cornland (2002), Rubin et al. (2006) and Hoefnagels (2008) [40].

When comparing the actual development of NGCC and PC plants to the expected development of their CCS counterparts, we observe that investment costs for NGCC CCS technology are only 20-30% higher than those of a conventional NGCC plant, while for PC plants, the additional investments for the CS components cause a strong increase, (for underlying reasons, see Section 3.2.3, and Hoefnagels, 2008). Again, the final cost of electricity depend also on other factors, such as fuel costs (which are much lower for coal), O&M costs and the load factor. For a comparison of the cost of electricity (CoE) see Figure 4.5.

Using experience curves for future outlook - the case of onshore & offshore wind

As argued in Chapter 1, experience curves can also be translated into projection for the development of electricity costs, the necessity of learning investments and shifting baselines. To illustrate this, we take the case of onshore and offshore wind development between 2010 and 2020, and compare them to anticipated development of CCS technologies[40]. In Figure 4.3, we first present the past cost developments and the anticipated future projection of the experience curve investment costs for onshore and offshore wind farms.

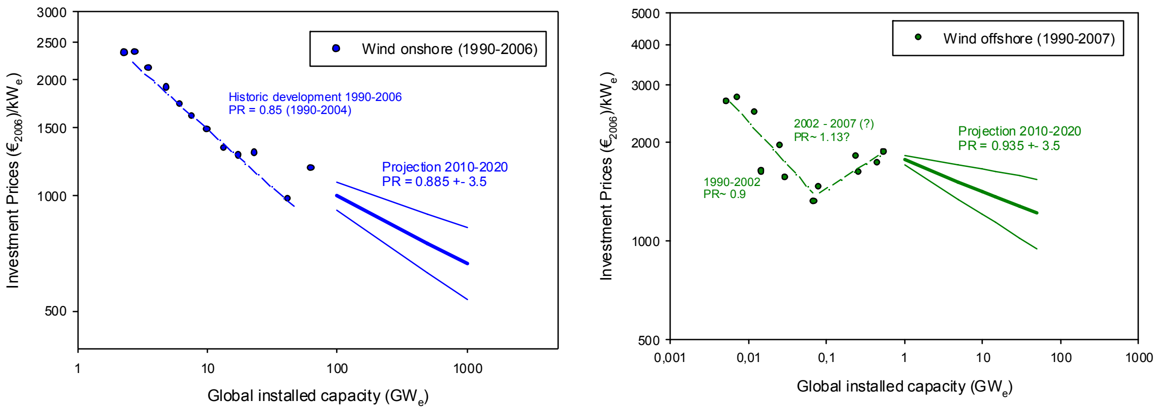

Figure 4.3 Past cost developments and the anticipated future projection (optimistic, average and pessimistic scenarios) of the experience curve investment costs for onshore and offshore wind farms.

A number of remarks have to be made on the future assumptions: for *onshore wind* farms, as argued in Section 3.1.1, we assume that the recent price increase for wind turbines and wind farms will be compensated by additional supply capacity by the wind turbine manufacturers, and that from 2010 onwards, the cost decline will continue. However, as in the literature PRs varying from 85% (Junginger, 2005) to 91-92% (Neij et al., 2003) were found, we assumed an average of 88.5% for our projections (with 85% and 92% as optimistic and pessimistic scenarios. We assumed that total installed capacity would increase from about 63 GW in 2006 to 1000 GW in 2020. *For offshore wind*, we also assume that a cost decline will be occurring again in the future. However, as the large majority of planned wind farms will be located in deeper waters further away from shore, we assume the current costs (of 2006) as starting point for future projections. As presented in Section 3.1.2, studies expect PRs for offshore wind between 90-97%, which we took as optimistic / pessimistic scenarios, with 93.5% as average. Installed capacity was assumed to increase to 50 GW in 2020.

Next, using numbers for load factors, O&M costs, interest rates, economic life times etc. representative for the Dutch situation (Van Tilburg et al., 2007) [40], we obtained the expected range of costs per kilowatt-hour (kWh), as displayed in Figure 4.4.

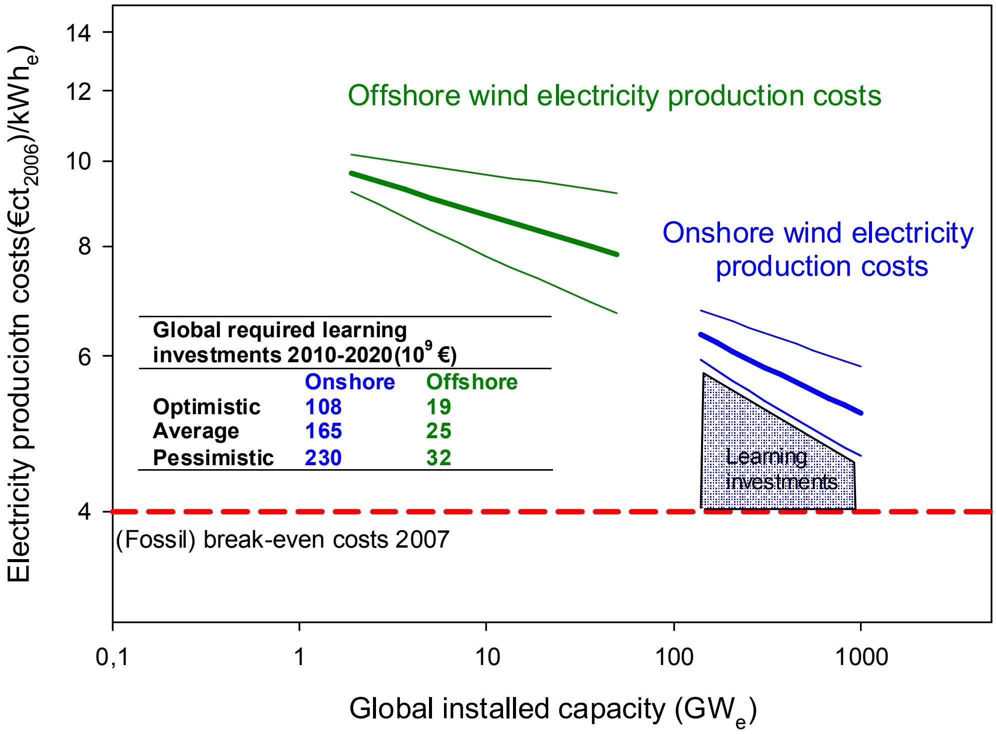

Figure 4.4 Illustrative Projected development of onshore and offshore wind electricity production costs between 2010 and 2020, including global learning investments and fossil reference break-even cost

Note that for this simplification, no improvements between 2006-2020 in terms of load factor, O&M costs etc. are assumed. Thus, the experience curve likely underestimates possible cost reductions (especially for offshore wind energy). Also, Figure 4.4 is strictly speaking not an experience curve, as on the y-axis the costs (i.e. performance) per kWh is given, while on the x-axis, cumulative capacity is assumed, which is not a good measure for the amount of experience gained with electricity production.

As shown, the support needed for learning investments (i.e. financing the difference between the electricity production costs and the baseline[41] in this period varies: for *onshore wind* it lies between € 108-230 billion, though this also depends on the chosen baseline and time frame, see Appendix E. We also assume that simultaneously the amount of wind power installed onshore in the netherlands will increase from 1.8 GW in 2007 to 5 GW in 2020, and the learning investments for the Dutch government would be annual on average 130 M€ (varying from 90-180 M€). In this analysis we assumed a constant baseline of 4 €ct/kWh. If this was to rise to 6 €ct/kWh (assuming further increases in gas and coal prices), onshore would reach break-even-point before 2020, and learning investments would be much lower (-4 to 80 M€ on average per year, see appendix E).

For *offshore wind,* even though the costs per kWh are higher, required learning investments between 2010-2020 on a global scale would be much lower. This is due to the fact that simply much less capacity will be installed until 2020 (50 vs 1000 GW). If the Dutch target of 6 GW by 2020 is to be maintained (which would represent 12% of installed capacity in 2020), learning investments would be on average 340 million €.year (ranging from 260-440 M€/year).

We emphasise again that the calculated learning investment are indicative, and that a full-scale and integral analysis of the required investments for a multitude of technologies was not the aim

[41] In Dutch "onrendabele top".

of this study. Forsuch an analysis, we refer to the forthcoming Energy Technology perspectives 2008 study of the IEA.

Comparing different technologies on the CoE
As a comparison, we also estimated the cost of electricity for natural gas combined cycle (NGCC) and pulverized coal (PC) Carbon Dioxide Capture and Storage (CCS) technologies. For this we used experience curve projections of Rubin et al (2006) and Hoefnagels (2008), and adapted these data as far as possible for the Dutch situation[40].

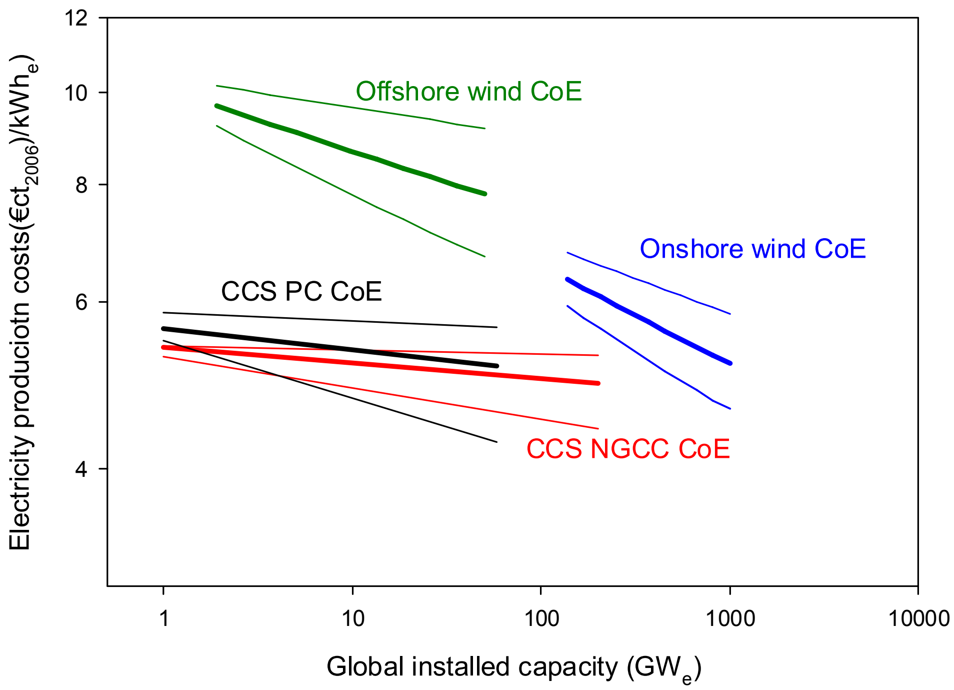

Figure 4.5 2010 - 2020 Outlook for the Cost of Electricity (CoE) of onshore & offshore wind vs. CCS PC & NGCC CCS (including transport & storage).

As above, from this figure a number of interesting trends are observable: both the CoE of PC and NGCC plants are expected to be lower than onshore and offshore wind until 2020. However, it is also clear that the slopes of the CCS experience curves are shallower than the slope of onshore wind, and it is likely that on the longer-term, the CoE of onshore wind farms will become lower than those of CCS. For offshore wind, the uncertainty in the slope is too high to draw any hard conclusions. It remains clear that while costs may decline by 10-30%, they will remain higher than the other technologies presented here beyond 2020.
Translating cost reductions in required CO_2 prices
One aim of this review study was to demonstrate how declining production costs can also be translated in $CO_{2eq.}$ reduction costs. For energy supply technologies, the (in general) higher costs of electricity can be translated into a price of CO_2 which would be required to bridge the gap to electricity from cheaper but CO_2 emitting technologies. We demonstrate this using the example of onshore and offshore wind farms. Assuming that electricity from wind power has a negligible CO_2 emission, and that taking an average emission of 0.59 kg CO_2/ kWh for Dutch centralized electricity production, a certain price of CO_2 per tonne would be needed to cover the additional costs. In Figure 4.6, these costs are displayed. For offshore wind cost of CO_2 would have to be between 50-100 €/tonne to make exploitation of offshore wind farms lucrative. For onshore wind farms, CO_2 prices as low as 20-40 €/tonne might be sufficient by 2020 to render onshore wind farms economically viable without governmental support[40]. To demonstrate the sensitivity of these calculations on variations in the base case, three different scenarios (reference gas, increasing reference and financial learning) are shown in Appendix E.

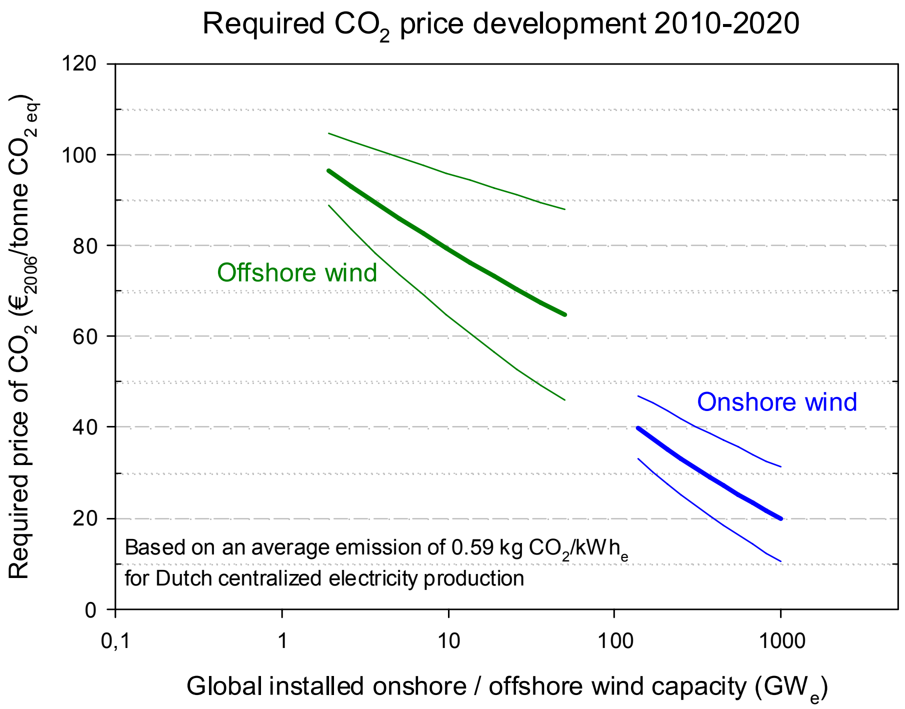

Figure 4.6 Illustrative required price of CO_2 from 2010-2020 to cover the additional costs of electricity from onshore and offshore wind farms.

4.1.2 Energy demand technologies

Analyzing both historic cost reductions and future cost reduction potentials for energy demand technologies is especially interesting for novel and energy efficient technologies. Efficient energy demand technologies are generally more expensive than conventional standard technologies but offer substantial life time savings of energy, energy related costs, and reduced CO_2 emissions. In this section, we use historic cost data to project future cost dynamics until the year 2020 for two selected energy demand technologies, i.e., compact fluorescent light bulbs and condensing gas boilers. We furthermore analyze the cost effectiveness for energy and CO_2 emission savings offered by the selected technologies.

The historic data for compact fluorescent light bulbs (CFLs) indicate that costs follow an experience curve, resulting in cost reductions at a rate of 18.8% (PR = 81%) with each doubling of cumulative CFL capacity. Assuming a growth rate for the global CFL market of 10% per year, we might expect that purchasing CFLs in 2020 will be 36% cheaper than in the year 2006 (Figure 4.7). These projections assume that the additional experience gained during future CFL manufacturing will lead to similar cost reductions as in the past. This assumption might, however, not hold for two reasons:

- Major cost reductions have been achieved in the past by outsourcing of CFL production to low wage regions. As countries like China and India might also experience increasing incomes in the future, further cost reduction potentials from decreasing labour costs seem to be very limited.
- Prices for energy and resources (e.g. copper, phosphorus) are expected to increase in the future.

Both factors might compensate future experience gains in the manufacturing of CFLs and might even lead to increasing production cost and thus increasing market prices in the period until 2020.

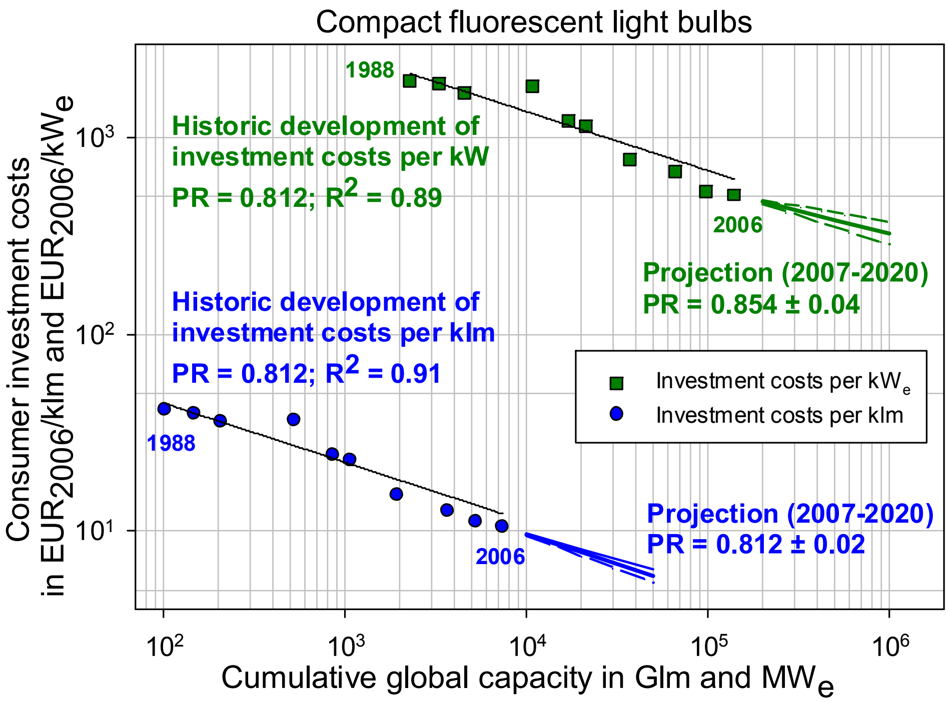

Figure 4.7 Overview of historic experience curves and future cost projections until the year 2020 for compact fluorescent light bulbs; Data sources: Weiss et al. (2008), Iwafune (2000)

Despite the observed reductions of investment costs for consumers (i.e., reductions of market prices), purchasing a CFL is still a factor 10-20 more expensive than buying a conventional incandescent light bulb that is currently sold at 8-12 €/kW (0.5-0.8 €/klm)[40].

We find similar trends for condensing gas boilers (Figure 4.8). Consumer costs seem to follow an experience curve while declining at a rate of 14.1% (PR = 86%) with each doubling of cumulative European boiler capacity produced. Consumer costs for purchasing condensing gas boilers are expected to decrease by roughly 35% until the year 2020 (assuming a growth rate of 7% for the condensing gas boiler market in Europe). Similar to CFLs, also condensing gas boilers are more expensive, i.e., they require higher initial consumer investments than conventional non-condensing standard boilers. Condensing gas boilers were sold in the Netherlands in 2006 at 52 €/kW_{th} while conventional non-condensing boilers cost in average only 43 €/kW_{th}.

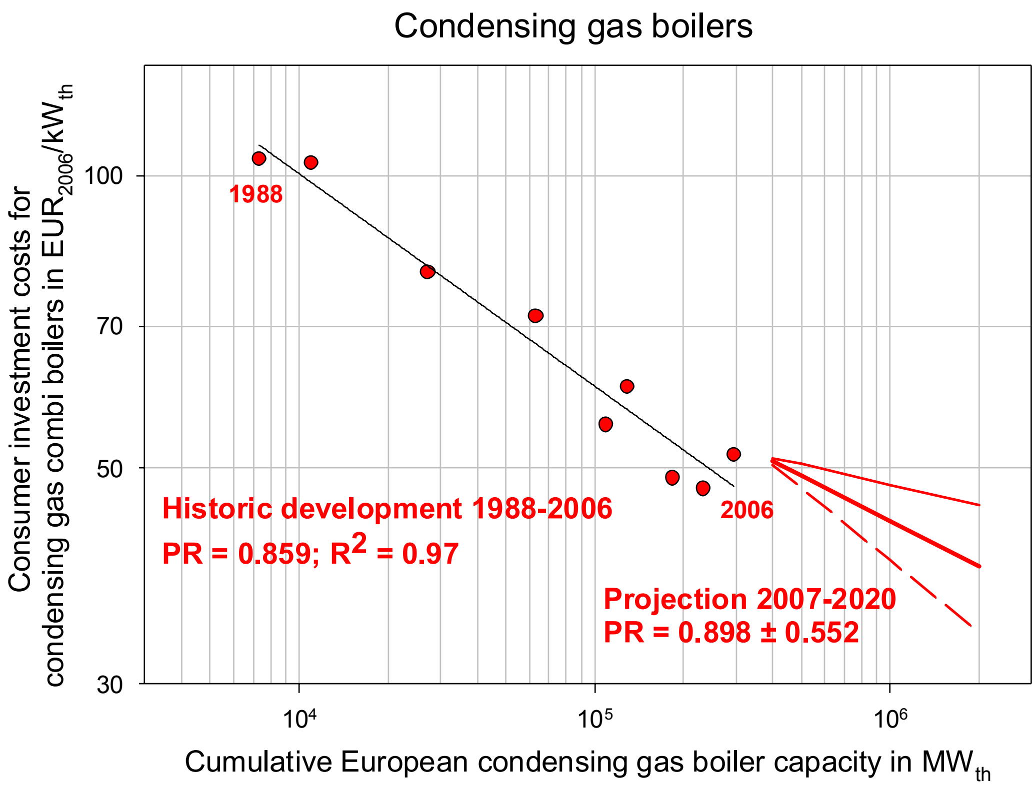

Figure 4.8 Overview of historic experience curves and future cost projections until the year 2020 for condensing gas boilers; consumer investment cost refer to condensing gas combi-boilers (warm water production and space heating) sold in the Netherlands; Data source: Weiss et al. (2008).

For both energy demand technologies, consumer investment costs have to be regained over the products' life cycle via energy savings. The achieved cost savings depend on three crucial factors: (i) the level of energy consumption (e.g., power of a particular light bulb and the hours it is switched on in a household), (ii) the energy efficiencies of the efficient and the standard technology, and (iii) the energy price. Figure 4.9 illustrated the combined effect of technological learning in the manufacturing of CFLs, condensing gas boilers, and their conventional counterparts (i.e., incandescent light bulbs and non-condensing gas boilers) as well as of energy consumption and energy prices on the technology related costs for CO_2 emission savings.

Despite their relatively high price, we find that CFLs have been saving CO_2 emissions in a cost effective way in the entire time period of our analysis (i.e., 1988-2006). For each tonne of CO_2 that is not emitted, consumers save € 20-310. The decreasing cost for emissions that are saved due to the use of CFLs can be mainly attributed to two factors: (i) the drastic reduction in production costs since 1990, achieved mainly by outsourcing of CFL production to low wage regions and (ii) increasing electricity prices.

Our results for condensing boilers show a somewhat different picture. In the years after market introduction condensing gas boilers have been cost effective, saving emissions and consumer costs at 20-35 €/t CO_2. In late 1980s to mid 1990s, condensing gas boilers have not been cost effective[42] for consumers due to improved energy efficiencies of cheaper non-condensing standard boiler and relatively low natural gas prices. In the years afterwards, both increasing natural gas prices and price reductions for condensing gas boilers helped reducing consumer related costs. In 2006 gas condensing boilers contributed to cost savings for the consumers and CO_2 emission savings at a rate of 125 €/t CO_2.

[42] We exclude governmental subsidies from our calculation. If governmental subsidies would be included, consumer costs would be considerably lower than indicated in Figure 4.9 for several years (see Weiss et al., 2008).

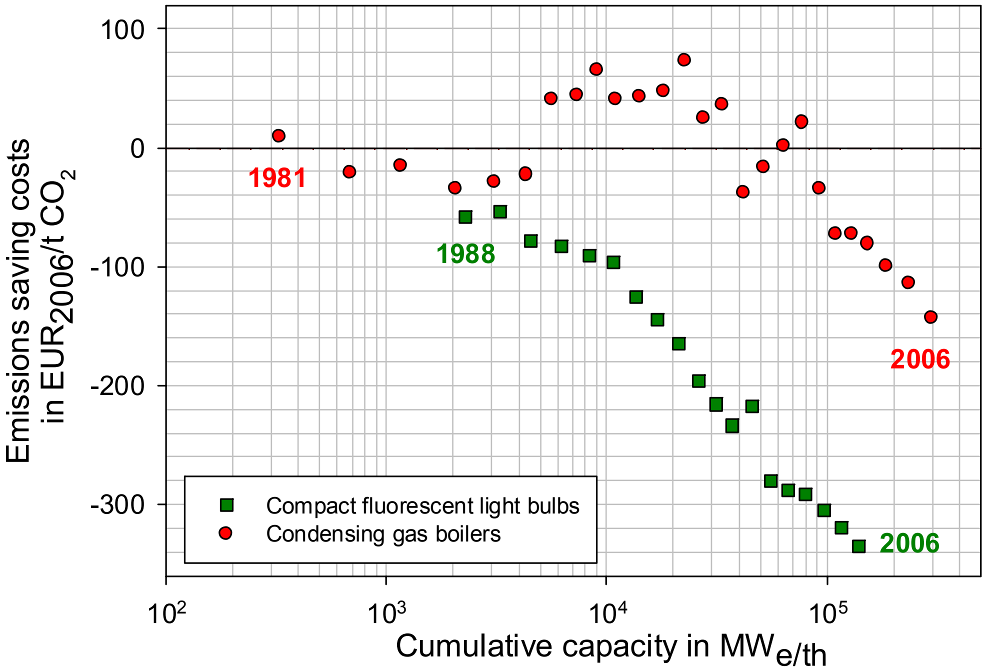

Figure 4.9 Overview of CO_2 emission savings costs for CFL's and condensing gas boilers in the Netherlands, negative costs are equivalent to savings; Data source: Weiss et al. (2008).

Our findings indicate that efficient energy demand technologies can save CO_2 emissions at no additional and even negative costs. Energy efficiency improvements in households and other economic sectors might hence offer savings of CO_2 emissions far more cost effectively than renewable energies or carbon capture and storage in combination with coal or gas power plants. We conclude that our results highlight the importance of energy efficiency for achieving a sustainable global energy system. We recommend further research to identify emission saving costs and absolute emission saving potentials for a larger group of energy demand technologies.

Whether or not energy efficiency technologies can effectively contribute to CO_2 emissions mitigation will depend on the deployment of markets and the market success of novel and innovative technologies. In that respect, some more general aspects are important:

- The market success of efficient energy demand technologies does not only depend on the life cycle costs but on a large variety of different factors (e.g., product design and sales price, preferences and raising awareness of consumers)[43]. Policies aiming at the support of energy demand technologies should therefore carefully analyze product characteristics, costs, and energy saving potentials on the level of individual technologies before designing *tailor-made* governmental programs.
- Consumers are often not willing (or able) to spend additional money on energy efficient products when buying energy demand technologies because life cycle costs and energy savings remain often vague or even unknown at the point of decision making. This points to the need for introducing additional information on product labels (e.g., such as it was done with the European Union's energy labelling program for appliances and light bulbs).
- Consumers intend to apply relatively high discount rates for their additional investments in energy efficiency technologies. The assumed discount rates do generally increase with decreasing product prices and decreasing amount of income available for spending. This

[43] Compact fluorescent light bulbs, for example, have been cost effective from a life cycle perspective since they have been introduced to the market in 1980 (see Figure 3.35 in Section 3.3.1.2). They, nevertheless, still constitute only a niche in the global lighting market.

fact points to the importance of sales prices (especially for low priced energy demand technologies such as light bulbs or refrigerators) as a factor that is often decisive for the market success of energy efficient demand technologies.

4.2 Methodological lessons and recommendations for scientists and modellers

1. Experience curve theory seems to apply for (almost) all energy technologies - also efficient energy demand technologies

For all existing energy technologies, prices (as proxy for production cost) seem to follow experience curves. Interestingly, as reported earlier by Neij (1999), we do find that different types of technologies have different bandwidths of Progress Ratios:

- PRs for large-scale plants which highly specific/customized turn-key costs seem to be relatively low at 90-100% (e.g. pulverized coal plants and NGCC plants, advanced fossil fuel plants and offshore wind farms). Because of the strong custom-built nature of such plants, it is almost impossible to develop meaningful experience curves for these types of plants. One especially problematic case is nuclear energy, where we observe studies displaying diverging price developments. PRs for modular technologies such as PV are higher, at around 80%.
- PRs for (biological) feedstock production for biomass technologies tend to be very high, 55/68% (though only two observations).
- While in the (recent) literature rather limited attention has been given to demand-side technologies, ample studies were found demonstrating that the experience curve is applicable- though with additional problems. The frequency distribution of energy demand technologies in the residential and building sector, i.e., household appliances, lighting technologies, and technologies for active and passive space heating and cooling seems to be normal-distributed with an average of 85-90%
- Frequency of progress ratios for the refinery sector and the production of bulk chemicals and other materials was found to be more or less equally distributed between 65-90 %, i.e. no clear indication of 'dominant' PR-range

2. Experience curve theory appears not to include the effects of increasing raw material costs, at least not on the short term

The experience curve approach was established in the 1960s and 1970's, i.e. before the publications of 'the limits to growth' (Meadows, 1972) and similar publications, pointing out the limited availability of resources. While in past decades it has become clear that resource scarcity can be (partly) circumvented by more efficient user of resources, the question remains whether this can be continued indefinitely or not. Even though renewable energy technologies are by definition not dependent on an exhaustible energy resource, materials required to manufacture them may be come more expensive. Clear examples from the PV industry (increasing silicon prices), wind onshore & offshore (increasing steel and copper prices), but also for PE and PP production (increasing oil prices). Increases in raw material prices can - at least on the short term- drastically increase production costs which are reflected in experience curves by (at least temporarily) increasing production costs. For the longer term, it can be speculated that this will increase either efficient material use (e.g. thinner wafers in PV) or stimulate substitution effects (e.g. using concrete or lattice towers instead of tubular steel towers in wind turbines).

As a general observation, the experience curve approach will only apply to incremental improvements, and should not be used to explain short-term radical changes in costs.

3. Experience curve theory does also not include limitations due to geographical potential constraints

Next to rising raw material prices, also the geographical potential for (especially renewable) energy technologies is limited and may contribute to increasing costs, which is again not included in the experience curve theory, which classically only is applied on products (e.g. cars, computers etc.) which are not bound by geographic potential. We found several examples:

- Production of second-generation biofuels: as shown in the Refuel project, with cumulative experience it is expected that biomass conversion costs will decrease. However, (part of) this cost reduction may be cancelled out by increasing feedstock costs as the increasing larger volumes produce require the use of less suitable soils and thus higher feedstock production costs (in the EU setting).
- Offshore wind energy: future wind farms are planned further offshore and in deeper water, as the available nearshore potential is limited. This caused (amongst other factors) the average costs for foundations and grid connections to increase. This effect is to a more limited extent also visible for onshore wind farms: for example, in Germany, the sites with the best wind resources have been occupied, which requires new plants to be built in less windy places, implying larger rotor diameters, taller towers, lower load factors and thus increasing costs.

However, Schaeffer (2008) remarks that ´geographical constraints´ can also induce new learning paths. Repowering for wind could be an important one, nearshore development at other locations in the world. The larger towers and rotor diameters needed for the inland locations in Germany might help learning to use these turbines also in undeveloped wind rich areas, bringing the average costs of electricity for wind down. For biomass new kinds of biofuel production might be undertaken (fast growing algae for instance), which will lead to less dedicated areas. In other words, where the learning systems experiences stress, the most innovation will take place

4. Energy efficiency improvements may also follow the experience curve pattern

We find indications that energy efficiency improvements may also follow experience curve patterns. This seems to be especially true for technologies where energy consumption and energy efficiency are decisive criteria for market success. As a conceptual framework for this observation, we consider that reducing production costs is the primary aim of any producer in a market economy because it allows to reduce the market price of products (and thus getting a price advantage over competitors) and to increase profit margins. The energy efficiency of demand technologies has for a long time not been decisive for the market success of products because energy was abundant and cheap. Increasing energy prices, however, result in increasing costs for consumers and have therefore the same effect as increasing market prices for a product. The higher energy prices and the higher the absolute energy consumption, the more decisive will energy efficiency be as a factor for the market success of energy demand technologies. If that assumption holds, than it is also true that companies who improve the energy efficiency of their products might have an advantage over their competitors equally to a company that is able to reduce product prices by reducing its production costs. Improving the energy efficiency of energy demand technologies is a process of learning and gaining of experience similar to the process of reducing production costs. Unlike production costs that might in principle asymptotically approach zero, energy efficiency improvements are, however, restricted by thermodynamic minimum energy requirements. Indications for an energy efficiency experience curve are found for global ammonia production, ethanol production in the US, and various household appliances, such as washing machines. With the exception of ammonia production, data uncertainties however prevent hard conclusions.

An interesting observation is that policy interventions may be able to actively ‘bend down’ experience curves for *energy efficiency* (at least temporarily, see Figure 3.32) while this phenomenon is generally not found for *cost* experience curves. One explanation for this observation is given by the fact that companies always aim at reducing production costs in a market economy while energy efficiency has long been so unimportant (e.g., because energy use in the production phase was only a minor cost component or because energy efficiency of demand technologies did not matter to consumers) that only little attention was paid by both producers and consumers. This led to the situation that once energy efficiency began to matter, improvements could be achieved at no or only little extra costs.

5. Experience curves for energy demand technologies face several additional dilemmas compared to energy supply technologies

i) The product characteristics, i.e., the technical components of energy demand technologies changed in the decades since these products are sold at the market. For example, washing machines do no longer only wash clothes but they also centrifuge dry them. Today freezers and refrigerators are sold in all variations, combinations, and sizes. Ozone depleting CFCs were replaced by butane or tetrafluoroethane as cooling substance. All studies on household appliances have therefore one characteristic in common, i.e., they analyze technological learning for products that serve a certain function (i.e., laundry cleaning or keeping food fresh) but that vary at the same time greatly with regard to the technological solutions used to serve this function.

ii) Energy efficiency improvements and investment costs can go hand in hand but do not necessarily have to: Putting less isolation material in a refrigerator will make it cheaper, but at the same time less energy efficient.

iii) The production of energy demand technology has become cheaper in the past due to the outsourcing of production to low wage countries. While the amount of, i.e., labour input into the production did not change, the price of labour became cheaper. This example shows that the reduction of production costs for demand technologies is not only a function of learning and the gaining of experience but also of prices for production factors (e.g., labour).

6. No structural trend was identified that PRs change over time or with increasing market diffusion

As discussed in Chapter 2.2., it is still a debated issue, whether or not the experience curves flattens out with increasing market penetration, i.e. whether the PR is constant or not. Based on the comprehensive overview of studies for varying technologies, we have not found indications that experience curves tend to ‘flatten out’ over time or with increasing market share (i.e. market share reaching a saturation point)[44].

7. Experience curve extrapolation holds clear advantages above ‘only’ bottom up studies, but error/uncertainty margins have to be included

Experience curves have been shown to be a valuable tool for both analysing past developments and quantifying future cost reductions. As was recently shown by Alberth (2008), they are vastly superior to using time as explanatory variable for forecasts, and they can be especially useful when supported by bottom-up engineering studies. However, especially for long-term forecasts, small variations in PRs can lead to significantly deviating cost reductions in scenarios or completely different model outcomes in energy and climate models. Therefore, calculating error margins in progress ratios as shown by van Sark (2008a) and discussed in Section 2.2. is recommended, both to express the quality of the fit (compared to the use of R^2) and as yardstick for optimistic and pessimistic scenarios for future outlooks.

[44] This is a different phenomenon than the stabilization/increase of market prices, caused by various reasons discussed in Section 4.3.

8. Experience curves and innovation systems theory may complement each other, a hybrid approach for short to medium-term scenario analysis could be explored

So far, the experience curve approach has been mainly utilised in top-down and bottom-up energy and climate models, for which it is well-suited, as it provides an elegant way to model endogenous technological change. However, while experience curves can quantify cost reductions with cumulative market diffusion, by themselves they cannot forecast whether the actual market diffusion will occur.

Especially the transition-management approach, applied by Dutch policy makers a few years ago, could possibly benefit from a hybrid approach of quantifying potential future production costs reduction of a new technology, and qualitatively evaluating the current and future chances of success based on the fulfilment of the various functions of innovation. Especially for technologies expected to gain market maturity in the short-to-medium term (e.g. 5-15 years) such an approach would seem promising. While such a hybrid approach needs to be developed in more detail, and does probably pose serious methodological questions to be solved, it could be developed into a valuable tool to support transition management.

9. Possibilities to apply the experience curve concept to new fields

As a final recommendations for scientists, we note that policy makers also have considerable interests to further develop and apply the experience curve concept to new areas. For example, during a workshop to discuss the preliminary results of this report, Dutch policy makers suggested to investigate technological learning and associated cost reductions for new agricultural practices (e.g. remote-sensing guided precision agriculture), and to further look into the local learning mechanism for energy-saving technologies in the built-environment.

4.3 Possibilities and limitations of experience curves for policy support on accelerating technological progress - lessons for policy makers

1. The optimal distribution between R&D and market support measures remains difficult to determine

One of the key questions often brought forward by policy makers is “what the optimal distribution between supporting R&D and market support measure is”, i.e. how much financial support should be given to achieve maximum cost reduction with minimal means. Unfortunately, also after the review of dozens of studies, this ‘holy grail’ has not been found. Experience curves by themselves could - at best - only contribute to such an analysis as one component of a set of tools. While this report that much progress has been made on establishing experience curves in many ways, it is clear the ´black box´ of technology learning has not yet been opened, as we still do not know very much on how learning is occuring and which factors are most influential - an important precondition to determine optimal support policies. Both Neij (2008) and Schaeffer (2008) remark that alternative, more disaggregated methods would be needed for a comprehensive analysis. The current knowledge which is primarily based on analysis of statistics needs to be complemented by in-depth case studies using social science approaches like ethnographic studies, study of company archives, interviews, etc.

It is clear is that technological learning depends on a variety of factors (such as stage in the market diffusion process, geographical distribution of the technology, market composition, technology specific aspects, etc.). Therefore, it is the question whether it is possible to develop a general model which *ex post* addresses this question adequately.

One factor that makes it increasingly difficult to evaluate the impact of R&D on technological learning and cost reductions is the difference between public and private R&D. While public R&D expenditures are relatively well-known, private R&D expenditures are often confidential.

Thus the impact of overall R&D expenditures on technological learning and production costs is hard to quantify.

However, as the case studies of basically all successful technologies show (e.g. PV, wind onshore), it would appear that (public) R&D investments are not only required at the beginning of innovation and market introduction phases, but need to be continued also when large-scale market introduction is reached. It is recommended that market-pull measures such as investment subsidies and feed-in tariffs should be high in the beginning, but progressively lowered (see point 3).

Finally, Schaeffer (2008) remarks that most in-depth analyses teach that the learning process is much more complicated than just R&D and market support. Thus, the main question is to determine how policy can enhance the learning process in the most optimal way. While R&D and market support would be part of the package, also supporting (the construction of) learning networks, the exchange of information, are relevant components. Such an approach is close to the transition approach already undertaken by the Dutch government departments.

2. No proof is found that policy can 'bend - down' the experience curve

Policy has undoubtedly a crucial role in supporting technological earning and cost reductions of new technologies. However, policy makers sometimes express the hope that by investing heavily in public R&D, technological learning (and thus cost reductions) may be accelerated. In other words, the speed with which the technology learns would be increased. This would imply that the experience curve could be 'bent downwards', i.e. the slope of the curve could be changed either temporarily or constantly (e.g. changing the PR from 90% to 80%).

However, in all studies investigated, we seldom find curves which (temporarily) change the slope and curve downwards (i.e. the progress ratio decreases). In none of these cases, this was linked to intensified policy support. While this is no scientific proof that R&D cannot do so, we can state (as in section 4.2 point 6), that no structural trend was identified that PRs change over time or with either increasing market diffusion, or with changing R&D support for that matter.

Neij (2008) expresses the view that policy instruments like R&D may be seen as a break in the experience curve if it results in radical technological change (c.f. crystalline silicon PV and thin-film PV). However, it could be argued if the radical changes incline the use of a new experience curve (as stated for offshore wind turbines in this report).

On the other hand, policy support can very likely accelerate the 'riding down' of the experience curve, i.e. using financial policy measures such as subsidies or feed-in tariffs to stimulate extra market volume, which in turn drives down production costs. Determining the exact height of these support measures is however not easy, as shown in the next paragraph.

3. Over-stimulation of markets may increase demand drastically, which may result in increasing prices - which are not captured by experience curve analysis

As was shown in various parts of sections 3 and 4.1., market prices for PV, wind onshore and wind offshore, market prices have either stabilized or increased over the past 5 years. One main reason for this is likely the strongly increased demand for these technologies by policy targets and policy measures. For example for, onshore wind farms, turbine manufacturers report full order books for the coming years, indicating a shortage of production capacity.

However, before attributing all price increases to too high support measures, one should take into account:

- Increasing production costs because of increasing raw material costs (e.g. steel, copper, silicon) and limited geographical potential (see section 4.2 points 2 and 3)

- Increasing prices of the reference power technologies. In recent years, the investment costs of conventional power technologies (e.g. NGCC and PC plants) have increased drastically as well.
- Fluctuating exchange rates. For example, most wind turbines are manufactured in Europe, due to the declining US$, prices in the US for imported turbines given in US$ increased even further.

Stabilizing or increasing prices on the short term does however not mean that no technological learning occurs. In other words, production costs may still decline, but this is no longer reflected in market prices. Also, in well-functioning markets, it is likely that prices will decline again on the longer term towards production costs, when production capacity/supply has caught up with demand and a shake-out phase occurs. Yet, it must be emphasised strongly that **experience curves allow for projections for the development of production costs; they do not forecast the development of market prices, and they are not a short-term tool**.

Summarizing, as argued above, support policy is crucial for emerging technologies, yet *over*-stimulating markets may - at least temporarily lead to increasing prices. Careful and long-term yet flexible support policy is required to effectively stimulate the development of renewable energy technologies, while at the same time preventing over-stimulation and free-rider effects.

4. For experience curves describing energy efficiency, we do find indications that these slopes can be influenced by policy measures such as labelling programmes

As was stated under 4.3 point 2. policy seems not able to change the slope of experience curve for production costs. As was shown in section 3.3 for demand-side technologies, the experience curve approach also seems applicable to measure autonomous energy efficiency improvements. Interestingly, we do find strong indications that in this case, policy can bend down (at least temporarily) the experience curve and increase the speed with which energy efficiency improvements are implemented. However this phenomenon needs to be investigated more thoroughly before any firm conclusions can be drawn on the topic.

5. Experience curves can help policy makers to determine the effect of their support measures on overall technology cost reductions[45]

Often, considerable governmental budgets are spent to support the diffusion of renewable and energy-efficient energy technologies and thereby stimulate technological learning. However, it is often unclear to policy makers, to what extent this support will lead to cost reductions. This depends to a large extent, how much capacity is already installed (on a global level), and how much additional capacity will be generated through the policy support. Especially supporting new technologies which already have achieved a considerable market (e.g. onshore wind with 83 GW), market support measures are still vital (as presented in 4.1), but further cost reductions will occur more slowly over time. As The Netherlands is a small country, the influence on the experience curves of energy technologies of these changes of policy support has not been very large. There could be different rationales for a small country to support certain technologies with R&D support, market support, learning networks etc.

If the aim of policy support measures is to substantially contribute to technology development and achieve rapid cost reductions, this can probably only be achieved by supporting technologies for which one or a few pilot plants already mean substantial increase of installed capacity (and thus opportunities to learn). If the market is still small, early mover countries that build up a domestic market and support their industry in developing export markets, can develop a considerable competitive advantage within a certain technology area, if they continue this support over a considerable time. Denmark and wind energy technology is a very good example. From the late 1970s to the late 1990s Denmark has supported strong market growth

[45] This section is partly based on the comments of G.J. Schaeffer (2008).

incentives in their own country as well as support to other early market countries (e.g. US in the early 1980s). This was combined with R&D support and other kind of support, e.g. for learning networks and standardization efforts.

If the market for a certain technology is already substantial (e.g. wind or solar energy today), the influence of any Dutch policy on the experience curves of these technologies will always be negligible. The relevant question is then “how will our country get at least a fair piece of the pie?” Those countries with a consistent support of market, R&D and other learning processes will be best positioned. In this case, again, the experience curve of the technology will act more as a reference cost path that needs to be followed, or even beaten, to get the competitive advantage.

6. Policy maker should be aware of the possibilities and limitations of using experience curves in energy models when interpreting their results

Many energy and climate models exist, designed to support policy decisions, and many of them use experience curves to model endogenous technological change. As was discussed in Section 2.4, for a policy-maker, key attention should focus on the question why the model outcomes presented provide justification for the policy suggestions. To this end, one ought to grasp the basics of the model used, and in respect to experience curves, how endogenous learning is modelled. As model results tend to be very sensitive to small changes in PRs, a sensitivity analysis is essential to demonstrate the robustness of model outcomes.

7. For some new large-scale technologies (such as offshore wind, 2nd generation biofuels & electricity production), more international cooperation & structured knowledge exchange is required

Technologies such as large-scale FT plants or offshore wind farms do benefit strongly from large scales, e.g. specific investment costs go down, but absolute investment costs are high. Frequently changing and often not-harmonized policies in e.g. EU countries make investors reluctant to commit more international cooperation, coordinated action and support for these technologies could be very beneficial for stable investments. We also note that, while on the national level, information exchange for new technologies is often organized well-structured knowledge exchange on specific technologies on an international level remains limited. It is also noted that for many technologies, local/national learning processes (i.e. learning processes related to installation and operation of new technologies) play an important role in the technology diffusion process. This tacit knowledge is not simply exported with the physical artefact.

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List of Abbreviations, Units, and Signs

ABWR : Advanced Boiling Water reactor
AC : Alternating current
AEEI : Autonomous Energy Efficiency Improvement
AP : Air Pollution
BCG : Boston Consultancy Group
BOS : Balance of system
BWR : Boiling Water reactor
CC : Combined Cycle
CCS : Carbon Capture and Sequestration
CFC : Chloro-fluoro-carbon
CFL : Compact fluorescent light bulb
CHF : Swiss Franc
CHP : Combined Heat and Power
CO_2 : Carbon dioxide
CO_{2eq} : Carbon dioxide equivalent
CoE Cost of Electricity
Combi : Combining space heating and warm water production
cont. : Continued
CPI : Consumer Price Index
CSP : Concentrated Solar Power
DC : Direct current
DME : Dimethyl Ether
DRAM : Dynamic random access memory
EEG : Erneuerbare Energien Gesetz (Renewable Energy Act)
EPR : European Pressurized Reactor
EPROM : Erasable programmable random access Memory
ESP : Electrostatic Precipitator
ETP : Energy Technology Perspectives
EU : European Union
EUR : Euro
EUR_{2006} : Prices in Euros as of 2006
EWEA : European Wind energy Association
FGD : Flue Gas Desulphurisation
FIP : Feed-in Premium
FIT : Feed-in Tariff
FL : Fluorescent light bulb
FT : Fischer Tropsch
GDP : Gross Domestic Product
GHG : Greenhouse gas
GTCC : Gas Turbine Combined Cycle
h : Hour
HDPE : High-density polyethylene
HRSG : Heat Recovery Steam Generator
HTR : High Temperature Reactor
HVDC : High Voltage Direct Current
IC : Integrated Circuit
IEA : International Energy Agency
IGCC : Integrated Gasification Combined Cycle
IT : Information Technology
ITER : International Thermonuclear Experimental Reactor
K : Degrees Kelvin
KB : Kilobyte
kW : Kilowatt
kWh : Kilowatthour
l : Liter
LDPE : Low-density polyethylene

LED : Light emitting diode
LHV : Lower heating value
LFL : Linear fluorescent light bulb
LNG : Liquid Natural Gas
LR : Learning Rate
LWR : Light Water Reactor
m^2 : Square meter
m^3 : Cubic meter
MEP : Milieukwaliteit Electriciteits Productie (Environmental Quality of Electricity Production)
MOS : Metal oxide semiconductor
Mt : Megatonnes
MW_{th} : Megawatt heat
N : Nitrogen
NGCC : Natural Gas Combined Cycle
No. : Number
NREL : National Renewable Energy Laboratory
NSI : National System of Innovation
O&M : Operation and Maintenance
OECD : Organization for Economic Cooperation and Development
PBMR : Pebble Bed Modular Reactor
PC : Pulverized Coal
PE : Polyethylene
PP : Polypropylene
PPI : Producer Price Index
PR : Progress Ratio
PS : Polystyrene
PV : Photovoltaic
PVC : Polyvinylchloride
PWR : Pressurized Water Reactor
R^2 : Coefficient of determination
RAM : Random access memory
R&D : Research and Development
RD&D : Research, Development and Demonstration
RITE : Research Institute of Innovative Technology for the Earth
ROC : Renewable Obligation Certificate
RPS : Renewable Portfolio Standard
RTD : Research and Technological Development
SD : Standard deviation
SCR : Selective Catalytic Reduction
SEC : Specific energy consumption
SED : Specific energy demand
SEGS : Solar Energy Generating Systems
SMR : Steam Methane Reforming
STC : Standard Test Conditions
STE : Solar Thermal Electricity
SSI : Sectorial System of Innovation
t : Tonne
TPES : Total Primary Energy Supply
TSIS : Technology Specific Innovation System
TV : Television
TWh : Terrawatthour
UK : United Kingdom
US : United States (of America)
USC : Ultra Supercritical Coal-fired
USD : US Dollar
V : Volt
W : Watt
WGS : Water Gas Shift
\- : No information given

Appendix A Technical and geographical characteristics of offshore wind farms in Europe

Tables A.1-A.3 show the main technical and geographical characteristics of offshore wind farms in Europe, including wind farms realised from 1991, under construction, and (more or less firmly) planned up to 2014.

Table A.1 Technical and geographical characteristics of offshore wind farms (1-24) in Europe

№	Country	Project	On line	Turbine supplier	Turbine diameter [m]	Turbine capacity [MW]	Number of turbines	Total capacity [MW]	Lay-out	Distance to shore [km]	Water depth [m]	Hub height [m]	Foundation type	Annual generation [GWh/a]
1	S	Nogersund († 2007)	1990	Wind World	25	0.22	1	0.22		0.35	6	37.5	Tripod	
2	DK	Vindeby	1991	Bonus	35	0.45	11	5.0	two rows	1.5 - 3	2.5 - 5	37.5	Caisson	11
3	NL	Lely († 2006)	1994	NedWind	40	0.50	4	2.0	single line	0.8	4 - 5	39	Monopile	4
4	DK	Tuno Knøb	1995	Vestas	39	0.50	10	5.0	two rows	6	3 - 5	40.5	Caisson	13
5	S	Bockstigen	1998	Wind World	37	0.55	5	2.75	cluster	4	5.5 - 6.5	40.5	Monopile	9
6	S	Utgrunden	2000	Enron	70	1.50	7	10.5	cluster	12	7 - 10		Monopile	37
7	UK	Blyth	2000	Vestas	66	2.00	2	4		1	6	58	Monopile	11
8	DK	Middelgrunden	2001	Bonus	76	2.00	20	40	curved line	2 - 3	2 - 6	64	Caisson	99
9	S	Yttre Stengrund	2001	NEG-Micon	72	2.00	5	10	line	5	8	60	Monopile	30
10	DK	Horns Rev	2002	Vestas	80	2.00	80	160	carré	14 - 20	6 - 14	70	Monopile	600
11	DK	Samsø	2003	Bonus	82.4	2.30	10	23	line	3.5	11 - 18	61	Monopile	69
12	DK	Rønland	2003	Vestas/Bonus	80/82.4	2.15	8	17.2				78/79	Monopile	70
13	DK	Nysted	2003	Bonus	82.4	2.30	72	165.6	carré	9	6 - 10	69	Caisson	547
14	DK	Frederikshavn	2003	Vestas/Bonus/ Nordex	90/82/90	2.65	4	10.6		0.5	1 - 4		Suction bucket/ monopile	21
15	IRL	Arklow Bank	2003	GE	103	3.60	7	25.2		7 - 12	5	74	Monopile	95
16	UK	North Hoyle	2003	Vestas	80	2.00	30	60	five rows	7 - 8	7 - 11	67	Monopile	200
17	UK	Scroby Sands	2004	Vestas	80	2.00	30	60		2.3		68	Monopile	171
18	UK	Kentish Flats	2005	Vestas	90	3.00	30	90	five rows	8 - 10	5	70	Monopile	285
19	D	Rostock - Breitling	2006	Nordex	90	2.50	1	2.50		0.5	2	80		9
20	UK	Barrow	2006	Vestas	90	3.00	30	90	four rows	7	15 - 23	75	Monopile	305
21	NL	Egmond	2006	Vestas	90	3.00	36	108		10 - 18	18 - 20	70	Monopile	357
22	DK	Grenaa-harbour	*2007*			2.75	3	8.25						
23	S	Lillgrund	2007	Siemens	93	2.30	48	110		10	10	70	Caisson	330
24	UK	Moray Firth	2007	REpower	126	5.00	2	10		25	44	88	Four-legged jacket	40

Table A.2 Technical and geographical characteristics of offshore wind farms (25-48) in Europe (continued)

№	Country	Project	On line	Turbine supplier	Turbine diameter [m]	Turbine capacity [MW]	Number of turbines	Total capacity [MW]	Lay-out	Distance to shore [km]	Water depth [m]	Hub height [m]	Foundation type	Annual generation [GWh/a]
25	UK	Burbo Bank	2007	Siemens	107	3.60	25	90	three rows	10	1 - 8	88	Monopile	315
26	NL	Q7 (IJmuiden)	2008	Vestas	60	2.00	60	120		23	19 - 24	59	Monopile	400
27	D	Borkum West	2008	REpower/Multibrid	126	5.00	12	60		43	30	90	Tripod	260
28	UK	Lynn & Inner Dowsing	2008	Siemens	107	3.60	54	194		5	6 - 13	80	Monopile	659
29	B	Thornton Bank	2008	REpower	126	5.00	6	30		25	27	59	Tripod?	
30	UK	Robin Rigg	2009	Vestas	90	3.00	60	180		9	0.3 - 8.4	84	Monopile	631
31	DK	Horns Rev II	2009					200		42	6 - 14			800
32	DK	Kriegers Flak III	*2009*				91							
33	D	Mecklenburger Bucht	2009					30		20				
34	D	Borkum-Riffgrund	*2009*				77	231			23 - 29			
35	D	Baltic I Darss	*2009*				24	69		16				
36	D	Borkum-Riffgrund West	*2009*				80	400		45	~ 30			
37	D	Sandbank 24	*2009*				80	400		54	20 - 35			1,600
38	D	Baltic I	2009				21	58		15 - 16	16 - 19			
39	D	Nördlicher Grund	2009				80	400		84	23 - 40			
40	D	Adler Grund	*2009*				80	400		40				
41	D	Nordergründe	*2009*					125		15	4 - 14			
42	D	Nordsee Ost	*2009*				80	400		30	~ 22			
43	D	ENOVA North Sea WP	*2009*				48	288		47	26 - 34			1,152
44	D	Dan-Tysk	*2009*				80	400		45	~ 30			
45	D	Gode Wind	*2009*				80	400		33	16 - 19			
46	S	Gasslingegrundet	2009				10							
47	S	Kriegers Flak II	2009				128	640		16 - 24	35			
48	S	Utgrunden II	*2009*					86			7			

Table A.3 Technical and geographical characteristics of offshore wind farms (49-78) in Europe (continued)

№	Country	Project	On line	Turbine supplier	Turbine diameter [m]	Turbine capacity [MW]	Number of turbines	Total capacity [MW]	Lay-out	Distance to shore [km]	Water depth [m]	Hub height [m]	Foundation type	Annual generation [GWh/a]
49	S	Klasarden	*2009*					42		7 - 11	1.5			
50	UK	Rhyl Flats	2009	Siemens	107	3.60	25	90		8		80	Monopile	
51	UK	Gunfleet Sands	2009	Siemens (30X) &		3.60	30	172			8	81.5	Monopile	369
52	UK	Cromer			107	3.60	30	108		7	23			350
53	UK	Ormonde		Vestas	90	3.00	36	108		10 - 15	22			
54	UK	Thanet	*2009*	Vestas	90	3.00	100	300		7	18			
55	B	Thornton Bank	2010	REpower	126	5.00	27	135		25	27	59	Tripod?	
56	D	Butendiek	*2010*			3.00	80	240		34	18 - 22			960
57	D	BARD Offshore	2010	BARD	122	5.00	80	400		90	39 - 40	90	Tripod	
58	D	Sky 2000	*2011*				50	150		15 - 20			Monopile?	960
59	D	Kriegers Flak I					80	400		30				
60	UK	Teesside	*2011*					90		1.5				
61	UK	Cirrus Array	*2011*					284		7				
62	UK	Greater Gabbard	*2011*	Siemens	107	3.6	140	500		23	15		Monopile	1,750
63	UK	Gwynt y Môr	*2011*					750		13 - 15	12 - 34			2,345
64	UK	Lincs	*2011*					250		8	8 - 18	- 100		
65	UK	Sheringham Shoal	*2011*					315		17- 22	15		Monopile?	
66	DK	Nysted II	2011					212		9	6 - 9			
67	D	Amrumbank West	2011				80	400		36	20 - 25		Monopile?	
68	NL	BARD NL 1	*2011*					400		60				
69	B	Thornton Bank	2012	REpower	126	5.00	27	135		25	27	59	Tripod?	
70	B	Bligh Bank	*2012*				66			40	20 - 35			
71	S	Sodra Midsjobanken	2012					1,000			50			
72	UK	Tunes Plateau						250			35			
73	UK	West of Duddon Sands						500						
74	UK	Humber Gateway	2012			3.60	83	299		8				
75	UK	London Array	2012			2.9	341	1,000		20	8 - 23			3,100
76	UK	Atlantic Array	2012				350	1,500		20				
77	UK	Walney	*2012*			4.50	102	459		14				
78	D	Arkonabecken	2014			5.00	80	400		32				

Sources: Wind Service Holland (Internet Source 32); Douglas Westwood, 2006

Appendix B Investment costs of offshore wind farms in Europe

The investment costs of 28 offshore wind which have been presented before in Appendix A may be put in perspective in a systemic way by applying Producer Price Indexes of countries of interest and by conversion to a common currency, viz. the Euro of 2006:

1. A Producer Price Index is used to convert an investment cost to a corresponding value for the year 2006 in the same currency - e.g., Danish Crown (DKK), Swedish Crown (SEK), British Pound (£) or Euro (€) - in which the investment cost was reported;
2. Aforementioned currencies of the year 2006 are converted to the common value of $€_{2006}$.

The result of this two-step approach for conversion of costs is shown below in Table B.1.

Table B.1 Main determinants and investment costs of338 offshore wind farms 1992-2010

№	Country	Project	On line	Capacity	Cumulative capacity	Investment cost	Specific investment cost
				[MW]	[MW]	[$M€_{2006}$]	[$€_{2006}$/kW]
1	S	Nogersund († 2007)	1990	0.22	0.22		
2	DK	Vindeby	1991	5.0	5.2	13.3	2,679
3	NL	Lely (offline 2006)	1994	2.0	7.2	5.5	2,770
4	DK	Tuno Knøb	1995	5.0	12.2	12.4	2,485
5	S	Bockstigen	1998	2.75	14.9	4.5	1,635
6	S	Utgrunden	2000	10.5	25.4	20.6	1,962
7	UK	Blyth	2000	4	29.4	6.3	1,570
8	DK	Middelgrunden	2001	40	69.4	52.6	1,315
9	S	Yttre Stengrund	2001	10	79.4	14.6	1,462
10	DK	Horns Rev	2002	160	239.4	291.3	1,821
11	DK	Samsø	2003	23	262.4	37.4	1,628
12	DK	Rønland	2003	17.2	279.6		
13	DK	Nysted	2003	165.6	445.2	287.6	1,737
14	DK	Frederikshavn	2003	10.6	455.8		
15	IRL	Arklow Bank	2003	25.2	481.0		
16	UK	North Hoyle	2003	60	541.0	123.3	2,055
17	UK	Scroby Sands	2004	60	601.0	114.1	1,901
18	UK	Kentish Flats	2005	90	691.0	158.6	1,762
19	D	Rostock - Breitling	2006	2.50	693.5		
20	UK	Barrow	2006	90	783.5	146.7	1,630
21	NL	Egmond aan Zee	2006	108	891.5	203.6	1,885
22	DK	Grenaa-harbour	2007?	8.25	899.8		
23	S	Lillgrund	2007	110	1,010.2	190.2	1,723
24	UK	Moray Firth	2007	10	1,020.2		
25	UK	Burbo Bank	2007	90	1,110.2	153.5	1,706
26	NL	Q7 (IJmuiden)	2008	120	1,230.2	376.3	3,136
27	D	Borkum West	2008	60	1,290.2		
28	UK	Lynn & Inner Dowsing	2008	194	1,484.6	434.8	2,237
29	B	Thornton Bank	2008	30	1,514.6		
30	UK	Robin Rigg	2009	180	1,694.6	465.0	2,583
31	DK	Horns Rev II	2009	200	1,894.6	456.2	2,281
50	UK	Rhyl Flats	2009	90	6,352.6	272.1	3,023
51a	UK	Gunfleet Sands I	2009	108	6,460.6	265.4	2,457
51b	UK	Gunfleet Sands II	2009	64.8	6,525.4	182.2	2,812
54	UK	Thanet	2009?	300	7,041.4	733.5	2,445
60	UK	Teesside	2011	90	8,056.4	200.0	2,222
75	UK	London Array	2012	1,000	14,795.2	2,210.5	2,210

Note: DK capital goods PPI, Swedish PPI, UK Manufacturing excl. foods PPI, NL machine industry PPI.

For the original cost data of Table B.1, the following sources have been used (Table B.2).

Table B.2 Literature/internet sources used for original cost data offshore wind Table B.1

№	Country	Project	On line	References
1	S	Nogersund († 2007)	1990	
2	DK	Vindeby	1991	Internet Source 33
3	NL	Lely (offline 2006)	1994	Internet Source 34; IEA, 2005a
4	DK	Tuno Knøb	1995	Madsen, 1996
5	S	Bockstigen	1998	Internet Source 35-36
6	S	Utgrunden	2000	Kühn et al, 2001; Internet Source 37
7	UK	Blyth	2000	New Energy, 2001; Internet Source 38
8	DK	Middelgrunden	2001	Larsen et al, 2005
9	S	Yttre Stengrund	2001	Internet Sources 39-40
10	DK	Horns Rev	2002	Frandsen et al, 2004
11	DK	Samsø	2003	IEA, 2005a
12	DK	Rønland	2003	
13	DK	Nysted	2003	IEA, 2005a; SEI, 2004
14	DK	Frederikshavn	2003	
15	IRL	Arklow Bank	2003	
16	UK	North Hoyle	2003	Internet Source 1
17	UK	Scroby Sands	2004	Internet Source 2
18	UK	Kentish Flats	2005	Internet Sources 3 and 41
19	D	Rostock - Breitling	2006	
20	UK	Barrow	2006	Internet Source 4
21	NL	Egmond aan Zee	2006	Shell Venster, 2005; Internet Source 32
22	DK	Grenaa-harbour	2007?	
23	S	Lillgrund	2007	Internet Source 5
24	UK	Moray Firth	2007	
25	UK	Burbo Bank	2007	Internet Source 6
26	NL	Q7 (IJmuiden)	2008	REW, 2007; Internet Source 42
27	D	Borkum West	2008	
28	UK	Lynn & Inner Dowsing	2008	Internet Sources 7-8
29	B	Thornton Bank	2008	
30	UK	Robin Rigg	2009	Internet Sources 9 and 43
31	DK	Horns Rev II	2009	Internet Source 10
50	UK	Rhyl Flats	2009	Internet Source 11
51a	UK	Gunfleet Sands I	2009	Internet Source 12 and 44
51b	UK	Gunfleet Sands II	2009	Internet Source 13
54	UK	Thanet	2009?	Moll, 2007; Internet Source 14
60	UK	Teesside	2011	Internet Source 15
75	UK	London Array	2012	Internet Sources 16 and 45

Based on these data of 33 offshore wind farms, Figure B.1 shows the development of the specific investment cost as a function of time. It turns out, just like (Isles, 2006) showed before, that the specific investment cost declines steadily until about 2003. Then, the specific investment cost increases relatively fast until today. With regard to the future cost of offshore wind, it seems that cost may come down again towards 2010 and beyond.

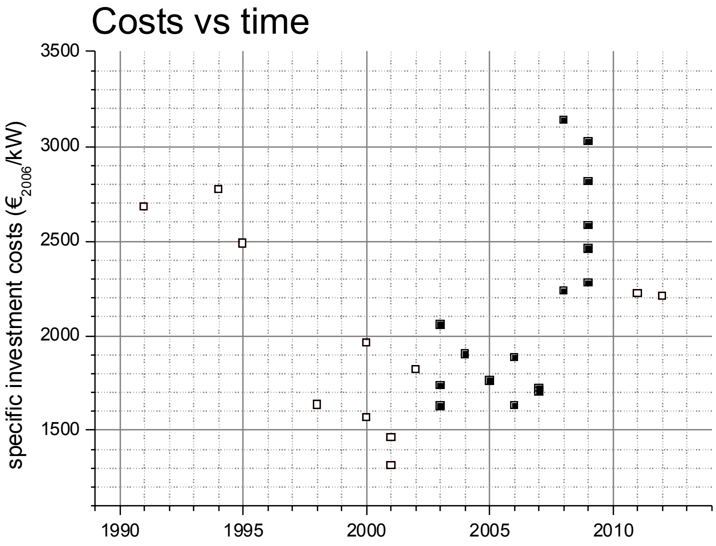


Figure B.1 Specific investment cost of offshore wind farms as a function of time

The costs may be presented on a log-log scale (Figure B.2). This Figure confirms the findings of (Isles, 2006). The cost increases which may be observed since about 2003 may be attributed to:

- Lack of competition amongst turbine manufacturers, as some of them withdrew from the market more or less recently, which was already noted by (Isles, 2006).
- Sharply rising prices for steel and copper (this study).
- Larger distance from the shore and increasing water depth.

The third factor mentioned above may be considered as structural, not temporary. However, competition among turbine manufacturers (factor one) will stiffen as the market for onshore wind becomes more saturated (Denmark, Germany). Also, prices of steel and copper may remain high for some time, but in the longer term not necessarily on the same high level as today.

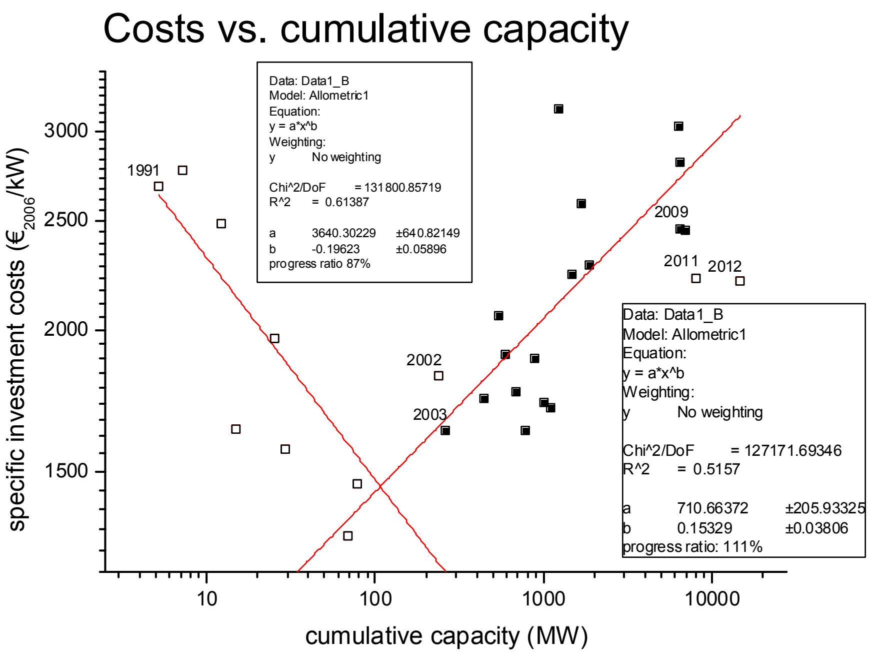


Figure B.2 Specific investment cost of offshore wind as a function of cumulative capacity

Appendix C CO_2 emissions, emission intensities, and the experience curve

In the publication ‘experience curves for energy technology policy’ (IEA, 2000) it is argued that the global economic system can be regarded as learning system with respect to CO_2 emissions intensity and global GDP. While giving no explanation about a theoretical framework that might be used to explaining the established functional relationship (see Figure C.1), a progress ratio of 79%is found, thereby indicating a decarbonisation rate of 21% for the global economy. Similarly, Nakicenovic (1996) calculates a progress ratio for the USA of 82% covering the period of 1850-1990.

We argue that both results do not capture the general relationship between CO_2 intensity and cumulative global GDP correctly. The results are not sufficiently underpinned by a sound theoretical explanation thereby falsely indicating a relationship between CO_2 emission intensity and cumulative GDP that cannot be found if time series data are extended. Analyzing CO_2 emissions and global GDP back until the year 1751, we find that carbon intensity does not decrease at a constant rate with each unit increase of cumulative global GDP (Figure C.1).

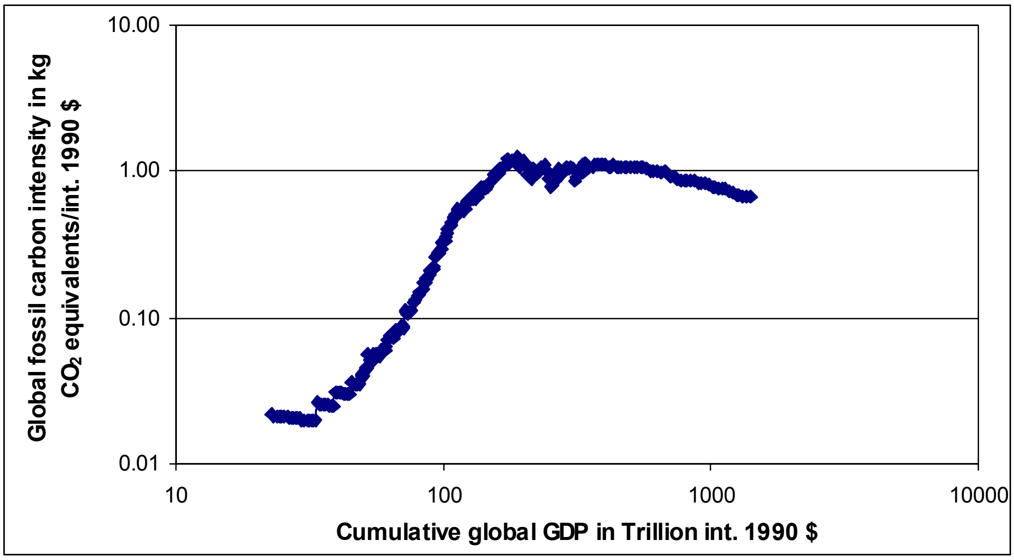


Figure C.1 Fossil carbon intensity and cumulative global GDP in the period of 1751-2004 (Data sources: Marland et al. (2007) and Maddison (2007))

We therefore argue that the dynamics of CO_2 emissions can not be modelled as a learning system. Figure C.1 indicates that emission intensities might not or not entirely depend on learning mechanisms but are rather a function multiple interacting factors such as availability and price of fossil energy carriers, technological development of the economy (e.g., the shift from biomass to fossil fuels as principle source of energy supply in the industrializing economies of the early 19th century), shifts in the structure of the economy (e.g., shift from agriculture to industry-dominated economy in the early and mid 19th century and from an industrial to a service economy at the end of the 20th century), and the general perception regarding climate change and the harmfulness of CO_2 emissions. The monetisation of CO_2 emissions as a consequence of, e.g., the EU emissions trading scheme suggest that we might find an experience curve-like relationship between CO_2 intensity and cumulative GDP for individual countries or regions in the most recent years. This relationship might, however, not be observed in all regions of the world (e.g., in emerging countries like China and India) because CO_2 emissions and even CO_2 emission intensities are likely to grow due to (i) the increasing consumption (in absolute and relative terms) of carbon intensive coal as energy source and (ii) the exclusion of CO_2 emissions as a direct cost factor for the economy.

Appendix D Assumptions for outlooks in Chapter 4.1

D.1 Assumptions for onshore & offshore wind:

	Unit	Onshore wind	Offshore wind
Global cumulative installed capacity in 2006	GW_e	63	0.514
Global cumulative installed capacity in 2010	GW_e	139	1.9[c]
Global cumulative installed capacity in 2020	GW_e	1000	50
Investment costs (base year)	$€_{2006}$ / kW	1170 (2001)	1880 (2003)
Optimistic/average/pessimistic PR	-	85/88.5/92	90/93.5/97
Annual O&M costs[a]	€2006/kW	39	80
Load factor [a]	hours	2200	3350
Economic lifetime[a]	years	15	15
Required project return[a]	%	6	11
Imbalance costs[a]	€ct/kWh	0.6	0.4
Average electricity production costs in 2007 of Dutch electricity park[d]	€ct/kWh	4	
Average CO_2 emission of Dutch electricity park[b]	kg/kWh	0.59	

a Based on van Tilburg et al. (2007).
b Based on de Jong et al. (2006).
c See Appendix B. For 2010, we took a conservative estimate (1.9 GW), assuming the extremely large offshore wind farms will be realized after 2010.
d Source: CBS/Statline, 2008, based on average costs 2000-2005.

D.2 Assumptions CCS NGCC and PC:

Progress ratios for various power plant technologies equipped with CO_2 capture technology (maximum ranges from sensitivity analysis) (Rubin et al. 2007).

	Capital costs	R^2	O&M costs	R^2	Cost of electricity	R^2
NGCC plant	97.8 (96.4-98.8)	0.96	96.1 (94.5-99.6)	1.00	96.7 (95.2-99.4)	1.00
PC plant	97.9(96.5-98.9)	0.97	94.3 (91.7 - 98.0)	0.99	96.5 (94.6- 98.5)	0.98
IGCC plant	95.0 (92.4 - 97.5)	0.99	95.2 (92.7 - 98.8)	1.00	95.1 (92.5 - 97.9)	0.99
Oxyfuel plant	97.2 (95.6-98.6)	0.97	96.5 (95.0-99.3)	0.99	97 (95.1 - 98.8)	0.98

Additional capacity
CCC scenario

Year	NGCC Plant		PC Plant	
	w CCS	w/o CCS	w CCS	w/o CCS
2001	0	0	0	0
2005	0	476	0	62
2010	1	741	1	136
2015	50	951	19	222
2020	200	940	57	324
2025	272	920	89	386
2030	348	848	245	374
2035	529	749	371	332
2040	621	645	468	284
2045	672	555	549	242
2050	680	477	606	206

Techno-economic parameters CCS plants excluding transport and storage

Plant type / Parameter	Scenario	Year 2001	Year 2010	Year 2020	Range 2010	Range 2020
NGCC (Post) Plant						
Efficiency (LHV)	Ref.	48%	53%	55%	52% - 55%	54% - 58%
	CCC	48%	53%	56%	52% - 55%	55% - 60%
Energy penalty (LHV)	Ref.	14.7%	13.4%	13.1%	13.3% - 10.1%	11.8% - 7.0%
	CCC	14.7%	13.4%	10.5%	11.4% - 7.1%	10.3% - 4.8%
Capital cost (€/kW)	Ref.	890.1	759.2	725.4	699.8 - 822.6	654.7 - 803.7
	CCC	890.1	759.1	638.3	699.7 - 822.5	518.2 - 752.1
O&M cost (€/MWh)	Ref.	3.9	3.7	3.6	3.4 - 3.9	2.1 - 3.5
	CCC	3.9	3.7	2.4	1.9 - 3.2	1.6 - 3.0
Fuel cost (€/MWh)	Ref.	46.7	41.9	40.6	40.3 - 42.8	38.0 - 41.3
	CCC	46.7	41.9	39.4	40.3 - 42.8	36.7 - 40.4
COE (€/MWh)	Ref.	58.3	51.7	50.0	51.0 - 51.8	45.1 - 51.8
	CCC	58.3	51.7	46.2	49.5 - 51.0	41.1 - 49.7
Mitigation cost (€/ton CO2)	Ref.	49.3	49.0	48.9	43.6 - 49.6	27.9 - 43.5
	CCC	49.3	49.0	34.2	22.7 - 39.7	17.6 - 36.8
PC (Post) Plant						
Efficiency (LHV)	Ref.	31%	32%	34%	31% - 35%	32% - 42%
	CCC	31%	32%	36%	31% - 35%	33% - 43%
Energy penalty (LHV)	Ref.	24.4%	23.7%	22.9%	23.6% - 20.5%	19.5% - 14.0%
	CCC	24.4%	23.7%	18.6%	20.3% 16.2%	18.2% - 12.8%
Capital cost (€/kW)	Ref.	1916.4	1821.1	1722.0	1773.1 - 1868.8	1629.9 - 1817.5
	CCC	1916.4	1821.0	1598.6	1773.1 - 1868.8	1424.5 - 1743.9
O&M cost (€/MWh)	Ref.	10.6	9.9	9.2	8.1 - 9.8	4.0 - 8.1
	CCC	10.6	9.9	5.4	3.5 - 7.6	2.3 - 6.7
Fuel cost (€/MWh)	Ref.	20.2	19.3	18.4	17.8 - 20.1	14.7 - 19.8
	CCC	20.2	19.3	17.5	17.8 - 20.1	14.5 - 19.0
COE (€/MWh)	Ref.	61.5	58.3	55.1	56.4 - 57.9	45.2 - 56.9
	CCC	61.5	58.3	48.4	51.7 - 55.6	39.7 - 53.5
Mitigation cost (€/ton CO	Ref.	31.8	33.0	33.9	38.4 - 31.5	25.5 - 26.8
	CCC	31.8	33.0	22.0	18.8 - 24.5	16.3 - 22.3

Further assumptions:

Technical parameters		Source
Natural Gas price (€(2006)/GJ(LHV))	6.2	CBS Statline, for 2005
Coal price (€(2006)/GJ(LHV))	1.7	CBS Statline, for 2005
Capacity factor	75%	Hoefnagels, 2008
Operation hours/year	6570	Hoefnagels, 2008
Cost of transport & storage (€ct/kWh)	0.3	Damen, 2007
Cost of transport & storage (€/tonne)	4	Damen, 2007
Financing		
Annuity	0.1174596	van Dril en Elzenga (2005)
Interest rate (%)	10	van Dril en Elzenga (2005)
Economic lifetime	20	van Dril en Elzenga (2005)
Exchange rate US$(2005) to Euro(2006	0.822199	OANDA.com

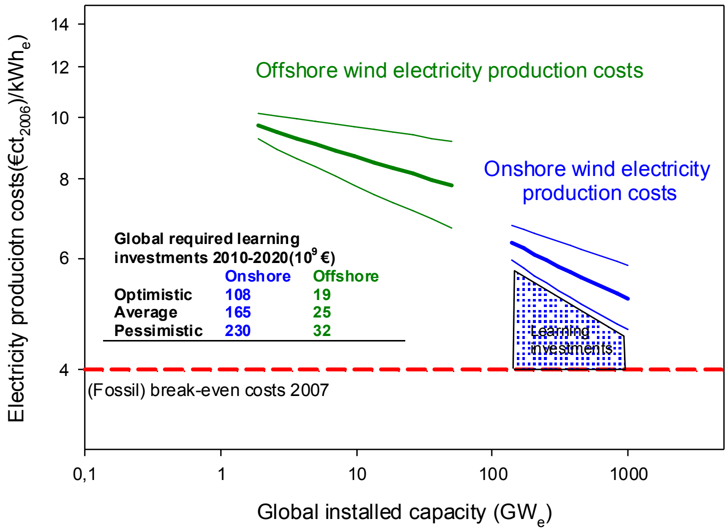
Appendix E Sensitivity analysis

To illustrate the effects of varying base parameters on the experience curves shown in Chapter 4, we briefly show the effects of three changing assumptions:

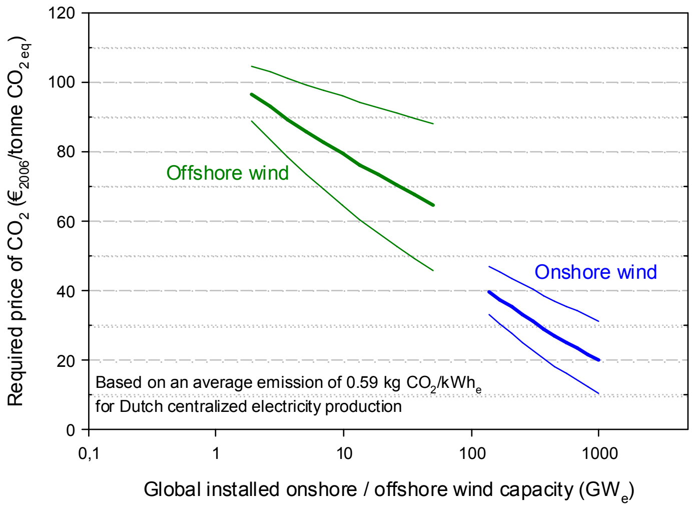
Base case	As described in Section 4 and Appendix D - based on current Dutch conditions.
Variant 1)	Coal, oil and gas prices continue to increase. The fossil fuel reference is therefore assumed to increase linear from 4 €ct/kWh in 2010 to 6 €ct/kWh in 2020.
Variant 2)	Technological learning for offshore wind farms results in increasing maturity of the technology, which in turn causes 'financial learning': the required project return for offshore wind farms decreases annually by 0.5% from 11% to 6% between 2010 and 2020.The project return for onshore wind remains 6%.
Variant 3)	Fossil fuel pries remains table, and electricity from onshore- and offshore wind farms is assumed to replace electricity from natural gas

For each variant, on the following pages the consequences for the resulting cost of electricity and the required price of CO_2 are presented graphically and briefly commented upon.

Base case



Required CO_2 price development 2010-2020



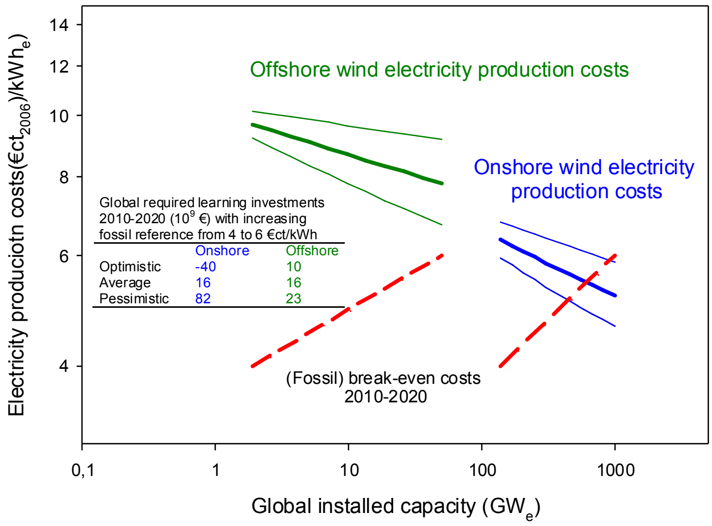
Comments
Note that the learning investments are only calculated for the period 2010-2020.
Hypothetical total learning investments from 2010 to reach break even at 4 €ct/kWh (in 10^9 €) are presented below:

	Onshore	Offshore
Optimistic	168	2013
Average	730	1271600
Pessimistic	11900	6300000000

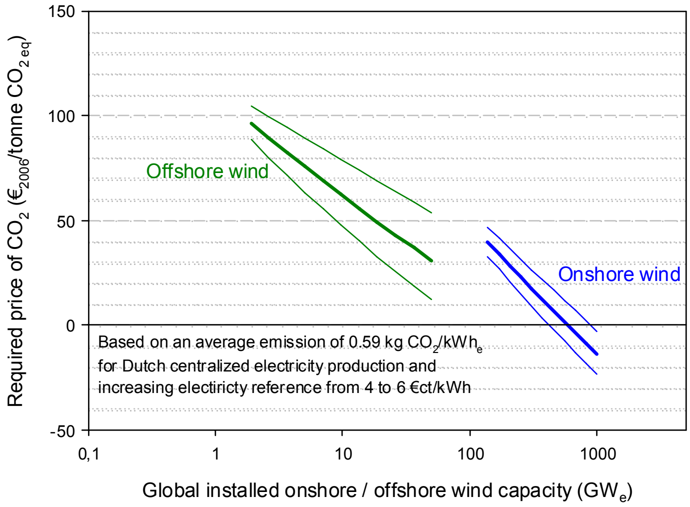
It should be clear these are hypothetical calculations. In reality, to reach a break even for offshore wind energy under the pessimistic scenario would require an installed a capacity of $1.8*10^{18}$ MW and a learning investment exceeding global GDP - clearly under such pessimistic assumptions, the development of offshore wind would cease.

Variant 1) Increasing reference electricity price from 4 to 6 €ct/kWh

Outlook for onshore & offshore wind 2010 - 2020

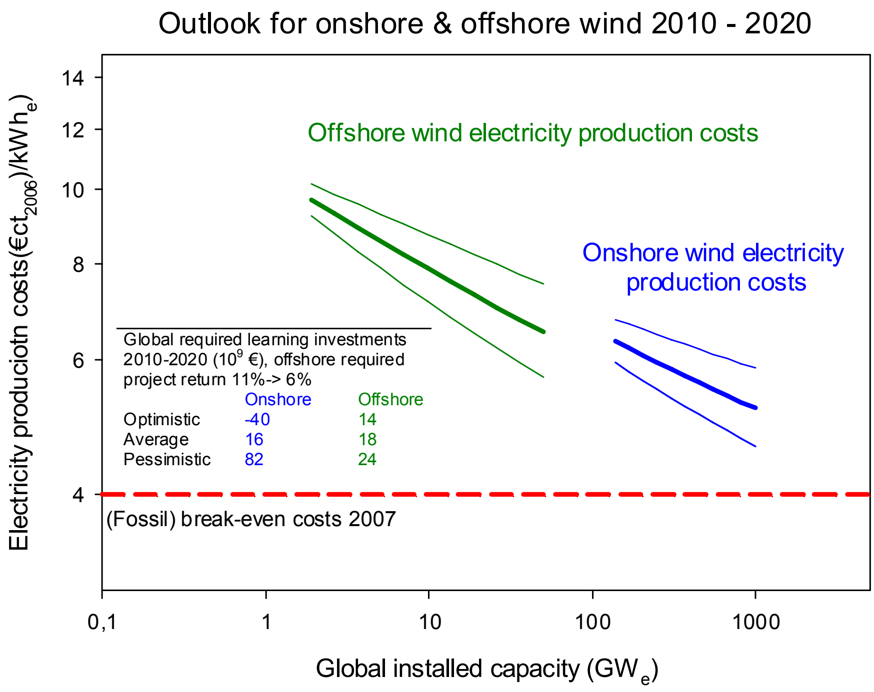


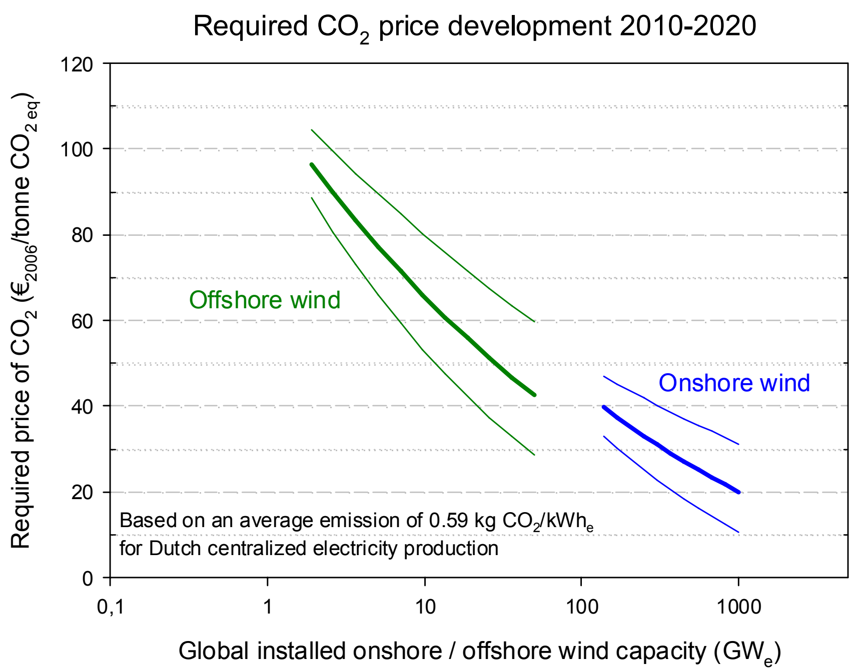
Required CO_2 price development 2010-2020



Comments:
Increasing baseline costs would be extremely beneficial for onshore wind farms, which would reach break-even point before 2020. For offshore wind, the gap to bridge would become considerably smaller, yet even under these favourable circumstances, a CO_2 price of 15-55 €/tonne would be required to make offshore wind competitive.

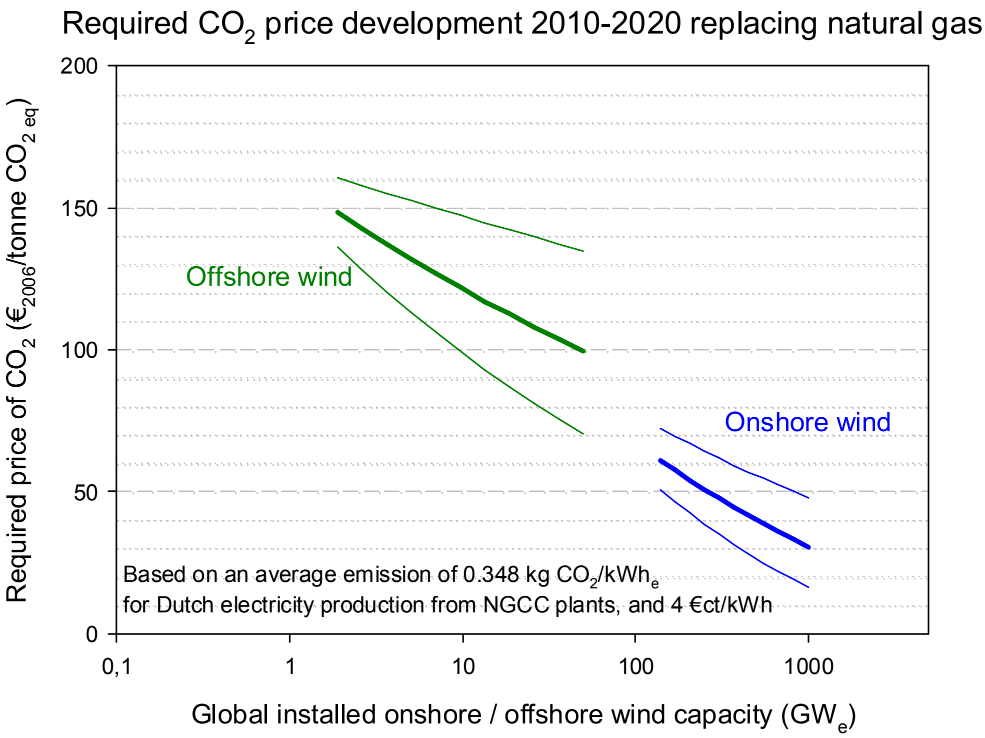
Variant 2) Required project return for offshore wind farms decreases from 11% to 6%





Comments:
Compared to the base-case electricity production costs of offshore wind farms decline far more rapidly, illustrating the importance of developing a reliable technology, which will gain the trust of investors to lower the required project returns.

Variant 3) Electricity from wind farms is assumed to replace electricity from natural gas



Comments:
Note that production costs of electricity from onshore and offshore does not change compared to the base scenario. Also the required learning investments remain the same as in the baseline variant, as the price of electricity in the fossil reference system was not assumed to change. The analysis illustrates the sensitivity of the assumption whether wind electricity will replace an *average* or *marginal* kWh produced. In case electricity from natural-gas fuelled plants is replaced, the required CO_2 price for onshore wind would on average double from 20 to 40 € / tonne.