Learning energy efficiency - Experience curves for household appliances and space heating, cooling, and lighting technologies

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Report NWS-E-2008-26
ISBN 9789086720309

Utrecht, 31 May 2008

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PREFACE

This report was commissioned by the Netherland's Ministry of Economic Affairs (Ministerie van Economische Zaken) and has been written by the Section of Science, Technology and Society, member of the Copernicus Institute, at Utrecht University, The Netherlands. Contact persons for the project are:

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The authors would like to thank all contributing authors for their valuable input into this research report. The authors thank furthermore Klaas-Jan Koops from the Ministry of Economic Affairs (Ministerie van Economische Zaken) for constructive comments and the very pleasant cooperation in the course of this research project. In addition, we would like to thank all participants of the policy workshop held at 25 September 2008 in Den Haag, The Netherlands. We acknowledge the valuable comments given by Hans-Paul Siderius from SenterNovem.

EXECUTIVE SUMMARY

Introduction and objective

Improving demand side energy efficiency is an important strategy for establishing a sustainable energy system. Large potentials for energy efficiency improvements exist in the residential and commercial buildings sector. This sector currently accounts for almost 40% of the European Union's (EU) final energy demand and offers the largest energy efficiency potentials among all economic sectors in the EU. The extent, to which existing efficiency potentials can be exploited, depends largely on the development, market implementation, and market diffusions of innovative novel and efficient technologies.

The market diffusion of novel technologies depends on a variety of factors[1], with up-front consumer investment costs, i.e., product prices being one of the most crucial. One *key barrier* for the market success of novel and efficient energy demand technologies is hence their high initial production costs. Novel technologies are often expensive at the phase of their market introduction but become cheaper with technological and organizational progress, upscaling of production – i.e., with technological learning and the gaining of experience in manufacturing processes and subsequent value chains. Technological learning is hence a *key driver* for realizing both cost reductions and efficiency potentials related to efficient energy demand technologies. It is hence of vital importance for strategic decision making to gain detailed insight into the rate of past cost reductions and into future cost reduction potentials for relevant energy demand technologies.

The dynamics of historic and future production costs can be analyzed with the so called *experience curve* approach. Experience curves model total production costs of a product or technology as function of cumulative production. Empirical experience curve analyses for numerous products indicate that production costs decline at a constant rate with each doubling of cumulative production. The experience curve concept has been extensively applied to and refined for *energy supply technologies* such as photovoltaics, on- and off-shore wind energy, and the use of biomass (IEA, 2000, McDonald and Schrattenholzer, 2001, Goldemberg, 2004, Junginger, 2005). The application of the experience curves approach to efficient *energy demand technologies* is, however, still scarce (e.g., Clair, 1983, Newell, 2000, Laitner and Sanstad, 2004).

The objective of this research project is to apply the experience curve approach to efficient energy demand technologies in the residential and commercial buildings sector. We select the following technologies for our analyses:

- Condensing gas boilers (*HR-Ketels*)
- Micro-CHP systems (*HRE-Ketels*)
- Heat pumps for residential space heating (*Warmtepompen*)
- Hot and cold storage systems (*Warmte en koude opslag*)
- Compact fluorescent light bulbs (*Spaarlampen*)
- Household appliances (washing machines, laundry dryers, refrigerators, freezers)

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[1] Next to market prices, factors such as compliance with existing legal and technical standards, consumer awareness and preferences, as well as user friendliness are important criteria for the market success of technologies.

Our choice is based on data availability and the potential contribution of the selected technologies to energy savings and efficiency improvements within the residential and commercial buildings sector of the Netherlands. By analyzing the cost dynamics of the selected technologies with the experience curve approach, we aim at quantifying technology-specific *learning rates*. Further objectives of our research are:

- to explain drivers and factors that cause the observed cost dynamics based on *bottom-up* technology assessment;
- to improve our understanding of critical methodological and empirical problems that are related to the application of the experience curve approach to energy demand technologies;
- to evaluate need and scope for policy interventions;
- to develop a list with conclusions relevant for policy makers.

For heat pumps, compact fluorescent light bulbs (CFLs), and household appliances, we extend the conventional experience curve approach and model COP (heat pumps), luminous efficacy (CFLs), and water and electricity consumption (household appliances) as a function of cumulative production, respectively. To our knowledge, this methodological extension was not made before.

In the case of condensing gas boilers and CFLs, we, furthermore, analyze, e.g., cost effectiveness and realized savings of energy and CO_2 emissions in the Netherlands. The results of this research are important for policy makers because they:

- provide a rationale for predicting future cost reduction potentials for efficient energy demand technologies;
- allow to analyze the cost effectiveness of novel and efficient energy demand technologies;
- allow to identify need for policy support for energy demand technologies.
- contribute to an evaluation of governmental technology support programs;
- allow to analyze the contributions of energy demand technologies to economy-wide energy efficiency improvements, energy savings, and CO_2 emission reductions;

Methodology and data sources

Approaches to quantify technological learning date back until 1936 when Wright (1936) found unit labour costs in airframe manufacturing to declined at a constant rate with each doubling of cumulative production. In 1968, the Boston Consultancy Group extended the concept of technological learning by analyzing the dynamics of total production costs in a *black box model* as function of cumulative production (BCG, 1968). The Boston Consulting Group found that with each doubling of cumulative production, total production costs decline at a constant rate. To distinguish their cost analysis from the analysis of labour costs, a new terminology was introduced. The graphical representation of *labour costs* as a function of cumulative production was and still is generally referred to as *learning curve*, the analysis of *total production costs* is referred to as the *experience curve*.

The principle relationship between production costs and cumulative production as it is hypothesized by the experience curve approach can be mathematically expressed as:

$$Ccum_i = C_{0,i} \cdot (Pcum_i)^{b_i}$$

where $Ccum_i$ represents the production costs of product *i*, $C_{0,i}$ the cost of the first unit of product *i* that is produced, $Pcum_i$ the cumulative production of product *i*, and b_i the product-specific experience index. Logarithmizing both sides of the equation yields a linear equation with b_i as slope parameter and log $C_{0,i}$ as intercept:

$$\log Ccum_i = \log C_{0,i} + b_i \cdot \log Pcum_i$$

Based on the slope parameter b_i, technology-specific *progress ratios* (PR_i) and *learning rates* (LR_i) can be defined as rates at which cost decline with every doubling of cumulative production:

$$PR_i = 2^{b_i} \qquad \text{and} \qquad LR_i = 1 - PR_i = 1 - 2^{b_i}$$

Learning rates for energy supply technologies typically range between 5% and 20% (IEA, 2000, McDonald and Schrattenholzer, 2001, Junginger, 2005), thereby indicating a decrease of production costs by 5-20% with each doubling of cumulative production.

In our experience curve analysis, we uniformly approximate *production costs* by publicly available *price data*. We uniformly deflate nominal prices to the level of the Euro in the year 2006. The use of price data as proxy for production costs introduces uncertainties to our results, if profit margins of producers are not constant within the analyzed time periods.

We partly approximate cumulative production by data on cumulative sales or cumulative installed capacities. We base our estimates on publicly available capacity, production, and sales data as made available by producer organizations, national and international production statistics, and personal communications with industry experts. We partly use inter- and extrapolation to generate estimates for years, in which no data are available to us. There are several features, which complicate (i) experience curve analyses and the calculation of meaningful learning rates for energy demand technologies and (ii) the use of experience curve results for policy making:

- Analyzing long time periods often implies changes in technology components, leading to inconsistencies in the analyzed product system. This point is especially relevant for the analysis of household appliances, which eventually provide a service (e.g., laundry cleaning) by a product that differs technically from the one manufactured 30 or 40 years before.
- Analyzing long time periods can lead to the situation that the same product provides additional services (e.g., washing machines do no longer only wash clothes but they offer specific washing programs to clean and centrifuge dry various types of laundry).

- Outsourcing of production to low-wage regions is often observed for energy demand technologies and leads to considerable cost reductions. These reductions can, however, often only be realized ones and might not be continued or repeated in future years. Similarly, prices of energy and materials have a considerable impact on total production costs but change at the same time independently from technological learning in the manufacturing of a technology. High volatility of prices for production factors (e.g., increase in steel prices or decrease of labour costs due to outsourcing of production to low wage regions) might cancel out or even exceed actual learning effects. Price changes of production factors are generally e*xogenous* to the learning system and introduce considerable uncertainty in the experience curve analysis, especially, if results are used for projecting future production costs.
- The definition of the system boundary for the learning system is often challenging. We typically find that in early years, products are usually developed and implemented at the domestic market with little or no exogenous influences from outside a company or a country. As the market grows, exogenous influences increase and result in technology spillover from markets in other countries or regions of the world. By establishing the system boundaries (e.g., cumulative production in the Netherland, Europe, or in the entire World) for the various technologies, we try to account for these dynamics as far as possible.
- Reducing production costs (for example in the research and development phase or during pilot testing prior to market introduction) does not *per se* imply that products will be successful at the market because product image, consumer convenience, user friendliness, and product design are criteria that are important for the market success of energy demand technologies while they are less relevant for energy supply technologies.
- Compared to the features just mentioned, energy efficiency is often of secondary importance for energy demand technologies. This is a major difference compared to energy supply technologies where conversion efficiencies and the resulting costs per unit energy (e.g., electricity) produced are the most important criteria for the market success of a technology.

An important methodological extension of the experience curve concept was applied for heat pumps, CFLs, and household appliances. For these technologies, we model not only production costs but also efficiency as a function of cumulative production. This methodological extension is new and was not done before. From the analysis, we expect additional insights into the dynamics of energy (and water) efficiency. For extending the conventional experience curve approach, we make use of publicly available data on energy (and water consumption in the case of washing machines), which we supplement by estimates based on data inter- and extrapolation.

In the following sections of the *Executive summary*, we present the results for each of the analyzed technologies individually. Afterwards, we draw general conclusions that are relevant for policy makers.

Condensing gas boilers (*HR-Ketels*)

Compared to conventional boilers, condensing gas boilers offer substantial savings of energy and related CO_2 emissions. Condensing gas boilers cool the flue gas by (an) additional heat exchanger(s) to such an extent that condensation occurs. This allows for utilizing both the heat of the flue gas and the latent heat contained in the flue gases' water vapour. Condensing gas boilers reach efficiencies up to 107% LHV (compared to 75-90% LHV of conventional non-condensing boilers) but require an additional ventilator for flue gas removal and a connection to the sewage system for the discharge of condensate.

Condensing gas boiler were developed in the Netherlands and introduced to the Dutch boiler market in 1981. Market shares remained, however, below 15% until 1990 due to several constraints:

- The price of condensing gas boilers as well as installation, and maintenance costs remained relatively high compared to conventional, non-condensing boilers.
- Energy, i.e., natural gas prices were still too low for making consumer investments in this innovative boiler technology attractive.
- Product reliability was low in the years after market introduction.
- Training and experience of installation companies was insufficient.

Once initial problems were solved, condensing gas boilers gained considerable market shares in the early 1990s. Factors contributing to this development include also:

- the granting of subsidies;
- the change from open to closed boiler systems that caused a considerable price increase of conventional non-condensing gas boilers;
- the introduction of energy standards for newly built houses, which could be reached by installing condensing gas boilers.

By 1996, condensing gas boilers reached market shares of more than 50% and in the year 2000, market shares exceeded even 80%. Nowadays condensing gas boilers are the standard boiler technology of the Netherlands.

We construct experience curves separately for condensing gas space heating boilers and for condensing gas combi boilers (i.e., boilers that provide both space heating and hot tap water). Based on Dutch boiler prices and cumulative boiler sales in the Netherlands, we identify learning rates of (7.0 ± 0.9)% for condensing gas space heating boilers and (14.0 ± 1.2)% for condensing gas combi boilers (Figure S1).

The difference between the learning rates for space heating and combi boilers can be explained by the additional experience that was gained by integrating hot water units into space heating boilers. Our results are in line with the learning rates found for other energy technologies (i.e., 15-18% for on-shore wind farms (Junginger, 2005), 22% for photovoltaics (McDonald and Schrattenholzer, 2001), 8% for electricity production from bio-fuelled CHP plants (Junginger, 2005) but somewhat higher than the learning rate of 4% that was identified by Haug et al. (1998) for condensing gas boilers. We attribute the latter differences to deviations regarding system boundary and time period analyzed.

We explain the observed cost, i.e., price reductions with:

- upscaling of condensing gas boiler production;
- improved efficiency and automation of boiler production;
- size reduction (i.e., decrease of material consumption) for heat exchangers
- improvements in control electronics;
- optimization of boiler components (burners, pipes, pumps) and internal boiler settings;
- outsourcing of component production since 2000 to specialized companies and component manufacturing in low-wage countries.

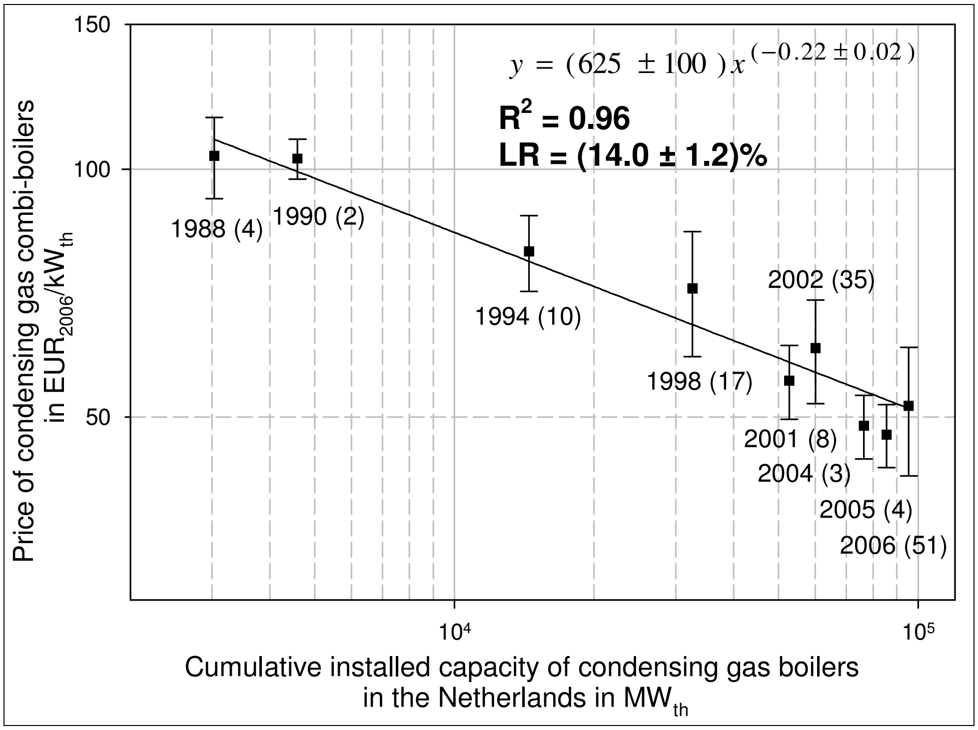

Figure S1: Experience curve for condensing gas combi boilers in the Netherlands (period of 1988-2006; error bars indicate the standard deviation of price data; in brackets number of data included in the respective year of analysis)

In the recent past, the development in condensing gas boiler manufacturing was driven by mergers of boiler producers. These offer further potentials for upscaling of production processes and the removal of barriers for technology spillover.

The replacement of conventional boilers by condensing gas boilers saves energy and CO_2 emissions. In 2005, natural gas savings due to the installation of condensing gas boilers amount to 1.47 Mt CO_2 in the Netherlands. These savings are equivalent to 0.9% of the total Dutch fuel use emissions (UNFCCC, 2007). In the total time period of 1981-2006, condensing gas boilers saved natural gas equivalent to roughly 13.5 Mt CO_2, 7.2 billion m^3, or 2.7 billion EUR. These savings can be compared to the total additional costs of 1.6 billion EUR at the consumer side for purchase, installation, and maintenance of condensing gas boilers and ~70 million EUR subsidies spent (partly) by the Dutch government in support of condensing gas boilers. Combining subsidies, consumer costs, and natural gas savings, we estimate *net* savings of ~1.0 billion EUR or 75 EUR/t CO_2 that was not emitted. This result demonstrates the high cost efficiency of condensing gas boilers.

Based on the presented cost and saving calculations, we estimate yearly consumer cost savings for condensing gas boilers. In the period of 1981-2006, additional costs for purchase, installation, and maintenance of condensing gas boilers declined considerably compared to conventional non-condensing boilers (Figure S2).

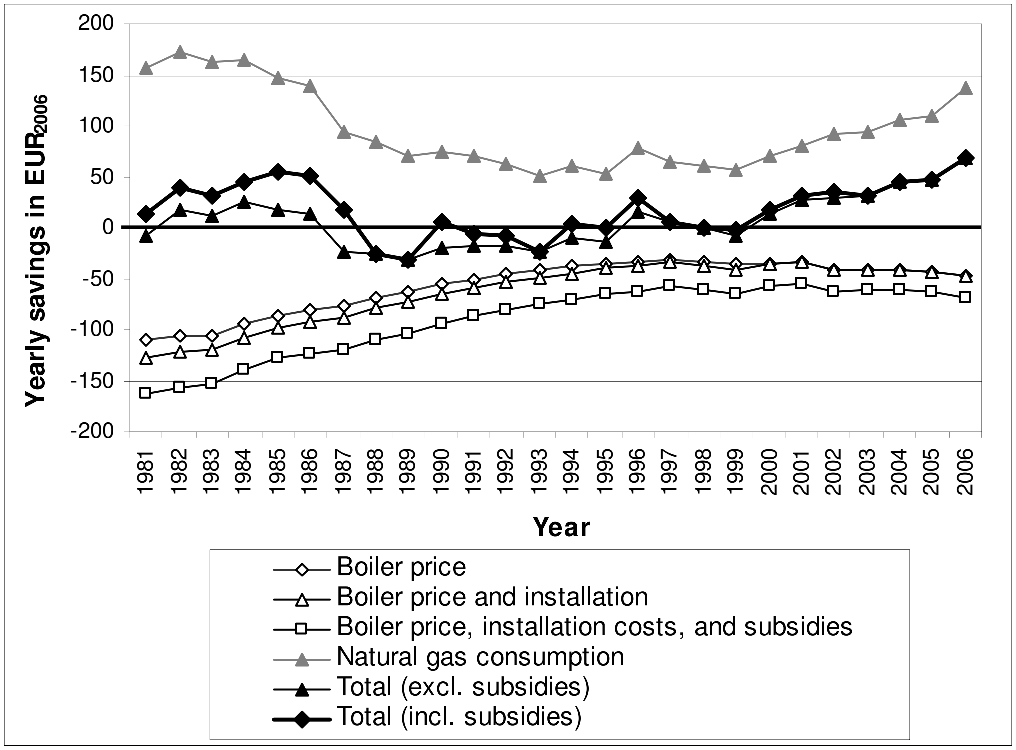

Figure S2: Yearly inflation corrected cost savings of condensing gas space heating boilers in the Netherlands (standard savings scenario)

At the same time, savings of energy costs increased since the early 1990s, contributing to overall yearly cost savings of up to 70 EUR in recent years. Based on the results presented in Figure S2, we draw the following conclusions:

- The purchase of a condensing gas boiler has been profitable for average Dutch households in most years.
- Energy prices boiler efficiencies have a considerable effect on the achieved yearly cost savings.
- Condensing gas boilers generate *net savings* for consumers of up to 70 EUR per year.
- Subsidies have been important to improve the profitability of condensing gas boilers in early years (i.e., 1987-1993) when natural gas prices were comparatively low.

Analyzing payback times for condensing gas boilers on a more disaggregated level with the Dutch Residential Model, we find for the majority of households payback times of less than 15 years (i.e., shorter than the lifetime of condensing boilers). While payback times have been above 15 years for 30% of Dutch dwellings at the end of the 1980s (thereby indicating that condensing gas boilers cannot recover their additional costs within lifetime), we find for later years that additional costs for condensing gas boilers can be recovered within 3-4 years after purchase by all households. Subsidies helped to make condensing gas boilers profitable for households with relatively little natural gas consumption.

We conclude that the experience curve approach is applicable for condensing gas boilers in the Netherlands, thereby indicating a considerable reduction of production costs. Our results show that subsidies helped to make the purchase of condensing gas boilers profitable for consumers and offered opportunities for product innovation in the Dutch industry. Relatively limited policy support (i.e., ~70 million EUR):

- achieved very cost effective reduction of energy consumption and CO_2 emissions (i.e., cost savings of roughly 75 EUR/ t CO_2 saved);
- contributed to the success of an innovative and efficient energy demand technology on the Dutch and European market;
- supported Dutch boiler manufacturers in becoming technology leaders.

However, the example of condensing gas boilers in the Netherlands also shows that governmental technology support might need a long breath (i.e., more than a decade) and favorable boundary conditions (e.g., high energy prices) to make an innovative energy demand technology a success story.

Micro-CHP systems (*HRE-Ketels*)

Micro-CHP systems produce both heat and power at small scale with electrical capacities typically being in the range of 1-5 kW_e. In this research, we focus on micro-CHP systems that use a Sterling engine of around 1 kW_e for electricity production. These systems are currently tested in a pilot project and might be introduced to the Dutch market by 2008. Boiler producers and the gas supplier GasTerra regard micro-CHP systems as follow-up technology for the condensing gas boilers in the Netherlands. Micro-CHP systems are, however, very expensive and it remains questionable whether the additional costs (i.e., projected 6,000 EUR at the point of market introduction) can be recovered by consumers through energy savings in a reasonable amount of time. Policy support might hence be needed in the first years after market introduction.

Historic experience curves cannot be constructed for micro-CHP systems. Based on a market and price scenarios provided by the *Werkgroep Decentraal* (WGD, 2007), we, however, perform an analysis for achievable cost reductions, market diffusion, and requirements for governmental subsidies. Based on information from Ruijg (2005) and MBC (2007), we conduct a sensitivity analysis, using less optimistic assumptions regarding initial market price (10,000 EUR instead of 6,000 EUR) and energy cost savings (acceptable additional price of 900 EUR rather than 1,500 EUR for achieving a payback time of 5 years).

Using market and cost projections as published by WGD (2007), we identify projected learning rates of (i) (16.1 ± 1.9)% for the additional costs (i.e., costs associated with the sterling engine and its integration into a *more or less* conventional condensing gas combi boiler) and of (ii) (12.2 ± 1.1) % for the total price of micro-CHP systems. In view of the results for other technologies (e.g., condensing gas combi boilers), we regard the identified learning rates reasonable. We performed an uncertainty analysis based on the data provided by WGD (2007) (low-cost scenario) by introducing error margins of ± 5% to the identified learning rates. The results of this analysis show that only small changes in learning rates have a considerable effect on the additional costs for micro-CHP systems, i.e., limiting the period in which subsidies are required until 2012 or extending the period until 2030 (Figure S3).

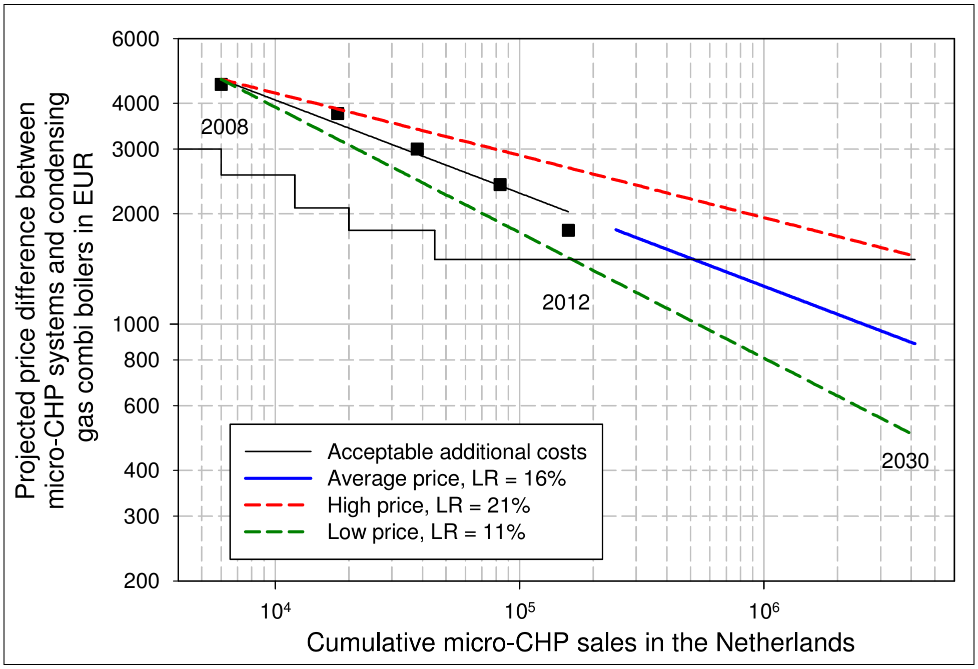

Figure S3: Sensitivity analysis – low-cost scenario: Experience curve for the additional price of micro-CHP systems compared to average condensing gas combi boilers; numbers in the diagram indicate the year, which the data refer to; market growth and acceptable additional consumer price as assumed in Table 10. The area between the acceptable additional costs line[2] and the projected price difference indicates the required subsidies for micro-CHP systems (Data source: WGD (2007))

While the projected learning rate (for additional costs of micro-CHP systems) is in range with our findings for condensing gas boilers, the assumed market penetration rates, i.e., the growth of yearly micro-CHP sales, seems very optimistic. Historic experience with condensing gas boilers and other novel and expensive efficiency technologies show that market growth was generally much slower than the growth being

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[2] The acceptable additional costs are higher than 1,500 EUR in the period 2008-2012 because it is assumed that (i) early adopters are willing to accept higher payback times than the average Dutch households and that (ii) micro-CHP systems are first installed in houses with above average heat demand and natural gas consumption.

predicted for micro-CHP systems. The resulting price reductions for micro-CHP systems of 60% within 4 years after market introduction appear to be extremely high. Comparable rates of yearly price reductions have not been observed for other technologies analyzed in this report. Given the results presented in Figure S3, we regard it likely that:

- the *total* amount of subsidies required for micro-CHP might be in the range of 120-160 million EUR (see also Figure S4);
- the *time period* in which the total amount of subsidies has to be paid is likely to be substantially longer than predicted by WGD (2007).

Considerable deviations from the average estimates of *total* required subsidies are possible, if micro-CHP systems learn slower or faster, i.e., if the learning rate is lower or higher than the projected 16% and if the assumptions presented by WGD (2007) do not hold. Our sensitivity analysis results in extremely high subsidy requirements, if the initial market price of micro-CHP systems is higher than the projected 6,000 EUR and if the achievable energy cost savings are lower than projected. In our high-cost scenario, we calculate subsidy requirements of well beyond one billion EUR for the case (i) that the initial micro-CHP price is 10,000 EUR at the point of market introduction and (ii) that the achievable energy cost savings are lower than projected, i.e., resulting in an acceptable additional price of only 900 EUR instead of 1,500 EUR. This result would seriously question the economic feasibility of micro-CHP systems, if the assumptions made for the high-cost scenario calculations hold in future years.

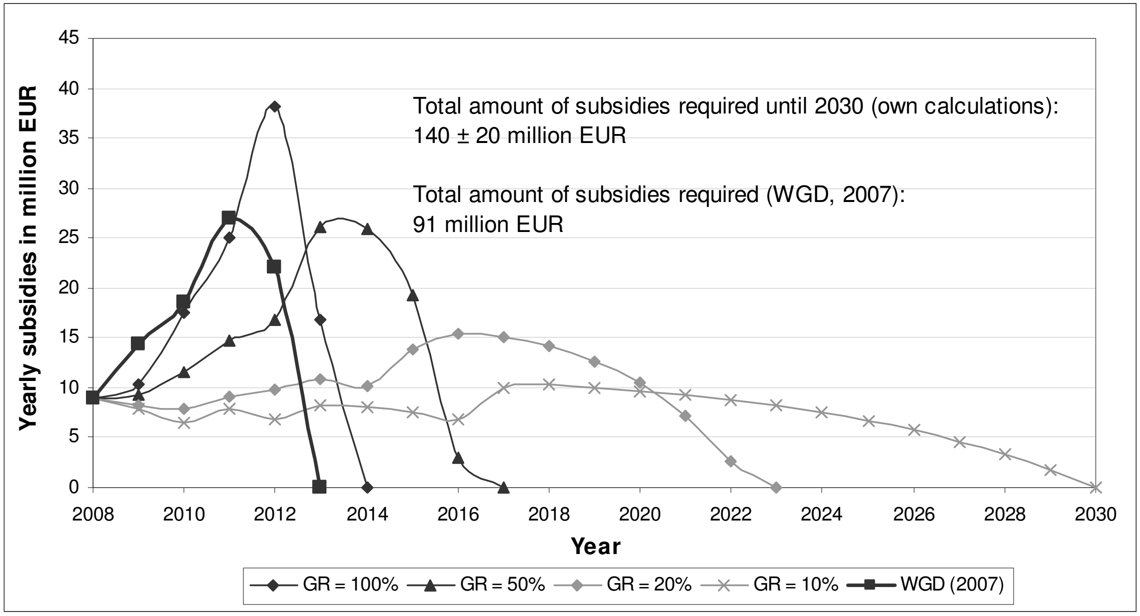

Figure S4: Sensitivity analysis – low-cost scenario: Required subsidies for micro-CHP systems under various market growth scenarios; assuming an initial additional price of 6,000 EUR, market growth rates (GR) of 10% - 100% and a learning rate of 16% for the additional costs of micro-CHP systems compared to condensing gas boilers

The results presented for micro-CHP systems are based on a relatively simple sensitivity analysis, using the assumptions as stated by WGD (2007) as well as data provided by Ruijg (2005) and MBC (2007). A more detailed analysis that addresses the uncertainties related to the assumptions made can yield more comprehensive projections for cost reductions and subsidy requirements. Such an analysis should also differentiate different household types, thereby generating more detailed and reliable estimates of the market potential of micro-CHP systems in the Netherlands.

Heat pumps (*Warmtepompen*)

Heat pump technology has been used for a long time in refrigerators and air conditioning systems. The basic principle of a heat pump is the transfer of heat from a cold reservoir to a hot one by adding work to the system. Heat pumps can use various heat sources, i.e., ambient air, the underground (bedrock, soil), or groundwater.

The use of heat pumps for energy efficient space heating received first attention during the years of the first oil crisis. In Western Europe, heat pump markets for residential heating developed in the late 1970s relatively autonomous from each other in individual countries. In many of these (e.g., Austria, France, Germany) we find heat pump sales to increase steadily in the years around and after the second oil crisis (1979-1980). The heat pump market collapsed, however, in the mid to late 1980s due to low energy prices and reliability problems and began only to increase in the late 1990s spurred again by rising energy prices and the need to reduce energy related CO_2 emissions. By the year 2002, heat pump capacity in the residential sector reached 110 MW_{th} in the Netherlands. Heat pumps are, however, still not cost competitive for many applications and constitute only a niche in the national heating market. Two main types of heat pumps for residential heating can be distinguished (i) electricity-driven vapour compression heat pumps and (ii) gas-fired absorption heat pumps.

In the course of this project, it became apparent that time series data for heat pump sales are available for many European countries but price data are scarce to non existent (especially for years before 1995). Large parts of the openly available price and market data on heat pumps were already published by Martinus et al. (2005). We base our experience curve analysis on heat pump data available from Switzerland. We model not only costs but also energy performance (i.e., the COP) as an exponential function of cumulative production.

Swiss price and production data indicate a reduction of production costs at the rate of 25-42% with each doubling of cumulative production (see example given in Figure S5). The functional unit chosen as independent variable for our experience curve analysis has a considerable effect on the identified rate of cost reduction. For the German heat pump market, Martinus et al. (2005) found learning rates of 30% (based on cumulative MW_{th} installed) for industrial heat pumps indicating also a similar decline of production costs for heat pumps in the period of 1980-2002.

By extending the conventional experience curve approach, we find the coefficient of performance (COP) of Swiss heat pumps to increase at a rate of (13.8 ± 1.8)% (Figure S6) with each doubling of cumulative production.

This finding indicates an increase in the energy efficiency of heat pumps. The coefficient of determination is, however, relatively low ($R^2 = 0.58$). Our finding is thus subject to considerable uncertainties.

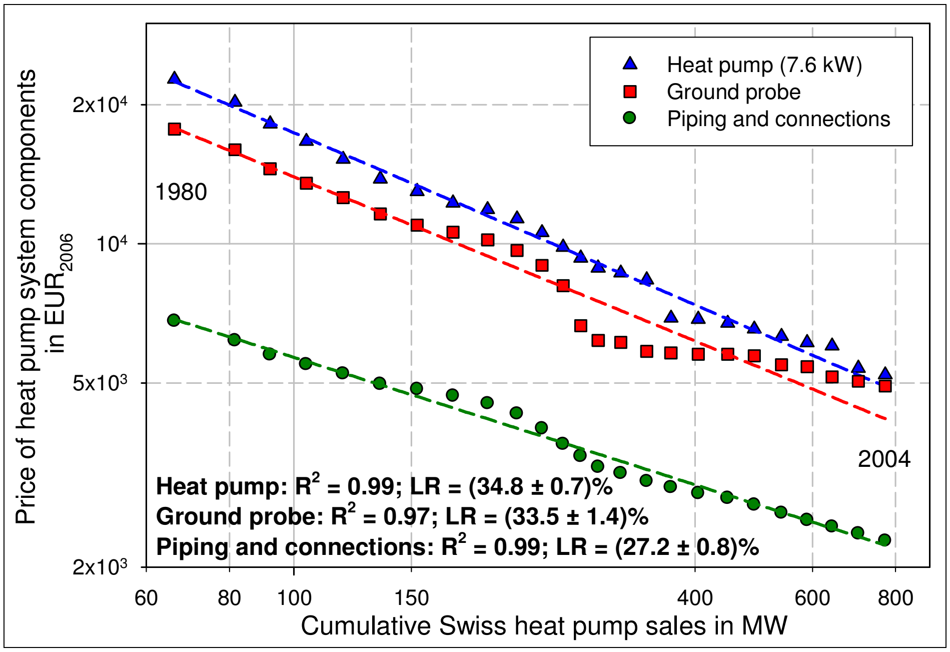

Figure S5: Experience curve for the components of heat pump systems in Switzerland covering the period of 1980-2004 (Data source: FWS (2007))

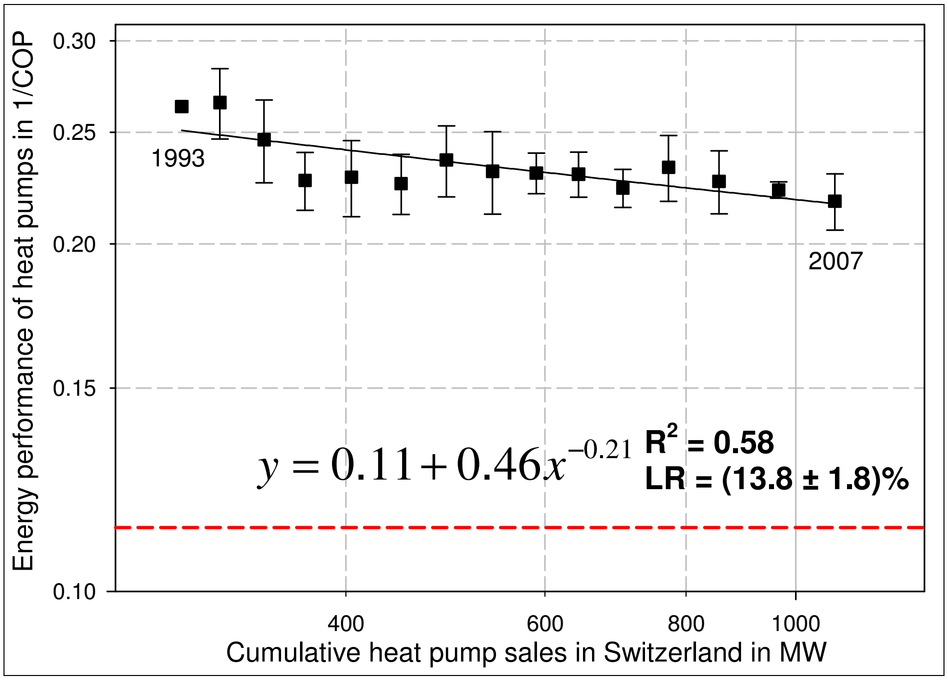

Figure S6: Experience curve for the COP of Swiss heat pumps; period of 1993-2007, the dotted red line indicates the thermodynamic maximum COP at given test conditions (Data sources: FWS (2007), WPZ (2008))

Combining cost and COP experience curves, we construct an experience curve for costs per kWh heat produced. We find an average learning rate of (27.7 ± 0.8)%. This finding indicates a considerable drop in consumer costs for heat pumps per unit of heat produced. A comparison of the costs of roughly (0.14 ± 0.02) EUR/kWh$_{th}$ in 2007 with the consumer costs of condensing gas boilers (0.08 EUR/kWh$_{th}$) shows however that heat pumps are not yet cost competitive in the Netherlands.

We regard the experience curve approach applicable to heat pumps, albeit with the limitation that data availability is scarce. It therefore remains uncertain, to what extent the cost decrease observed for Switzerland is also representative for residential heat pumps in the Netherlands. This question should be clarified by research, for which access to confidential data on heat pumps that are sold in the Netherlands is required.

Hot and cold storage systems (*Warmte en koude opslag*)

Hot and cold storage systems (also referred to as aquifer thermal energy storage systems) use in most cases the thermal energy of groundwater for space heating and cooling. The basic principle of a hot and cold storage system is rather simple: Groundwater is pumped via wells from the aquifer to the building, its heat content is extracted by heat exchangers, and the water is finally discharged to the aquifer. The uptake and discharge of water generates bodies of warm and cold water in the aquifer. Depending on the demand for cooling or heating, the pumping cycle can be reversed. There are several types of well configurations possible (e.g., mono-, doublet-, multiple-well systems). Due to relatively high installation costs, hot and cold storage systems are installed mainly in large commercial buildings, e.g., offices, hospitals, or universities.

The average capacity of hot and cold storage systems in the Netherlands is about 1 MW$_{th}$. In the 2006, a total of 500 hot and cold storage systems (mainly mono-well and doublet systems) with a combined capacity of 743 MW$_{th}$ were installed in the Netherlands. This capacity contributes to yearly savings of 625 TJ primary energy and 43 kt CO$_2$ (CBS, 2007b). In most recent years, rising energy prices made hot and cold storage systems also attractive for application in smaller buildings.

We limit our analysis to the Netherlands because the number of hot and cold storage installations in other countries is negligible (Willemsen, 2007). The Netherlands can therefore be considered to some extent autonomous with respect to the development of hot and cold storage technology.

First demonstration projects date back until 1985. Due to limited data availability, our analysis covers, however, only the time period of 1992-2007. We cover a total of 202 hot and cold storage systems, representing roughly 40% of all Dutch hot and cold storage installations. In our analysis, we include cost estimates for the installation of the *primary* system, i.e. for heat exchanger, control system, underground piping, piping from the aquifer to the heat exchanger, and for the groundwater filter. We exclude costs that are related to the heating system of buildings.

Establishing experience curves for hot and cold storage systems is complicated by the selection of a meaningful measure for cumulative experience. The parameter of cumulative number of installations is not suitable because it does not adequately account for variations in the size of hot and cold storage installations. Parameters such as cumulative capacity and water flux density depend to some extent on exogenous, non-technology-related parameters such as groundwater quality and permeability, depth and inclination of the aquifer.

The data on absolute installation costs that are included in our analyses show a wide range from 8,000 EUR_{2006} to 3.0 million EUR_{2006}. Our experience curve analysis yields both, trends towards increasing and decreasing average installation costs (i.e., learning rates between -22% and 12%) depending on the functional unit chosen (see one experience curve for hot and cold storage systems in Figure S7).

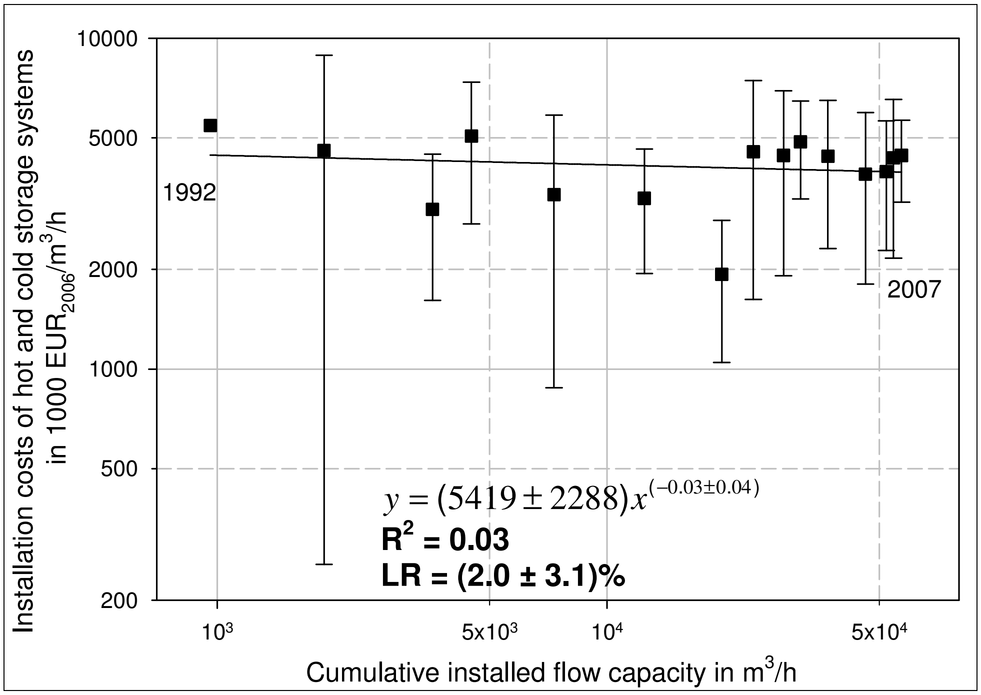

Figure S7: Experience curve - installation costs [1000 $EUR_{2006}/m^3/h$] of hot and cold storage systems in the Netherlands covering the period of 1992-2007; error bars indicate the standard deviation of average values

The identified trends are statistically week, i.e., they have a low coefficient of determination. The diverse results are caused by (i) varying profit margins of producers, (ii) relatively large fluctuations of material, i.e., stainless steel prices, and (iii) the fact that installation costs are to a large extent determined by exogenous, non-technology-related factors, i.e., geological underground conditions.

We therefore conclude that based on the data available, meaningful experience curves for hot and cold storage systems cannot be constructed. The complexity of the system and the factors affecting the magnitude of installation costs would require data analysis on a far more disaggregated level. Due to constraints with regard to data availability, it remains, however, questionable whether such analysis can be feasible.

With regard to the general dynamics of installation costs, we can identify various phases, some with a cost decrease (mid 1990s, 2002-2004) and others with a cost increase (1999-2003, 2005-2007). The observed cost dynamics can be attributed to increasing/decreasing market demand, rising material prices, and fluctuations of energy prices. Increasing energy prices make installations profitable (i) at sites with less favourable geological conditions and (ii) for buildings with a lower cooling/heating demand but might ultimately cause an increase in specific installation costs.

We therefore recommend to conduct more detailed *bottom-up* technology assessment to identify future cost reduction potentials for individual system components thereby excluding the effects of on-site geological characteristics. Such analyses might, however, require access to confidential company data.

Compact fluorescent light bulbs (*Spaarlampen*)

Compact fluorescent light bulbs (CFLs) have been introduced to the lighting market of the Netherlands and the USA by the Dutch company Philips in 1980. Despite the fact that CFLs have been sold for more than 25 years, they acquired only a minor shares on total light bulb sales. Global CFL sales are estimated at 1.2 billion in 2003, while incandescent light bulb sales account for more than 13 billion units (IEA, 2006a).

Despite relatively short life times and inefficient electricity use, the majority of consumers still chose for incandescent light bulbs because these offer warm-coloured light, are available in an enormous range of styles and sizes, can be dimmed, and because their unit prices are much lower than the ones of CFLs.

In this project, we construct experience curves for costs and efficacies[3] using market prices and efficacy data for CFLs sold in the Netherlands and in Germany. We use cumulative global CFL sales as indicator for cumulative experience in CFL manufacturing. We identify a learning rate for the costs of CFLs per capacity and luminous flux of (18.8 ± 2.4)% and (18.8 ± 2.2)%, respectively (Figure S8). Experience curves for CFLs have been presented in literature, indicating learning rates of 10% (Ellis et al., 2007) and 21% (Iwafune, 2000). Disaggregated experience curve analysis reveals that the costs for medium size light CFLs (60 W_e and 75 W_e incandescent light bulb capacity-equivalents) decrease significantly slower than the costs for CFLs with a capacity of 40 W_e and 100 W_e equivalents. We furthermore found that CFLs with a capacity-equivalent of 100 W_e have a significantly lower specific price [EUR_{2006}/W] than CFLs with a capacity-equivalent of 40 W_e.

The observed price dynamics can be attributed to a decrease of both production costs and profit margins. The reduction of ballast prices contributed considerably to the overall cost decrease of CLFs. For the manufacturing of both ballasts and entire CFLs, economies of scale and increased automation of production processes were important drivers for cost reductions in early years. Progress in electronics, miniaturization of components and after 1990 the shift of CFL production from Europe and the USA to low-wage regions like Eastern Europe and China, lowered production costs of CFLs considerably.

By extending the conventional experience curve approach to CFL efficacy [lm/kW], we find a learning rate of (1.6 ± 1.3)% at a very low coefficient of determination ($R^2 = 0.13$). This finding indicates a trend towards increasing efficacies, which is however statistically very weak.

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[3] Efficacy or luminous efficacy [lm/W] of a light bulb refers to the ratio of light production [lm] to power use [W].

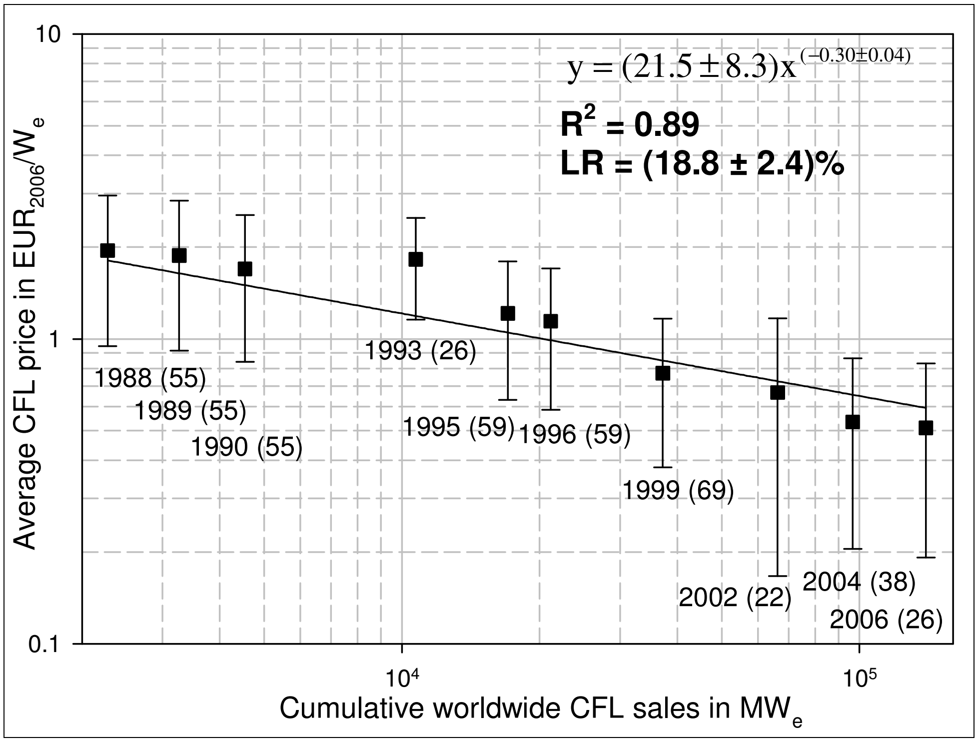

Figure S8: Experience curve for CFLs (price per capacity) for the time period of 1988-2006; the error bars indicate the standard deviation of average prices; in brackets number of data points included in our analysis

Industry experts argue that CFL efficacies do not follow an experience curve pattern because rather than improving CFL efficacies, producers aim at adapting light chromaticity to match as closely as possible the warm-coloured light of incandescent light bulbs. Improving the light quality of CFLs is generally regarded as important strategy to obtain higher market shares *despite* the fact that it loweres bulb efficacies. This is hence a clear case in which a further improvement of energy efficiency (i.e., bulb efficacy) is not regarded as crucial for the market success of a product. We therefore argue that the experience curve approach is *unsuitable* to analyze and especially project efficacy dynamics of CFLs.

Despite their high market price, CFLs have been cost effective on a life cycle bases from the year of their market introduction (Figure S9). We find yearly savings to increase from 1.60 EUR_{2006} per bulb in 1988 to 8.20 EUR_{2006} per bulb in 2006 (75 W_e incandescent light bulb equivalent). In the year 2006, CFLs offered savings of roughly 0.19 EUR per kWh_e saved and 330 EUR per tonne of CO_2 not emitted (results for the Netherlands). These savings can be even expected to increase in the future, if electricity prices continue to rise.

Our analyses show that CFLs can improve energy efficiency in the building sector in a very cost effective manner. This fact has, however, been only poorly acknowledged by most consumers. The *market break-through* of CFLs will hence depend on: (i) further price reductions, (ii) dynamics of energy prices and energy efficiency standards, and (iii) compliance of CFLs with consumer preferences regarding, e.g., bulb size and light quality.

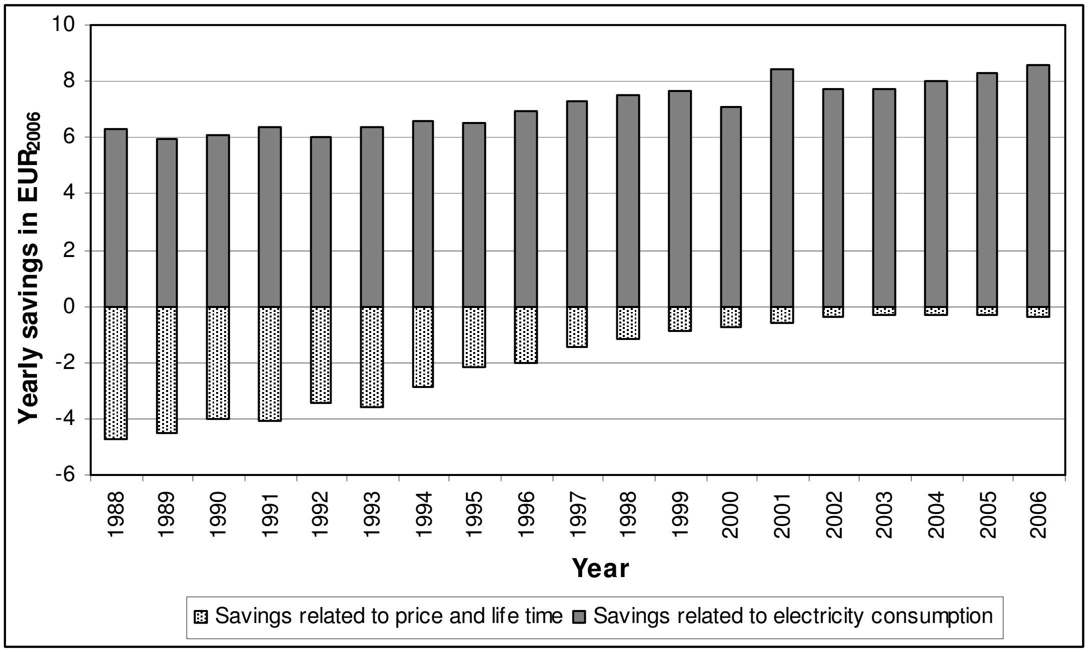

Figure S9: Contribution of cost components to the yearly savings of CFLs compared to conventional incandescent light bulbs in the Netherlands

Industry experts project increasing production costs for CFLs in coming years due to rising material and energy prices. Future developments in CFL technology will result in more diverse lighting products from both technical and design perspective. These developments include dimmable CFLs as well as CFLs with a wider spectrum of chromaticity.

Next to CFLs, light emitting diodes (LEDs) are an important technological innovation on the lighting market. LEDs quickly spread for many lighting applications, e.g., in the automotive sector. LEDs are very energy efficient, they can be flexibly combined for lighting applications of various sizes, and the chromaticity of light output can be adapted in a wide range. LEDs are, however, still to expensive for large scale application in the residential lighting sector. We recommend further research on this innovative technology.

Household appliances

Household appliances are mature products. Market commercialization of, e.g., electric washing machines took place in 1908. The first electric laundry dryers appeared on the US market at around 1915. Household appliances are produced by numerous manufacturers around the world; they are true global mass products. Worldwide sales of appliances increased steadily during past decades. In the year 2003, the worldwide market for washing machines reached roughly 65 million, sales of laundry dryers are in the range of 11 million, and refrigerator sales amount to 80 million. Producers of appliances have been typically located in Europe, North America, and Japan but falling trade barriers caused major production shifts to China, Eastern Europe and other low-wage regions since the 1990s.

Household appliances consumed in 2003 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 continuously increased in past decades and is expected to continue grow by another 25% (in OECD countries) until the year 2020. At the same time, considerable and largely untapped energy saving potentials have been identified for household appliances (Ellis, 2007).

In the first step of our analysis, we construct experience curves for washing machines, laundry dryers, refrigerators, and freezers based on price data for the Netherlands and on data for cumulative worldwide production. In a second step, we extend the conventional experience curve concept and model energy and water consumption as function of cumulative worldwide production. As it is the case for heat pumps and CFLs, this approach is new and was (to our knowledge) not attempted before.

We identify average learning rates of 32% for washing machines (1965-2005), 27% for laundry dryers (1969-2003), 9% for refrigerators (1964-2007), as well as 8% and 9% for two categories of freezers, i.e., chest and upright front door freezers (1970-1998/2003) (Table S1).

Table S1: Summary of experience curve results for household appliances

	Learning rates in %		
	Production costs	Energy consumption	Water consumption
Washing machines	31.7 ± 7.2	24.7 ± 2.2	27.3 ± 6.1
Laundry dryers			
- Average	27.2 ± 4.9	19.9 ± 3.1	-
- Non-condensing	34.6 ± 3.8	19.9 ± 2.8	-
- Non-programmable	33.3 ± 8.2	20.3 ± 2.8	-
- No time clock	24.7 ± 6.3	21.6 ± 3.5	-
Refrigerators	9.1 ± 2.0	19.9 ± 2.4	-
Freezers			
- Chest freezers	7.7 ± 1.2	15.7 ± 3.0	-
- Upright freezers	8.7 ± 3.8	10.8 ± 3.3	-

Our findings are generally in line with the results of Bass (1980) but somewhat lower than the results from Laitner and Sanstad (2004). The observed cost dynamics can be explained in early years by automation and stream lining of appliance production, by technological progress in components manufacturing, and in the years after 1990 with production shifts to low wage regions. Based on the Dutch price data used for our analysis, we cannot identify an increase of appliance prices due to the introduction of the EU energy label in the mid 1990s.

Disaggregating the cost experience curves, indicates that (i) water-efficient washing machines are on average more expensive and learn slower than water-inefficient washing machines, (ii) prices of low efficiency laundry dryers decline faster than prices of medium- and high-efficiency laundry dryers and (iii) that chest freezers are cheaper than upright freezers.

By extending the conventional experience curve approach, we find a general trend towards decreasing energy and water consumption, i.e., an improved efficiency of household appliances. We find learning rates for energy consumption of 25 % for washing machines (1965-2006, Figure S10), 20% for laundry dryers (1969-2003), 20% for refrigerators (1964-2007), as well as 16% and 11% for chest freezers and upright freezers (1970-1998/2003). Our results support the findings of Ellis et al. (2007) by showing that appliances became both cheaper and more energy efficient. By disaggregating the experience curves for energy and water consumption, we find:

- a convergence regarding energy and water consumption in washing machines, i.e., we find that energy and water consumption in inefficient washing machines decreases considerably faster than in efficient ones;
- indication that the learning rates for energy and water consumption in washing machines change depending on the time period analyzed (Figure S10);
- indication that policy measures (i.e., the introduction of the energy label for household appliances) can actively bend down the slope of the energy experience curve (e.g., for washing machines) thereby accelerating energy efficiency improvements.

Figure S10, however, also indicates that energy (and water) efficiency improvements do not *per se* follow a negative exponential relationship with cumulative production. We argue that deviations occur because efficiency has for a long time not been critical for the market success of appliances. In other words: Learning in energy (and water) efficiency deviates from an experience curve when energy (and water) consumption are less relevant for consumer decisions (depending on the specific case, this finding refers to certain periods of time or it can be a general feature of a technology).

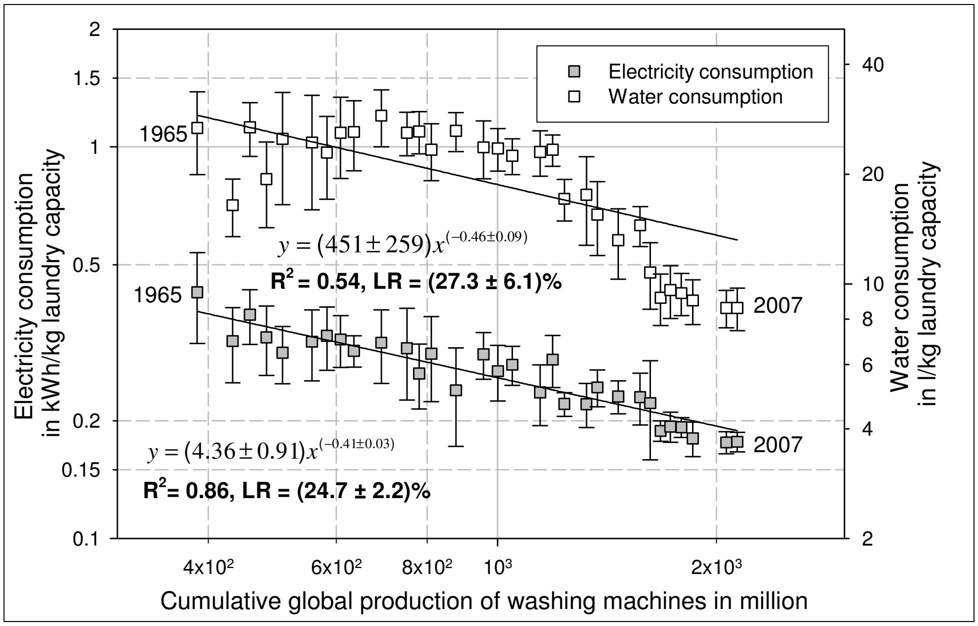

Figure S10: Experience curve for electricity and water consumption in washing machines in the period of 1965-2007; error bars indicate the standard deviation of averages; the drop in water and energy consumption (between data point 6-7 from the right might be caused by the labelling of energy consumption (Data sources: Consumentenbond (various years), UN (2000, 2007))

Unlike production costs, which producers always try to minimize in a market economy, energy efficiency only becomes an important criteria for market success, if (i) energy prices (and hence consumer costs during use phase) are high or if (ii) minimum energy performance standards and energy labels are sufficiently stringent. The data in Figure S10 indicate that the introduction of energy labels improved the efficiency of washing machines in a more or less singular event. In later years, energy and water consumption continues to decrease at rates that are equivalent to the autonomous improvements observed in the years prior to the introduction of energy labels. We therefore draw the following conclusions:

- Our data for washing machines (and to some extent also the ones for laundry dryers and refrigerators) indicate that the EU energy label improved the efficiency of appliances and that policy measures can *bend down* the slope of energy experience curves.
- To effectively improve the efficiency of household appliances, energy standards and labels should be continuously adapted and improved.
- There is, however, a thermodynamic boundary that determines the minimum energy consumption for certain product functions. This boundary can (for conventional technologies) be overcome by technological revolutions, e.g., switch from conventional laundry dryers to heat pump laundry dryer technology and by improvements in other areas of technology (e.g., improved detergents might allow to reduce washing temperatures).
- The extension of the experience curve concept offers potential insight into the dynamics of energy efficiency improvements and the effectiveness of policy measures.
- Our data provide no indication that the EU energy label caused an increase of appliances prices.

Our experience curve analysis allows for identifying principle cost and efficiency trends. The analysis does, however, not allow determining the exact level of energy standards/energy labels that should be chosen to reach substantial efficiency improvements on the one hand and to avoid drastic price increases for appliances on the other. To address this problem, far more detailed and disaggregated technology analyses are required.

A final point of discussion is related to the usefulness of energy taxes for improving the energy efficiency of appliances. Our experience curve analysis does not allow drawing well-substantiated conclusions on this issue. Based on our insight into the appliance market, we might however conclude that energy taxes might have only limited effectiveness (compared to energy labels and minimum energy performance standards) for improving the efficiency of appliances. Unless reported very clearly for each product, consumers often lack the knowledge about energy consumption of appliances and the related costs. Due to the fact that energy costs of appliances account only for a limited share on the total household energy costs (around 30%), elasticity of appliance energy consumption with regard to energy taxes might be low. We argue the energy taxes on the one hand and label programs and energy standards on the other hand might complement each other but should not be regarded as alternatives, at least in the case of household appliances.

Discussion and conclusions

In this research, we applied the experience curve concept to energy demand technologies that are relevant for the residential and commercial building sector (Figure 11). Contrary to the initial research proposal, we exclude from our analysis bulk materials for which energy costs constitute a major cost component in the manufacturing process (see Chapter 5.2)

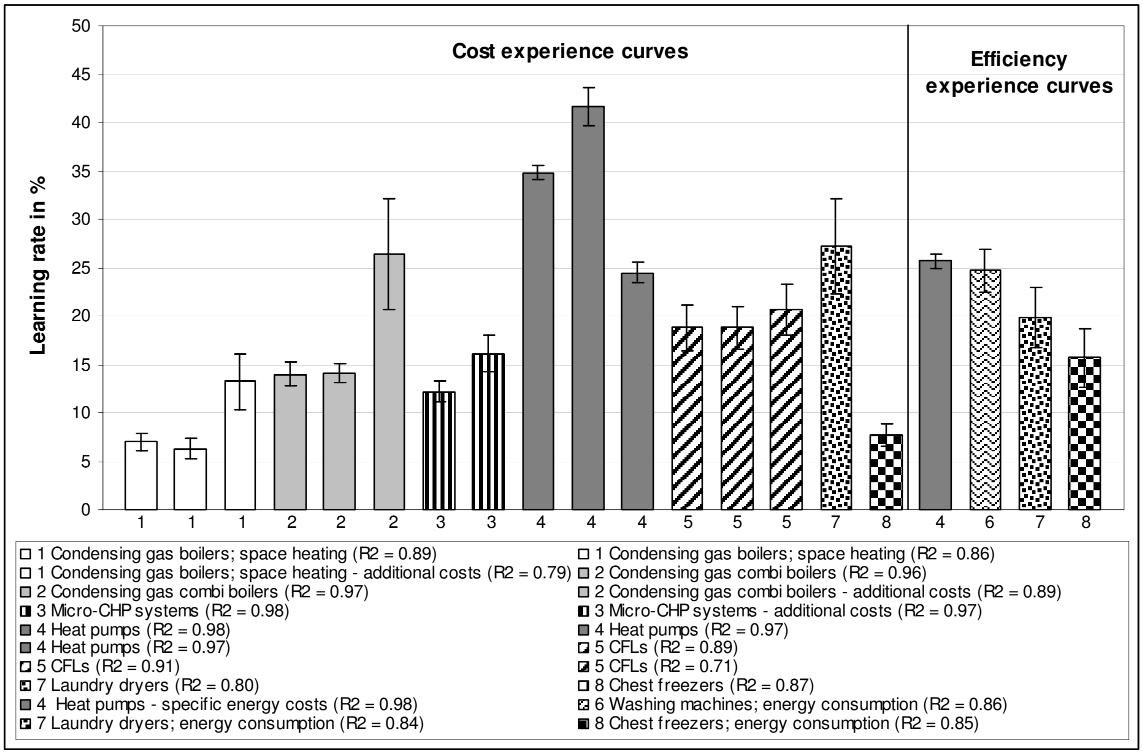

Figure S11: Overview of experience curve results; the error intervals represent regression errors only (we include here only experience curve results with a coefficient of determination larger than 0.7)[4]

Based on the results of our experience curve analyses, we draw the following conclusions:

- The experience curve approach is generally applicable to analyze cost dynamics of energy demand technologies.
- The experience curve approach is especially suitable for technologies, which remain homogenous with regard to their technical components and the services they provide and for which production costs are independent from exogenous, non-technology-related factors.
- Data quality and availability is a critical issue for experience curve analyses. Especially fluctuations in the price of production factors (e.g., wages, steel and

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[4] Under the label 'additional costs', we include here the results of our experience curve analysis for the additional costs of condensing gas boilers relative to non-condensing gas boilers and micro-CHP systems relative to condensing gas boilers.

energy prices) can limit the usefulness of experience curve analyses for projecting future production costs.

- Our analysis confirms a general trend towards declining production costs for energy demand technologies in the residential and commercial building sector. Disaggregating our cost experience curves for appliances, we find that costs for inefficient washing machines and laundry dryers decrease on average significantly faster than costs for efficient ones. We recommend more detailed analysis on the relationship between the rates of energy efficiency improvements and cost decline also for other products. A better understanding of these dynamics is vital for effective policy that aims at improving energy efficiency in the residential and commercial building sector.
- For cost forecasting, it is reasonable to assume learning rates of 10-20% for energy demand technologies. We regard the projected learning rates of 16% for micro-CHP systems as realistic. Already small deviation in the projected learning rates (i.e., in the range of 1-2%) have, however, considerable effects on mid- and long-term cost/price projections.
- The extension of the conventional experience curve approach for modelling the COP of heat pumps, the luminous efficacy of CFLs, and the energy and water consumption of appliances is useful and reveals new insight into the dynamics of energy (and water) efficiency. While the experience curve approach is not applicable to model the luminous efficacy of CFLs (see discussion in Chapter 5), our analyses indicates a general trend towards an improved efficiency of appliances. We find convergence regarding energy and water consumption of efficient and inefficient washing machines. We find furthermore that the European energy labelling program temporarily accelerated the rate at which energy efficiency of, e.g., washing machines and refrigerators improved. Our findings indicate that policies can actively bend down the slope of *efficiency experience* curves, a phenomenon that has so far not been observed for *cost experience* curves.
- Our analysis indicates that energy labels and minimum performance standards need regular adaptations, if these policy measures should remain effective.
- Improvements in energy efficiency are limited by thermodynamic minimum energy requirements (e.g., heating water to clean laundry at 60 ^{o}C) but can be *circumvented* by *efficiency revolutions* such as heat pump laundry dryers or technological innovation in other areas of industrial production (e.g., developing detergents that allow effective laundry cleaning at lower temperatures).
- Policies supporting novel and efficient energy demand technologies might need a long breath, as the example of condensing gas boilers in the Netherlands has shown. Referring to the case of micro-CHP, we regard projections for (i) market penetration, (ii) total amount of subsidy requirements and (iii) the time period, for which subsidies are required, overambitious. We recommend more detailed scenario analyses to clarify these points.
- Efficient energy demand technologies can save energy and CO_2 emissions in a very cost effective way.
- The subsidies spend in support of condensing gas boilers enabled major cost savings on the consumer side and provided incentives for product innovation in

the Netherlands. Relatively little governmental support triggered major energy and CO_2 emission savings in a very cost effective way.

- The optimal distribution between the support of (i) research and development (R&D) and (ii) market diffusion cannot sufficiently be addressed by the experience curve approach and remains difficult to determine.

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ABBREVIATIONS, UNITS, AND SYMBOLS

a - Year
ACT Scenario - **A**ccelerated **t**echnology **s**cenario
ANOVA - **An**alysis **o**f **va**riance
^{o}C - Degree **c**entigrade
CCS - **C**arbon **c**apture and **s**torage
CFC - **C**hloro**f**luoro**c**arbon
CCT - **C**olour **c**orrelated **t**emperature
CFL - **C**ompact **f**luorescent **l**ight bulb
CHP - **C**ombined **h**eat and **p**ower
CO - **Co**ndensing gas boiler (*hoog rendement 'HR'-Ketel*)
CO_2 - **C**arbon di**o**xide
Combi boiler - **Boiler** providing **combi**ned space heating and warm tap water
cont. - **Cont**inued
COP - **Co**efficient of **p**erformance
ECEEE - **E**uropean **C**ouncil for an **E**nergy **E**fficient **E**conomy
EJ - **E**xa**j**oule
EPN - **E**nergie **P**restatie **N**orm
EU - European Union
EU-15 - **E**uropean **U**nion consisting of 15 member states
EUR - **Eur**o
EUR_{2006} - Price given in **EUR** deflated to the price level of the reference year **2006**
GHG - **G**reen**h**ouse **g**as
Glm - **G**iga**lum**en
GR - Market **g**rowth **r**ate
GWh - **G**iga**w**att**h**our
HRE- Ketels - Micro-CHP systems
ICV - _**I**ndividuele **C**entrale **V**erwarming_
IE - **I**mproved **e**fficiency gas boiler (*verbeterd rendement VR-Ketel*)
IEA - **I**nternational **E**nergy **A**gency
klm - **K**ilo**lum**en
kW - **K**ilo**w**att
kWh - **K**ilo**w**att**h**our
kWh_e - **K**ilo**w**att**h**our **e**lectric
kWh_{th} - **K**ilo**w**att**h**our **th**ermal
LED - **L**ight **e**mitting **d**iode
LFL - **L**inear **f**luorescent **l**ight bulb
LHV - **L**ower **h**eating **v**alue
lm - **Lum**en
m^2 - Square **m**eter
MAP - **M**ilieu **A**ctie **P**lan

Micro-CHP	-	**Micro-c**ombined **h**eat and **p**ower systems
NL	-	The **N**ether**l**ands
nm	-	**N**ano**m**eter
OECD	-	**O**rganization for **E**conomic **C**ooperation and **D**evelopment
PAC	-	**P**ayback **a**cceptance **c**urve
PEM	-	**P**roton **e**xchange **m**embrane
PJ	-	**P**etajoule
PV	-	**P**hoto**v**oltaics
R^2	-	Coefficient of determination
R&D	-	**R**esearch and **d**evelopment
$	-	US Dollars
SFr	-	**S**wiss **Fr**ancs
SO	-	**S**olid **o**xide
ST	-	**St**andard efficiency gas boiler
TWh	-	**T**erra**w**att**h**our
UK	-	**U**nited **K**ingdom
US	-	**U**nited **S**tates of America
W	-	**W**att
W_e	-	**W**att (**e**lectric power)
W_{th}	-	**W**att (**th**ermal power)
Wp	-	**W**att **p**eak

1 INTRODUCTION

Energy efficiency improvements offer significant and largely untapped potentials for cost-effective reduction of both energy consumption and GHG emissions. In the year 2006, the EU formulated an action plan to improve the overall energy efficiency in its member states by 20% until the year 2020. This goal is equivalent to yearly savings of roughly EUR 100 billion of energy related costs, 16.3 EJ of primary energy, and 780 Mt CO_2 emissions (EU, 2006). For the Netherlands, Blok and de Visser (2005) identified economy-wide energy saving potentials of 600-700 PJ until 2020.

The residential and commercial building sector is generally regarded as the sector with the highest energy saving potentials among all economic sectors. In the Netherlands, roughly 40% of the total country-wide energy saving potential can be realized in this sector alone (Blok and de Visser, 2005). Within the EU, the residential and commercial buildings sector accounts for almost 40% of the total final energy demand, offering at the same time potential energy savings of up to 30% until 2020 (EU, 2006).

The identified energy efficiency potentials can, however, only be realized, if novel and energy efficient technologies are developed and successfully implemented at the market. The market success of these technologies depends on a variety of factors, e.g., compliance with existing legal and technical standards, consumer education, user friendliness, and up-front consumer investment costs, i.e., product price.

One key barrier for the deployment of novel energy efficient technologies is often their high production costs. Novel technologies are often expensive at the phase of their market introduction but eventually become cheaper with technological and organizational progress, upscaling of unit sizes, and mass production – i.e., with technological learning and the gaining of experience in manufacturing processes and subsequent value chains. Technological learning is hence a key driver for realizing cost reductions in the manufacturing of efficient energy demand technologies.

In order to identify need and scope for policy intervention, it is of special interest for policy makers to obtain insight into the rate at which cost reductions for energy efficient technologies occur. One important and widely applied methodology that allows for analyzing the dynamics of production costs is the so-called *experience curve* approach. The experience curve approach dates back to the work of Wright (1936) and the Boston Consulting Group (BCG, 1968) and analyzes the dynamics of total production costs of a technology as an exponential function of cumulative production (BCG, 1968)[5].

In the past three decades, the experience curve approach has been applied to analyze the decline of production costs for various technologies such as airplanes, cars, household appliances, semiconductors, and chemicals (e.g., Laitner and Sanstad (2001), Clair (1983), Cunningham (1980)). The experience curve approach received special attention with the emergence of renewable energy technologies in the late 1980s because despite their considerable potential for contributing to a sustainable energy system, these technologies were and still are relatively expensive. Both researchers and policy makers aimed therefore at quantifying the rate of cost reductions for renewable energy

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[5] In literature, the terms *learning curve* and *experience curve* are often used inter-changeably when referring to analyses that plot total production costs as a function of cumulative production. In line with Junginger (2005), we uniformly use in this report the term *experience curve* when referring to analyses of *total production costs* and we use the term *learning curve* when referring to analyses of *labour costs* only.

technologies to identify need and scope for policy support. The concept of experience curves has been extensively applied to and refined for *energy supply technologies* such as photovoltaics, wind energy, and biomass use for energy and fuels (IEA, 2000, McDonald and Schrattenholzer, 2001, Goldemberg, 2004, Junginger, 2005, Junginger et al., 2008). The application of the experience curve approach to efficient *energy demand technologies* is, however, still scarce (e.g., Clair (1983), Newell (2000), Laitner and Sanstad (2004)). *In this research project, we aim at applying the experience curve approach to energy demand technologies that are used in the residential and commercial buildings sector.*

The report is structured as follows: In the next section we give a more detailed overview of the analyzed technologies and the objective of our research. We provide an overview of the conceptual framework of technological development, product life cycles, and the theory of technological learning and experience curves in Section 3. In Section 4, we present the results of our experience curve analyses for each energy demand technology individually. In Sections 5 of this report, we discuss uncertainties and results of our analyses and we draw conclusions on the relevance of our findings for policy makers.

2 OBJECTIVES

This research project aims at applying the experience curve approach to efficient energy demand technologies that are used or that might potentially be used in the residential and commercial buildings sector. We analyze the following technologies:

- Condensing gas boilers (*HR-Ketels*)
- Micro-CHP systems (*HRE-Ketel*)
- Heat pumps
- Hot and cold storage systems (*Warmte en koude opslag*)
- Compact fluorescent light bulbs (*Spaarlampen*)
- Household appliances (washing machines, laundry dryers, refrigerators, freezers)

The selection of these technologies is based on data availability and the potential contribution of individual technologies to energy savings and efficiency improvements within the residential and commercial building sector of the Netherlands. For each of the selected technologies, we aim at:

- analyzing the applicability of the experience curve approach;
- analyzing the reduction of production costs, thereby quantifying technology-specific *learning rates*;
- identifying major methodological and empirical problems associated with the application of the experience curve approach.

Strictly speaking, the experience curve approach is only valid for the analysis of production costs. However, due to lack of detailed cost data, we generally approximate production costs by price data for the Netherlands[6]. This is a widely accepted approach but it calls for special care when interpreting the results.

For the selected technologies, we explain in detail the drivers and factors for the observed cost reductions based on *bottom-up* technology assessment. For selected technologies (i.e., condensing gas boilers and CFLs) we extend our analysis and explore the cost effectiveness of technologies with respect to realized energy savings.

In the case of heat pumps, compact fluorescent light bulbs, and household appliances, we extend the conventional experience curve approach. Next to production costs, we also attempt to model energy consumption (and water consumption for washing machines) as a function of cumulative production.

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[6] Exceptions are our experience curve analyses for heat pumps and CFLs. Due to lack of reliable price data, we base our analysis for heat pumps on price data from Switzerland. For the years 2002 and 2006, we include German price data for CFLs in our analysis.

The results of this research are important for policy makers because:

- they allow to obtain insight into the rate of past cost reductions for energy demand technologies;
- they can provide a rationale for projecting future cost reduction potentials;
- they contribute to an evaluation of the effectiveness of governmental technology support programs;
- they can quantify the contributions of selected energy demand technologies to energy savings and CO_2 emission reductions;
- they may give guidance regarding scope and need for policy support for novel energy demand technologies.

3 BACKGROUND AND METHODOLOGY

3.1 Energy efficiency and the reduction of CO_2 emissions

Efficiency improvements in end-use energy demand technologies can potentially contribute 45% to total global CO_2 emission reductions until the year 2050 (IEA, 2006a; Figure 1). Among all economic sectors, the residential and commercial buildings sector offers the greatest energy efficiency potentials (i.e., contributing 18% to the total global emission reductions).

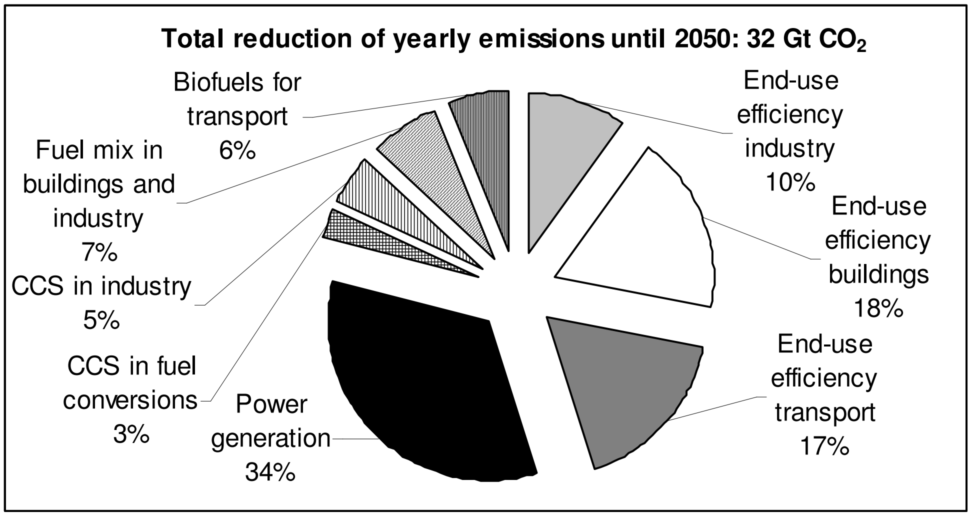

Figure 1: Sector contributions to total global emission reductions by 2050 relative to the base year 2003 in the ACT Map scenario[7] (Data source: IEA (2006a))

Disaggregating the global efficiency potentials of the buildings (residential and commercial buildings) sector, the IEA (2006a) identifies space heating (3%), air conditioning (3%), appliances (8%), water heating (1%), lighting and miscellaneous (4%), and fuel mix (5%) as the principal categories that offer considerable energy and CO_2 emission saving potentials.

As already outlined in the introduction of this report, Blok and de Visser (2005) identified for the Netherlands energy saving potentials of 600-700 PJ until 2020. The Dutch buildings sector accounts for around 40% (Figure 2) of these potentials[8]. Realizing these efficiency potentials will, however, require development and market diffusion of novel and efficient energy demand technologies. The IEA (2007a) estimates that out of the total emission saving potential offered by energy efficiency improvements (i.e., 45%,

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[7] The ACT Map scenario is relatively optimistic with respect to future energy efficiency improvements and CO_2 emission reductions. Its assumptions are realistic in the light of current technological knowledge and historic experience with technological progress. For a more detailed discussion of key features of the ACT Map scenario, we refer to IEA (2006a).

[8] The difference between the global potential of 24% (IEA, 2006a) and the estimate of 40% for the Netherlands (Blok and de Visser, 2005) can be explained by the substantial *relative* energy saving potentials that can be realized by improving building insulation in the Netherlands. On the global scale, this potential (in relative terms) is lower because a large majority of the population lives in a temperate, sub-tropical, or tropical climate.

see Figure 1), two thirds are already cost effective today, leaving only one third of the potential for future energy efficiency improvements to rely on direct governmental deployment support. However, the fact that many energy efficient technologies are cost effective on a life cycle basis does not necessarily mean that they can easily enter markets and acquire high market shares in short time periods.

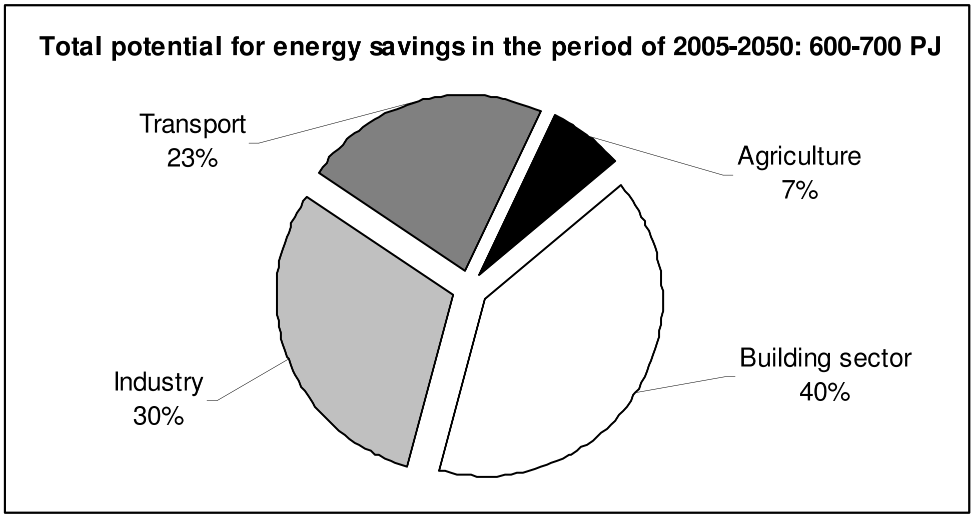

Figure 2: Energy saving potentials in the Netherlands (Data source: Blok and de Visser (2005))

Lack of consumer awareness, insufficient product quality, high purchase prices, and other market barriers often hamper the market diffusion of energy efficient technologies to such an extent that these technologies remain niche products over long time periods. Before analyzing the dynamics of production costs (as one factor for market success of novel demand technologies) in detail, we give a short overview of some more theoretical concepts of innovation and technological learning.

3.2 Product innovation and technological learning

3.2.1 Production costs and the life cycle of products[9]

Relatively high production costs are for many innovative technologies, e.g., efficient energy demand technologies a major obstacle that hampers market success. As many efficient energy demand technologies are novel compared to their conventional counterparts, they offer considerable potentials for the future reduction of production costs due to economies of scale, learning-by-doing, or optimization of production routes.

Several theoretical approaches have been formulated to capture the reduction of both production costs and product prices within the context of technology innovation in a market economy. Ayres et al. (2003) consider the reduction of production costs and commodity prices as being triggered by a feedback cycle of:

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[9] Parts of the text in this section are based on Junginger et al. (2008).

- increasing consumer income and enhanced consumer demand for products and services;
- technological innovation, learning by doing and economies of scale;
- sufficient availability of production factors (Figure 3).

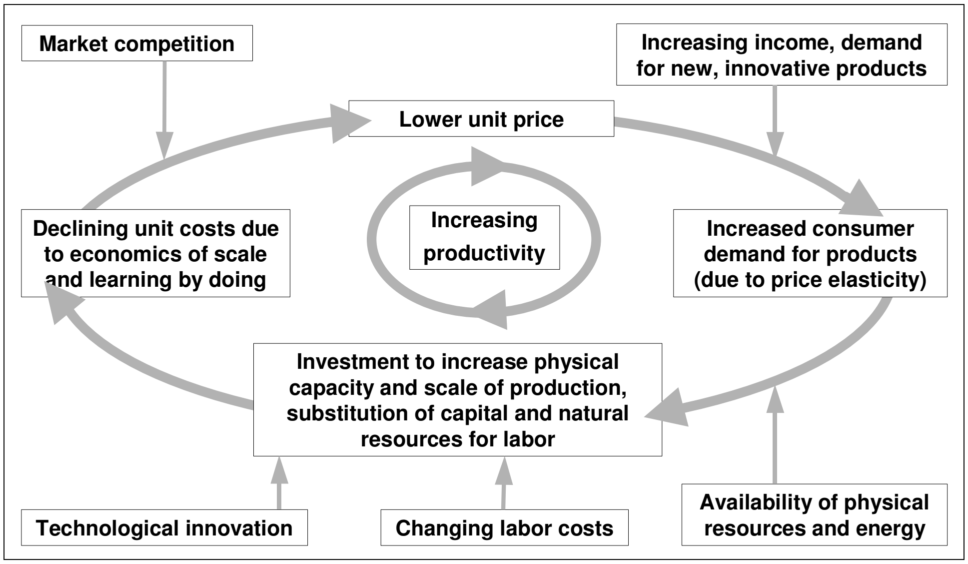

Figure 3: Economic development as feedback cycle between increasing consumer demand and decreasing production costs (adapted from Ayres et al. (2003))

Rising levels of consumption facilitates investment in production capacities, research, technological development, and product innovation. Economies of scale decrease production costs and increase the efficiency of production. Technological development and innovation lead to new products and technologies. Technologies that are implemented on the market occupy at the beginning niche markets but ultimately become standard technologies.

Focusing on the level of individual products, the classical linear model of technology development and market diffusion differentiates six life cycle stages (see Figure 4) (Grübler, 1998, Grübler et al., 1999). The invention phase, in which ideas create new problem solutions, is followed by an innovation phase, where innovative products or technologies are developed and applied in the laboratory or in the course of project demonstrations. Following this stage, products and technologies are introduced into niche markets, where novel technologies often have substantial performance advantages but are expensive compared to conventional standard technologies. Technological learning and economies of scale lead in the following to reduced production costs and improved product quality. In the course of this development, innovative technologies and products enter larger markets. As market potentials become exploited, saturation occurs with stable or even declining market shares. In cases where newly improved technologies enter the market, senescence occurs with declining market shares at the end of the product's or technology's life cycle. The individual stages of a product life cycle typically take several decades (Grübler, 1998), often display significant overlap, and are generally difficult to separate from each other.

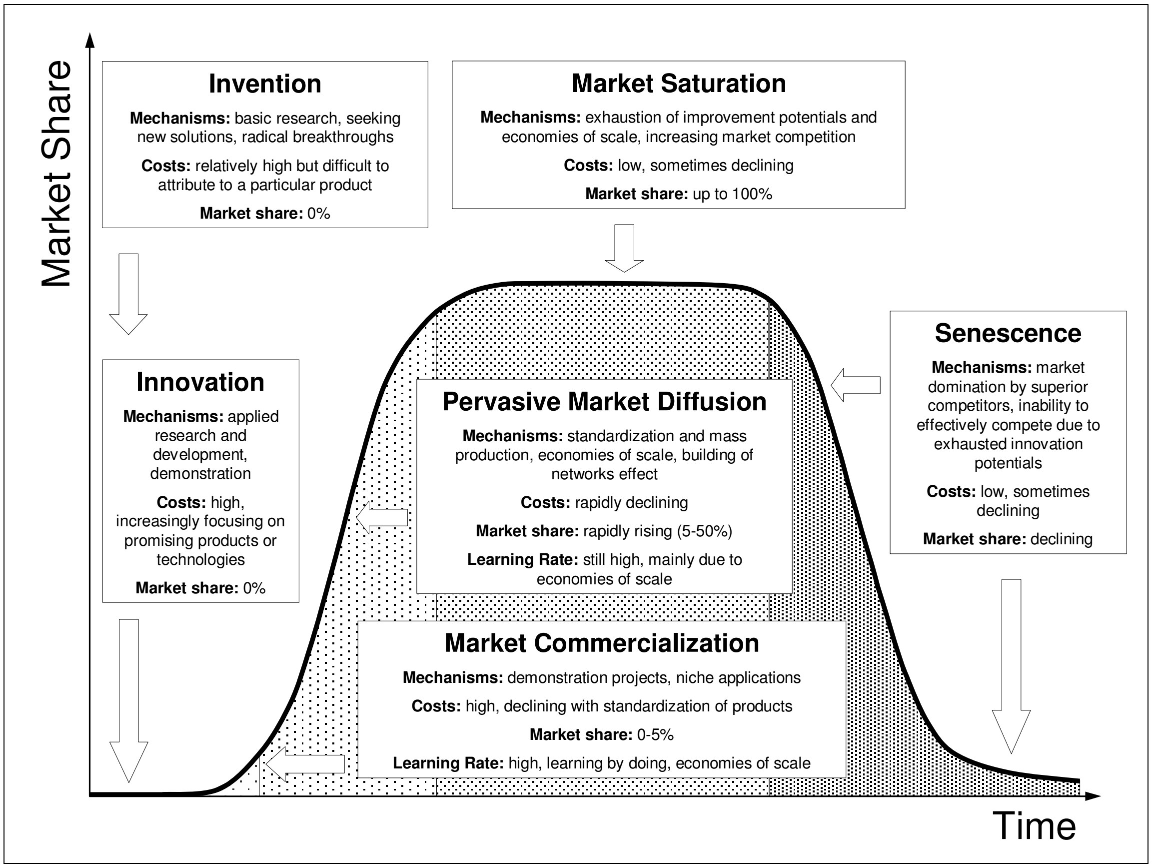

Figure 4: Stylized stages of a hypothetical life cycle for products and technologies (adapted from Grübler et al. (1999))

The market diffusion follows an S-shaped growth pattern, i.e. slow growth during the invention and research and development phase, high growth during the niche market commercialization and pervasive market diffusion, and again low growth during the market saturation stage (and negative growth during senescence).

The technologies analyzed in this research project are in different phases of their life cycle (Figure 5). We include into our analysis both novel technologies that are still in the test phase (e.g., micro-CHP) or that occupy only niche markets (e.g., heat pumps) and mature technologies that might soon become replaced by innovative new technologies (e.g., condensing gas boilers).

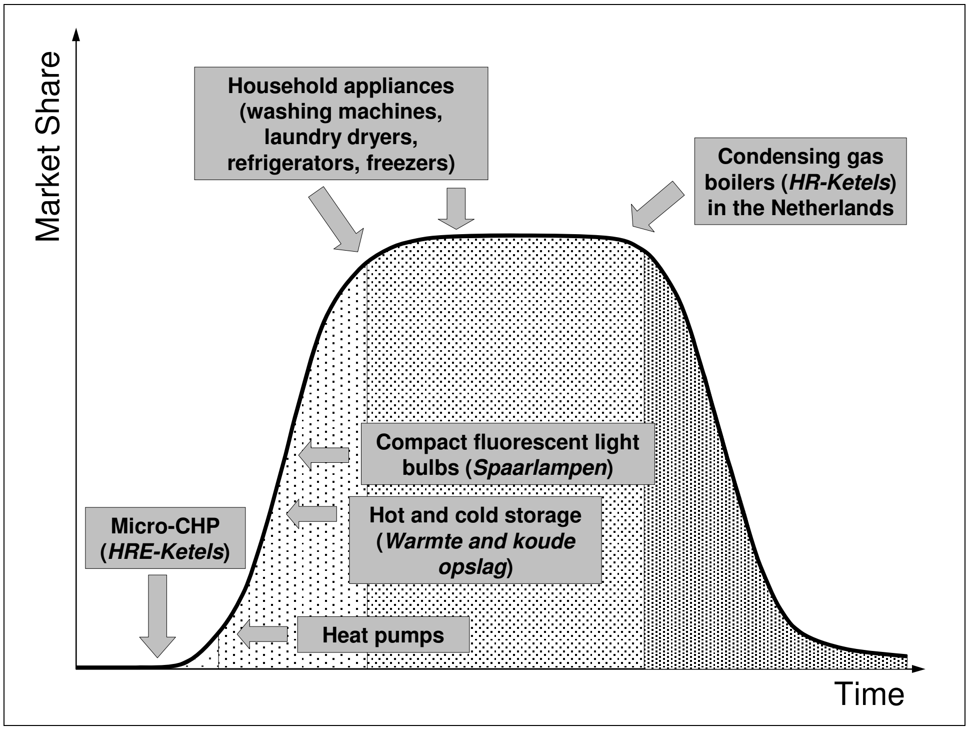

Figure 5: Products included in our analysis and the current stage of their life cycle[10]

The classical *linear* model of technology development and market diffusion has been criticized for its rather simplistic nature. Within the classical conception of *a linear* technology development, every technology develops according to predefined lines. In practice, however, technology development does not *per se* follow such a linear path. Condensing boilers in the Netherlands (see Chapter 4.1) are an example for a technology that followed to some extent the life-cycle stages as proposed by Grübler et al. (1999). Wind and solar energy are, however, technologies where market penetration and research/development activities have been undertaken in parallel. This is in contrast to, e.g., the development of fuel cells, where research and demonstration are the main features of their development, but market penetration has virtually still not occurred (Junginger et al., 2008). According to Schaeffer (2008), these insights are relevant for analyzing technology innovation because:

- there is no necessary order of stages of technology development;
- stages of technology development might be not finished *per se* after one cycle (earlier stages might be repeated or the whole cycle might be run through several times);

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[10] It is possible that two products that were introduced to the market in the same year are in different phases of their life cycle. Examples are condensing gas boilers and CFLs. Both have been introduced to the market in the early 1980s. Today, condensing boilers reached the point of market saturation or even senescence in the Netherlands, while CFLs are still in the phase of pervasive market diffusion.

- analyzing cost reductions as a function of cumulative production is only to a very limited extent useful, if technologies are predominantly characterised by research and demonstration over long time periods (e.g., fuel cells, see Schaeffer (1998));
- time trends can be used to analyze cost dynamics for products, which are not commercially introduced to the market.

3.2.2 Technological learning and the experience curve approach

The individual stages of a product life cycle are characterized by different combinations of *learning mechanisms*, each leading to technological improvements and a reduction of production costs. Following Junginger (2005), we differentiate the following mechanisms:

- *Learning by searching* - technology improvements occur mainly due to research and development, most important mechanism in the invention and innovation stage;
- *Learning by doing* - technology improvements occur in the course of product manufacturing, important mechanism in the stages of innovation and pervasive market diffusion;
- *Learning by using* - occurs upon market introduction of a product/technology, important during all phases in which a product/technology is sold;
- *Learning by interacting* - network interactions between actors (e.g., producers and consumers) improve knowledge communication and information diffusion, important mechanism in all stages of product life cycle;
- *Upsizing or downsizing* - redesigning products or technologies can improve quality and lower the cost of production, important mainly in the second half of the product life cycle;
- *Economies of scale* – apply, if a product/technology is produced on large-scale, standardization allows for upscaling of production plants, which in turn leads to reduced production costs.

In practice, various learning mechanisms often overlap each other and might even reoccur in iterative cycles. It is finally the combination of learning mechanisms that leads to the gaining of experience, technological learning, and subsequently to the reduction of production costs.

3.2.3 A short history of the experience curve approach[11]

Approaches to quantify the effects of technological learning and the resulting reduction of production costs date back to 1936 when Wright (1936) found unit *labour costs* in airframe manufacturing to decline at a constant rate with each doubling of cumulative airframe production. He noted the particular relevance of his findings for investigating future cost developments of airplane manufacturing. Wright's work was revisited a decade later by a group of economists at the then recently founded RAND

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[11] The text in this section is based on Section 2.1 in Junginger et al. (2008).

Corporation, who became interested in the application of technological learning to the production of war materials (Yeh et al., 2007). Arrow (1962) introduced the notion that cost reductions, as a result of learning, was the product of experience. In 1968, the Boston Consultancy Group extended the concept of technological learning by analyzing the dynamics of *total production costs* (and not only labour costs as it was done by Wright (1936)), thereby including additional learning mechanisms (e.g., research and development, economies of scale) and cost factors (e.g., capital, material, and energy) (BCG, 1968).

Analyzing total production costs, also the Boston Consulting Group (BCG, 1968) found constant rates of cost decline for each doubling of cumulative production. In order to distinguish the analysis of *total production costs* from the more simple analysis of *labour costs*, the following terminology was introduced:

- The graphical representation of *labour cost* dynamics is referred to as *learning curve*.
- The graphical representation of *total production costs* is referred to as *experience curve*.

This report complies with the terminology outlined above (see also Footnote 5). For several decades, both learning curves and experience curves have been used to describe the development of product and technology-related costs for a multitude of industrial products, such as cars, airplanes (Alchian, 1963), the aerospace industry in general, chemicals, semiconductors (Irwin and Klenow, 1994), and various energy technologies (Mc Donald and Schrattenholzer, 1999). Argote and Epple (1990) presented an overview of a total of 108 different studies, which apply the experience curve approach.

Nowadays, the experience curve concept is a common textbook concept. It is recognized within technology-intensive industries as important planning tool. The experience curve concept has gained attention from policy makers in the past two decades as rational for assessing future cost reduction potentials for renewable energy technologies.

3.2.4 Experience curve theory

The principle idea behind the experience curve concept is to model production costs as a *black box* as function of cumulative production. It is thereby assumed that production costs per unit of product (e.g., kWh electricity or one kW capacity of a condensing gas boiler) declines at a constant rate as function of increasing cumulative production. The costs per unit of product can thereby be expressed by an exponential equation (1):

$$Ccum_i = C_{0,i} \cdot (Pcum_i)^{b_i} \tag{1}$$

where $Ccum_i$ represents the costs of product i, $C_{0,i}$ the cost of the first unit of product i produced, $Pcum_i$ the cumulative units of product i produced, and b_i the product-specific experience index. Applying the logarithmic function to both sides of equation (1) yields a linear equation with b_i as slope and log $C_{0,i}$ as intersect with the y-axis (2).

$$\log Ccum_i = \log C_{0,i} + b_i \cdot \log Pcum_i \tag{2}$$

Plotting unit costs and cumulative production on a double logarithmic scale yields a linear experience curve as it is shown in the example of wind turbines in Figure 6.

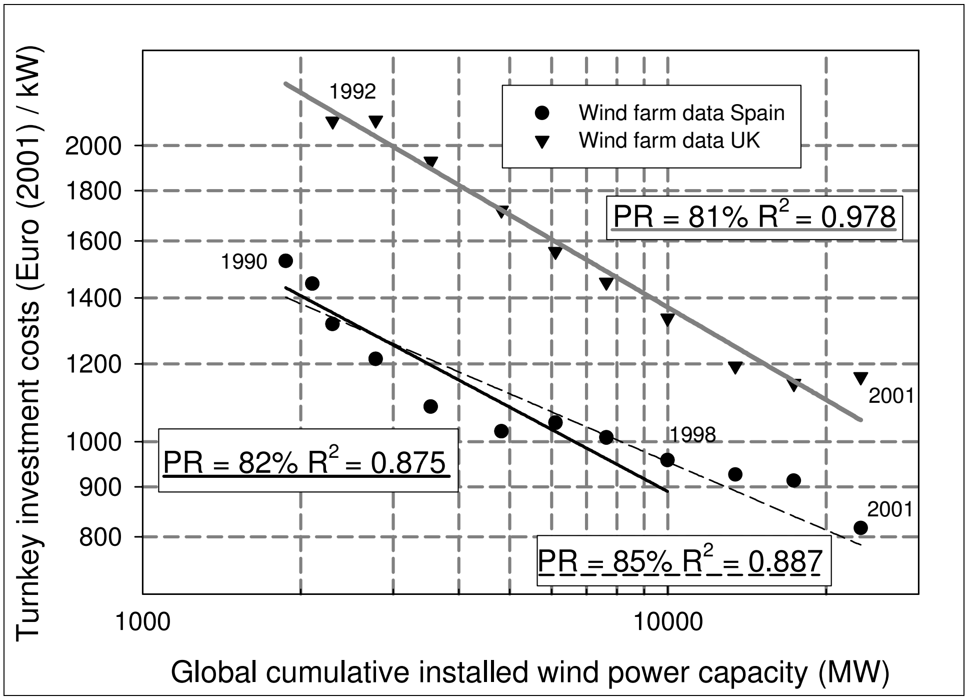

Figure 6: Example of an experience curve for wind farms in the UK and in Spain (Source: Junginger (2005))

Based on this approach, a product-specific progress ratio PR_i can be defined as rate, at which cost decline for every doubling of cumulative production (3).

$$PR_i = 2^{b_i} \tag{3}$$

From the PR_i, the learning rate LR_i can be deducted as follows (4):

$$LR_i = 1 - PRi = 1 - 2^{b_i} \tag{4}$$

A progress ratio of 81% as in the case of UK wind farms (Figure 6) equals a learning rate of 19% indicating a cost decrease of 19% for each doubling of cumulative installed capacity. Throughout this report, we will uniformly use the term *learning rate* to quantify the rate at which cost reduction occurs.

3.2.5 Applications of the experience curve approach

The experience curve approach is applied by decision makers for planning in industry and policy because it can be used to analyze and project the rate at which future cost reductions of a technology occur. Such analyses are particularly important in developing deployment policies for environmentally friendly energy supply and demand technologies (Text Box 1).

The experience curve gives an indication for the deployment costs (i.e., cumulated costs for introducing and establishing a product at the market) that are necessary to make a technology, such as PV, competitive, but it does not forecast when the technology will reach the break-even point. The time period necessary to reach the break-even point depends on the deployment rate of a technology and can hence be actively influenced by deployment policies.

Investments will be needed for many novel energy supply and demand technologies to ride down the experience curve and to bring prices to the break-even level. An indicator for the resources required for learning is the difference between actual price and break-even price, i.e., the additional costs for a technology compared with conventional standard technologies. We refer to these additional costs as *learning investments*.[12] Learning investments are required to make a technology cost-efficient but will be recovered at a later stage of the technology's life cycle while production costs continue to decrease beyond the break-even point.

It is important to note that the quantified *learning investments* are often substantially lower than the actual *deployment costs* of technologies because the market success of novel and innovative technologies is (next to technology-specific costs) also limited by other market barriers such as lack of consumer awareness, consumer convenience, as well as constraints related to legal requirements and infrastructure. To overcome these barriers involves often additional costs that are related to consumer education programs, training of personnel, or the implementation of novel governmental regulations.

The results of experience curves are also important for *scenario modelling* of, e.g., future energy consumption and CO_2 emissions. A number of renowned energy and climate models make use of the experience curve approach, e.g., *IMAGE-TIMER* (Hoogwijk, 2004), *MARKAL* (e.g., Smekens, 2005) or *DEMETER* (van der Zwaan and Gerlagh, 2006). These models take into account research and development expenditures and deployment policies, and project future energy mix and resulting CO_2 emissions. Model projections thereby assist policy makers in identifying optimal pathways towards sustainable energy systems.

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[12] The term *learning investments* refers to the cumulative investments that are necessary to make a technology *cost-competitive* relative to a reference technology. The term *deployment costs* refers to costs that are necessary to establish a technology at the market. Deployment costs are equivalent to learning investments, if market other barriers, which are not directly related to the costs of a technology, are non existent.

Text Box 1: Application of the experience curve approach for analyzing learning investments in photovoltaics technology

By applying the experience curve approach to, e.g., photovoltaics, it is possible to identify the amount of investments necessary to make this technology cost-competitive. The total of these *learning investments* represent a major part of the total deployment costs of photovoltaics. In the example of Figure 7, the costs of PV modules have to declined to a level of 0.5 US\$/W_p to make electricity produced from PV competitive with electricity produced in central power stations. To reach such cost levels would require about a fifty-fold increase of production capacity relative to present day capacity.

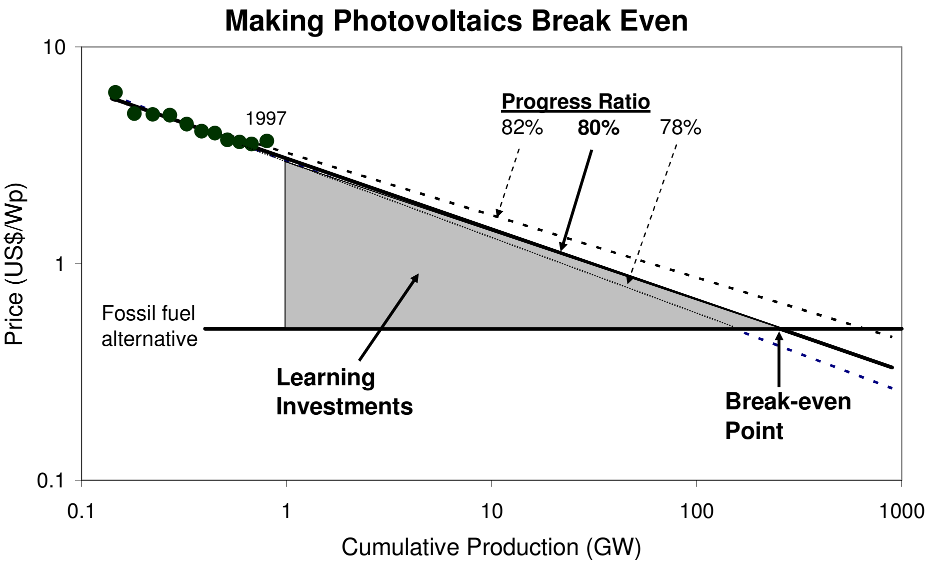

Figure 7: Break-even point and learning investments for photovoltaic modules; the shaded area indicates the remaining learning investments to reach break-even costs (Copy right: IEA (2000)).

With historic annual market growth rates of 15%, photovoltaic modules will reach the break-even point around the year 2025. Doubling the rate of growth will move the break-even point 10 years ahead to 2015. The necessary learning investments are indicated by the shaded triangle and amount to 60 billion US \$ (IEA, 2000). This amount is substantial considering the learning investments of 3-4 billion US \$ spent in support of PV modules until 1998.

3.2.6 Limitations and caveats of the experience curve approach[13]

The experience curve approach captures cost dynamics and technological learning in a simple, *black box* type of modelling approach. Applying and using the experience curve concept in practice is, however, often not as straightforward as it may seem. In this section, we focus on limitations and caveats of the experience curve approach. We

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[13] Parts of the text in this section are based on Section 2.2 in Junginger et al. (2008).

differentiate three key areas of uncertainty, (i) intrinsic experience curve assumptions, (ii) data sources and data quality, and (iii) the usefulness of experience curves for policy guidance.

(i) Intrinsic experience curve assumptions

The experience curve approach covers total production costs as a *black box*. The experience curve approach does thereby not differentiate between components of production costs that are subject to technological learning and components that are not subject to learning and experience. Examples for the latter are:

- variation in material costs as a consequence of changing raw material prices (e.g., steel and copper prices);
- variation in weather conditions leading to decline or increase of agricultural yields;
- variation of labour prices (e.g., as a consequence of outsourcing of production to low wage regions).

In the following we explain this methodological problem in a more formal mathematical way. We first recall the calculation of production costs according to Equation 1:

$$Ccum_i = C_{0,i} \cdot (Pcum_i)^{b_i}$$

The costs $Ccum_i$ depend on the production costs for the first unit produced ($C_{0,i}$), the amount of cumulative units produced ($Pcum_i$), and the product specific experience index (b_i). For the production of any unit of product *i*, the input of production factors leads to costs (C_i) that are related to the use of capital (CA_i), labour (LA_i), materials (MA_i), and energy (EN_i) (Equation 5).

$$C_i = CA_i + LA_i + MA_i + EN_i \tag{5}$$

The costs related to the input of production factors can be disaggregated into the specific price of each production factor and the specific quantities of production factors used:

$$C_i = Q_{CAi} \times P_{CAi} + Q_{LAi} \times P_{LAi} + Q_{MAi} \times P_{MAi} + Q_{ENi} \times P_{ENi} \tag{6}$$

where Q_{CAi}, Q_{LAi}, Q_{MAi}, and Q_{ENi} represent the quantities and P_{CAi}, P_{LAi}, P_{MAi}, and P_{ENi} the price of the production factors CA_i, LA_i, MA_i, and EN_i contributing to the total production costs C_i.

The experience curve approach combines all individual parameters into one single cost parameter (C_i). This approach disregards that in many cases technological learning reduces the *quantities* of production factors that are needed for production but has generally no influence on the *prices* of production factors. Intrinsic to the experience curve approach is therefore the assumption that the price of production factors is constant. The fact that this assumption does not hold in reality is less of a problem for novel technologies where learning effects (i.e., reductions of required *quantities* of labour or energy) are substantial and generally have a much stronger influence on the dynamics of total production costs than changing *prices*. However, as products mature, the number of units produced, which are needed to achieve a certain reduction in the quantity of production factors (e.g., reductions in the quantity of labour or energy consumed) increase exponentially. Dynamics of *prices* (i.e., price of labour, resources, materials, energy, and capital) become hence increasingly important as factors determining total production costs. High prices for raw materials, labour etc. might be countered by material substitution or production shifts to low-wage countries. The *price* of production factors is nevertheless exogenous to the learning systems. The price dynamics of production factors introduces often considerable uncertainty into the experience curve analysis and limit the usefulness of the experience curve approach for future cost projections.

A second methodological shortcoming refers to the fact that the experience curve uses cumulative output and a constant exponent, i.e., the experience index b_i as indicator for accumulated experience. This implies that production cost can *theoretically* be reduced to zero. Intuitively, one would, however, expect that this cannot be achieved. However, in practice, cost reduction possibilities are limited by market volume and market competition. In general, the phases of market saturation and senescence are reached long before production costs approach zero.

A final point of uncertainty relates to the fact that the experience curve approach describes the dynamics of production costs but does not explain the drivers behind observed cost reductions. To underpin empirical results, additional *bottom-up* technology analysis is necessary. Ideally, *bottom-up* technology analysis allows decomposing a technology into its components and reveals insight into the speed at which learning occurs on a sub-technology level. In other words: Such analysis might identify components that learn fast and others for which the opposite is true because they have a long history of being used in numerous other devices (e.g. electronic controls versus pipes in condensing gas boilers). While such analyses can be essential in order to be able to draw meaningful conclusions about the entire technology, lack of detailed technological data (especially over long time periods) limits insight and is often *the* major obstacle for this type of analyses.

(ii) Representativeness of price data and the system boundaries of experience curves

Experience curves are often constructed based on *market prices* and not on actual production costs. According to the Boston Consultancy Group, prices can be used as proxy for costs, but only if (i) markets are competitive and if (ii) profit margins remain constant in the time period analyzed (BCG, 1968). Both requirements are, however, often not met during the stages of market introduction and niche market commercialization. Companies often cross-subsidize new products, thereby selling them on the market at prices that are lower than actual production costs (e.g., hybrid cars (Muntwyler, 2007)). Substantial errors may occur, if market prices are used to project future cost dynamics of a technology.

A critical issue related to the construction of experience curves refers to the *geographic system boundaries of production data*. With the expansion of industrial production, the geographic system boundaries are often enlarged in the period of analysis.

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, condensing gas boilers were first developed and introduced to the market in the Netherlands independently from other countries in the early 1980s. Roughly ten years later condensing gas boiler technology spread all over Europe with the result that the regional boundaries for technological learning in the boiler manufacturing industry expanded from the Netherlands (in the period 1981-1990) to Western Europe and even the entire world (1991-recent years) (Overdiep, 2007). Restricting the system boundaries to the Netherlands for the total time period since 1981 would hence lead to an overestimation of technological learning.

(iii) The use of experience curves for policy guidance

Experience curve analyses have shown that governmental policies can facilitate the reduction of production costs by stimulating markets, i.e., increasing production volumes. In other words: Governmental policy can accelerate the speed at which products ride down their experience curve (see, e.g., Junginger et al., 2008). However, so far there has been no empirical evidence that governmental support can bend down experience curves, i.e., increase the slope of experience curves (Junginger et al., 2008).

A more controversial and highly relevant issue for policy makers is the (over-) stimulation of demand by (generous) policy support measures. Experience curve analyses indicate that stimulating cumulative production leads to decreasing production costs. Thus, in many countries, (renewable) energy technologies have received generous support to stimulate their market diffusion. This has often led to high diffusion rates, and can generally be considered a huge success. However, such policy can also cause increasing market prices for technologies, if there is a lack of competition among producers. In such a case, the prices of a technology do not follow the general decline of production costs. For example, prices of wind farms remained stable in Germany (and list prices of wind turbines even increased) during the period of 1995-2001. This development was probably caused by the generous German feed-in tariffs, and subsequently high demand for wind turbines. Similar dynamics can also be observed in recent years for PV modules (Junginger et al., 2008). Experience curve analysis can be used to identify the extent to which overstimulation of a technology occurs. The results of experience curve analyses are, however, subject to additional uncertainties, if price data do not follow the general trend of production costs. For historical analysis, it is therefore important to investigate how market demand and supply have developed over time and whether price-distorting effects occurred. If so, the results of an experience curve analysis should be critically discusses or even considered unsuitable to determine historical learning rates for production costs.

Empirical studies show that learning rates are technology-specific. Neij (1999) distinguishes three categories of technologies: modular technologies (e.g. PV modules), plants (e.g., power plants) and continuous processes (e.g., production processes for bulk chemicals). Learning rates for modular technologies are generally in the range of 5-30% (on average 20%), for entire plants (e.g., coal power plants) between 0% and 18%, and for individual (continuous) production or conversion processes to be between 10% and 36% (average 22%).

3.2.7 Extending the experience curve approach to energy and water efficiency

In this research report, we extend the conventional experience curve approach by modelling also energy and water efficiency of technologies as a function of cumulative production (i.e., COP of heat pumps, luminous efficacy of CFLs, and electricity and water consumption in household appliances). This methodological extension is new and was not made in this form before. Ramirez and Worrell (2006) modelled the specific energy consumption for ammonia and urea manufacturing with the experience curve approach. They argue that the experience curve approach is applicable to model energy consumption for these production processes because energy related costs account for more than 70% for the total production costs of ammonia and urea (Ramírez and Worrell, 2006). As for any other cost experience curve analysis, they thereby assume that production costs decline at a constant rate with each doubling of cumulative production. This assumption holds, if the following criteria are fulfilled:

(i) Product sales show high elasticity for market price and thereby production costs.
(ii) Producers always aim at minimizing production costs to remain competitive at the market and to maximize profits.
(iii) The prices of production factors remain constant.
(iv) The decline of production costs occurs, therefore, exclusively because the *quantities* of production factors used for production are reduced by mechanisms of technological learning.

If the efficiency of heat pumps, CFLs, and household appliances can be expected to follow an experience curve relationship, than assumptions (i) and (ii) should not only apply for *production costs* of a technology but also for the *efficiency* of technologies during the use phase. In our discussion, we can neglect assumptions (iii) and (iv) because they refer to the costs of production factors and are therefore not *directly* relevant for our discussion here[14].

Whether or not use phase *efficiency* follows an experience curve does in the next instance depend on the elasticity of the market with respect to product efficiencies. Market elasticity is determined by a variety of factors, among them:

- Existence of legally enforced minimum efficiency requirements – products with efficiencies lower than legally permitted are excluded from the market. Producers have therefore as strong incentive to improve the efficiency of their products.
- Share of use phase costs on the total product related costs – the propensity to reduce costs in the use phase increases, if the share of the use phase on the total product related costs is high.
- Absolute level of product related costs – the propensity to lower use phase costs increases, if the technology is expensive.
- Energy prices – higher energy prices lead to increasing use phase costs and enhance the propensity of consumers to lower costs.

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[14] One might argue that increasing energy prices might stimulate energy efficiency improvements in appliances. This argument refers, however, to the elasticity of product sales with respect to energy consumption of appliances rather than to the price of energy as production factors. High market elasticity with respect to energy and water consumption is considered as core criterion that needs to be fulfilled, if energy and water consumption should be expected to follow an experience curve pattern.

For modelling energy and water efficiency with the experience curve approach, we have to assume that the criteria mentioned above are fulfilled and that the market consequently shows high elasticity with respect to the efficiency of products. Only if these requirements are fulfilled, producers are continuously forced to minimize the energy and water consumption of their products, if they want remain competitive at the market.

In reality, however, these assumptions apply only to a limited extent. For energy demand technologies such as heat pumps, for which the primary product function is to convert or provide energy (e.g., heat) the assumption certainly holds. The COP of heat pumps was and is an important parameter that determines profitability and market success of a heat pump. The main argument in favour of CFLs was always their superior efficacy compared to conventional incandescent light bulbs. However, as the discussion in Chapter 4.5 shows, other product functions such as light quality and bulb size, are likely to be more important criteria for consumer decisions. Efficacy improvements therefore need to be balanced by improvements of other product characteristics. This ultimately leads to a situation that even decreasing CFL efficacies are acceptable, if, e.g., the light quality of CFLs improves considerably.

In the case of household appliances, energy consumption experienced increasing attention during the first and second oil crisis in the early 1970s and 1980s. In the years before, other product characteristics (such a washing quality or the total cleaning capacity of a washing machine) were far more important purchase criteria for consumers. Water consumption became an issue for the first time in the context of environmental discussions (which also included aquatic eutrophication) in the 1980. In combination with relatively low consumer awareness for life cycle and energy and water related costs, we can expect that the appliance market has been relatively inelastic for a long time with regard to energy and water consumption of appliances. This situation changed, however, in the 1990s when energy prices increased and discussions around climate change and anthropogenic CO_2 emissions facilitated consumer awareness. The building of consumer awareness was supported in the EU with the introduction of energy labels for household appliances in the mid 1990s. As a consequence, the market for household appliances became increasingly elastic with respect to energy and water efficiency. This forced producers to invest in the development of more efficient household appliances, if they wanted to remain competitive. The reduction of production costs and market prices on the one hand and the improvement of appliance efficiencies on the other hand became hence similarly important for producers in recent years.

We, therefore, conclude that it is generally valid to model energy and water efficiency and consumption of energy demand technologies based on an experience curve approach for recent years. The experience curve approach is, however, subject to greater uncertainties and partly inapplicable,

- for earlier years (before the period of 1980-1990) where energy prices were low;
- for technologies for which energy costs account only for a small share of entire life cycle costs;
- for technologies that provide services, which are of primary importance to consumers and which can only *indirectly* be related to energy consumption (e.g., cleaning laundry, keeping food fresh).

In the three cases mentioned above, the underlying assumptions for an experience curve model are only partly fulfilled. It is furthermore important that the experience curve analysis for energy consumption is limited by the thermodynamic minimum of processes (e.g., the heating of water in washing machines requires a defined minimum amount of energy). Ideally, the power fitting functions should thus include a constant term that accounts for the boundary of thermodynamic minimum energy requirements. We include thermodynamic minimum energy requirements in our experiences curves for the COP of heat pumps and for the luminous efficacy of CFLs. In the case of appliances, the thermodynamic minimum energy requirements are not explicitly modelled. In the case of washing machines, the inclusion of thermodynamic minimum energy requirements would require manifold assumptions on washing temperature, engine capacity requirements for laundry rotation, and centrifuge drying, etc. The minimum energy requirements for laundry dryers (excluding rotation of laundry) as well as for refrigerators and freezers are zero. For these appliances, the thermodynamic minimum is far from being reached and has, therefore, no practical relevance for the results of our experience curve analysis.

The thermodynamic minimum energy requirements cannot be lowered by additional appliance production. Thermodynamic minimum energy requirements can be, however, sometimes shifted by:

- technological revolutions (e.g., heat pump laundry dryers or steam compression dryers compared to conventional condensing laundry dryers);
- innovation in other technology areas (e.g., more efficient detergents allow to reduce washing temperatures and lower water requirements).

3.3 Research approach and data sources

The primary aim of this project it to develop experience curves for selected energy demand technologies. The analysis of these technologies consists of empirical data research based on open literature sources (see Table 1). Due to limited data availability, actual production costs are approximated for all technologies by market prices. The general implications of this approach have been discussed in Section 3.2.6 and will be discussed in more detail in the respective technology chapters in Section 4.

The price data used for constructing experience curves generally refer to the situation in the Netherlands (e.g., prices for condensing gas boiler, appliances, hot-cold storage, and partly CFLs). We include, however, also price data from Germany (i.e., prices for CFLs in the years 2002 and 2006) and Switzerland (i.e., entire experience curve analysis for heat pumps). We uniformly deflate nominal prices to the reverence level of Euros in the year 2006. Price data for heat pumps that were given to us in Swiss Francs were fist deflated to the reference level of SFr in the year 2006 and than converted to Euro, using an exchange rate between SFR and Euro of 1.57:1 (ECB, 2008). Similarly, German price data for CFLs as given by Stiftung Warentest (2002) for the year 2002 were deflated to the price level of 2006 based on the German consumer price index (Destatis, 2008).

We use international data for calculating cumulative production to account as completely as possible for the experience gained in the manufacturing of products. In cases where no production data were available, we used extrapolation and interpolation to estimate missing data, assuming growth rates of production as indicated by the available data. In a second stage of our analysis, we qualitatively discuss drivers and factors for the observed cost dynamics. We based this discussion on information from (i) open literature and (ii) personal communication with industry experts. In Chapter 4 we discuss in greater detail data sources, assumptions, and results for each technology individually.

Table 1: Overview of principal data sources used for constructing experience curves

Technology	Data source for market prices	Data source for cumulative production
Condensing gas boilers	Consumentenbond (various years), van Maaren (2007), Warmteservice (2007a)	Aptroot and Meijnen (1993), CBS (2007a), Sijbring (2007), van Maaren (2007)
Micro-CHP systems for household application	Overdiep (2007)	de Jong et al. (2006), Hendriks (2006)
Heat pumps residential heating	FWS (2000)	Martinus et al. (2005), FWS (2007), BWP (2007)
Hot and cold storage systems	Novem (1998a,b,1999a,b), IF Technology (2006), SW (2007)	
Appliances – washing machines	Consumentenbond (various years)	UN (2000), AM (2007), AHAM (2007b)
Appliances – laundry dryers	Consumentenbond (various years)	UN (2000), AM (2007)
Appliances – refrigerators	Consumentenbond (various years)	UN (2000), AM (2007), AHAM (2007a)
Appliances – freezers	Consumentenbond (various years)	UN (2000), AM (2007)
Compact fluorescent light bulbs	Consumentenbond (various years), Stiftung Warentest (2002,2006,2007), Philips (2007)	Iwafune (2000), Waide (2007), Borg (1994,1996)

4 TECHNOLOGY STUDIES

4.1 Condensing gas boilers (*HR-Ketels*)

4.1.1 Introduction and objective

The discovery of natural gas resources in 1956 near Groningen caused rapid changes in the energy infrastructure of the Netherlands. In the residential sector, these changes led to an increase in the number of natural gas based central heating systems (Brezet, 1994). Since the 1960s, natural gas became the most important primary energy carrier for space heating and hot water production in the Netherlands. By 1988, 96% of all Dutch households were connected to the natural gas grid. Roughly 82% of all Dutch households (i.e., 5.8 Mio out of 7.2 Mio in total) operate gas boilers for central heating and hot water production. In the year 2005, natural gas consumption for both space heating and hot water production in households accounted for 315 PJ (CBS, 2005), i.e.,:

- 74% of total final energy consumption (425 PJ) in Dutch households;
- 12% of the total final energy consumption (2612 PJ) in the Netherlands;
- 37 % of natural gas available for final consumption (849 PJ) in the Netherlands.

Space heating and hot water production contribute 11% (19 Mt CO_2) to the total fossil CO_2 emissions of the Netherlands (UNFCCC, 2007). In 2004, around 82% of Dutch household used central heating boilers for space heating (Milieucentraal, 2007). Condensing gas boilers are the dominant boiler technology in the Netherlands, constituting market shares of more than 90% on the total boiler market. Market shares in other European countries are increasing but remaining in many cases still considerably lower than in the Netherlands (Figure 8). For Europe as a whole, condensing gas boilers offer up to 5% savings of the total primary energy used for residential space heating and up to 4% savings of related CO_2 emissions (Weber et al., 2002).

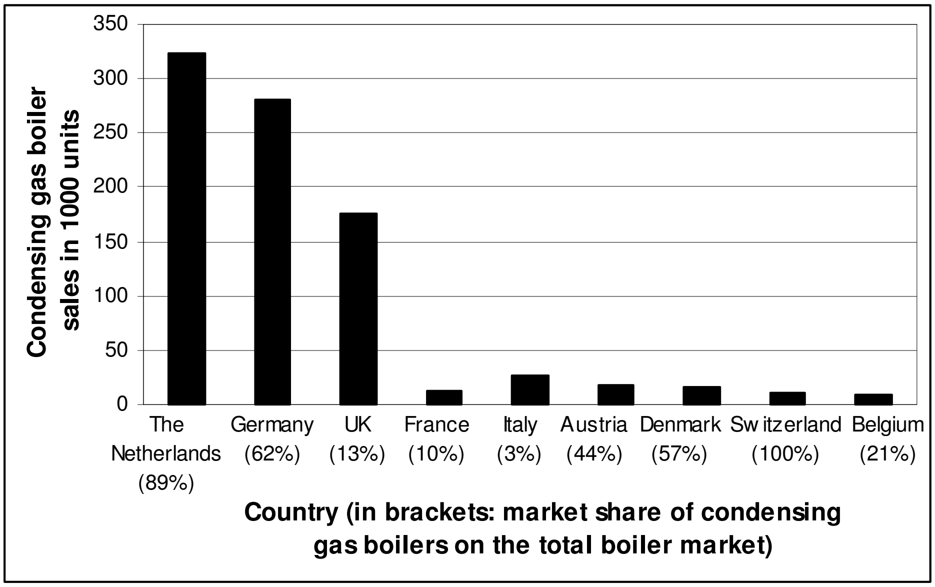

Figure 8: The Western European market for condensing gas boilers in 2005 (Data sources: Weber et al. (2002), van Maaren (2007))

In this chapter, we aim at describing the various stages of the product life cycle of condensing gas boilers in the Netherlands. We analyze cost reductions of condensing gas boilers by means of the experience curve approach based on Dutch market prices and cumulative condensing gas boiler sales in the Netherlands and in the EU-15. We, furthermore, calculate savings of consumer costs, energy, and CO_2 emissions related to the adoption of condensing gas boiler technology in the Netherlands.

In the following section of this chapter, we briefly explain the technology of condensing gas boilers (Section 4.1.2) and we give an overview of the market development in the Netherlands (Section 4.1.3). We present the general approach of our analysis and all relevant data sources in Section 4.1.4. The results of our experience curve and cost analyses are presented in the Sections 4.1.5-4.1.7. We draw final conclusions with regard to our analysis of condensing gas boilers in Section 4.1.8.

4.1.2 Technology description

In conventional gas boilers, a single heat exchanger is used to extract heat from the combustion gases (Figure 9). The temperature of the flue gases is nevertheless 160-280 °C when leaving the heat exchanger. This ensures that flue gases do not cool below the point at which condensation occurs and that thermal convection is strong enough to provide a natural draught, taking the fumes up and out of the chimney (Gasunie, 1982).

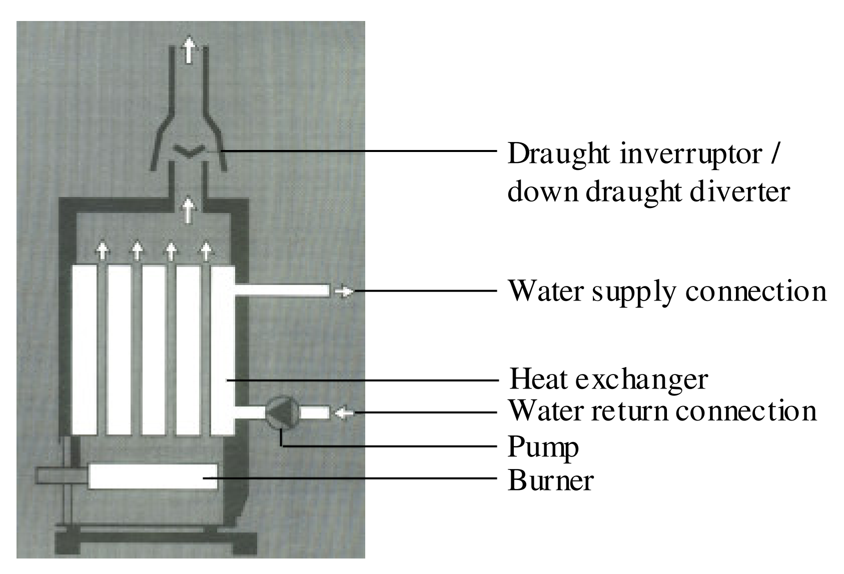

Figure 9: Simplified scheme of a conventional gas boiler (Source: Gasunie (1982))

However, the hot combustion gases still contain a considerable amount of valuable heat that is lost. The major objective for the construction of new, innovative boilers was therefore to recover as much heat from the flue gases as possible, thereby considerably improving the boilers' energy efficiency. Improving the energy efficiency has, however, various consequences, among them the *condensation* of water in the chimney (leading to very corrosive conditions) and the reduced thermal convection of flue gases being the most important ones. In so-called *condensing gas boilers*, the energy efficiency is improved by the following measures (Gasunie, 1982):

- improving the heat exchange, thereby reducing flue gases temperature
- using the latent heat of condensation of the water vapour contained in flue gases
- reducing idle losses due to increased internal resistance against air movements

These measures require technical modifications within the boiler. One possible configuration of a condensing gas boiler is depicted in Figure 10.

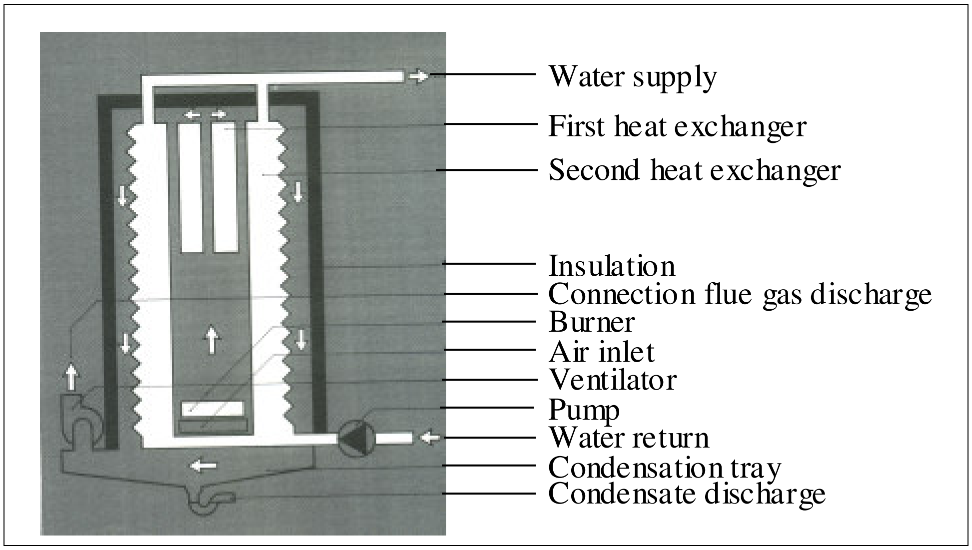

Figure 10: Simplified scheme of a condensing gas boiler (Source: Gasunie (1982))

The most important innovation in condensing gas boilers compared to conventional gas boilers refers to the installation (i) of additional heat exchangers to improve heat recovery within the boiler, (ii) of ventilators to accelerate the movement of exhaust gases, and (iii) of additional piping to discharge the condensate to the sewage systems. The boiler's ventilator only works when the furnace is operated and it acts as a cap preventing idle losses of warm air through the chimney. The boiler efficiency is increased furthermore by the installation of a pump connection, which prevents unnecessary circulation of water in the central heating system. Due to these adaptations, condensing gas boilers required also the modification of building infrastructure (Gasunie, 2007, Sijbring, 2007, Overdiep, 2007):

- The condensate (up to ten litres per day for an average Dutch household) needs to be managed by connecting the boiler to wastewater drains.
- As the flue gas of condensing boilers is moist and corrosive, the flue requires a corrosion-resistant pipe, e.g., made from non-corrosive aluminium or stainless steel.

Given these requirements, standards had to be defined for the installation of condensing gas boilers in Dutch households. These included the adaptation of governmental regulations, concerning the release of flue gases to the atmosphere and the discharge of condensate to the drains of the sewage system (Gasunie, 1982).

4.1.3 History of condensing gas boilers in the Netherlands

Technological development and market of condensing gas boilers

Since the 1960s, gas boilers became the standard technology for space heating and hot water production in the Netherlands. Conventional gas boilers had, however, relatively low efficiencies of around 70-80% (Mooi, 2004). In the mid and late 1970s, increasing energy prices and the expectation of a growing replacement market for technically obsolete and out-dated central heating boilers triggered the interests in developing innovative, energy-efficient gas boilers. However, in these years, the development of condensing gas boilers was hampered by fierce market competition, which cut not only profit margins of producers but also investments in research and development.

As early as 1973, the natural gas supplier *Gasunie*[15] started research to improve the energy efficiency of conventional gas boilers. In 1978, they came to the conclusion that boilers with a new technology had to be constructed (Aptroot and Meijnen, 1993). *Gasunie* then decided to develop a condensing gas boiler, which reduced energy losses by condensing the water vapour that is contained in the flue gases. Patents for a first prototype were applied for in 1978. First technological solutions were presented to boiler producers in 1979 but proved to be expensive and too complex. New technical solutions were developed and manufacturers were asked to further improve the practicability of the proposed concepts (Weber et al., 2002). Based on the first prototype constructed by *Gasunie*, condensing gas boilers of the same type were developed by Dutch boiler manufacturers until 1981.

Starting in 1981, condensing gas boilers of six Dutch manufacturers were successfully demonstrated in various projects and finally introduced to the Dutch boiler market. Ultimately, ten producers acquired licences in the early 1980s for the production of condensing gas boilers in the Netherlands from *Gasunie*. The first generation of condensing gas boilers reached efficiencies of around 93%[16] (Gasunie, 1982). The condensing gas boilers received a quality mark (*Gaskeur-label*) stating that the certified boilers reached an energy efficiency of 90% while complying fully with governmental safety requirements[17].

The additional requirements on the household infrastructure proved to be an important obstacle during the market introduction of condensing gas boilers. Consumer acceptance and confidence of installation companies in the innovative condensing gas boilers was initially hampered by the new technological solutions, which did not entirely comply with *standard* boiler technology, existing technical standards, and settings of household infrastructure.

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[15] N.V. Nederlandse *Gasunie* is a leading gas company in the Netherlands.

[16] All efficiencies are expressed in this report based on the LHV of fuels, e.g., natural gas. The thermodynamic maximum efficiency of condensing gas boilers is 111%. This efficiency assumes that the calorific value of the fuel is fully converted into useful heat.

[17] The *GIVEG-HR'* label provided by the VEG-Gasinstituut was introduced in 1986 to improve the market position of condensing gas boilers. In 1996, the name of the label was changed to 'GASKEUR-HR'. From January 1998, a new GASKEUR-HR labelling scheme was introduced, which distinguishes three efficiency levels: 100, 104 and 107% LHV.

For the relatively low increase in condensing gas boiler sales during the first 5 years after market introduction, four main reasons can be identified:

- Installers and boiler merchants were insufficiently trained and had too little experience with the new technology. This led to insufficient marketing activities.
- Condensing gas boilers were less reliable than conventional boilers.
- Condensing gas boilers were far more expensive than conventional boilers.
- Approximately simultaneously to the introduction of condensing gas boilers, also conventional boilers with improved efficiencies (80-90%) were offered at the market. Improved efficiency gas boilers had an additional heat exchanger, yielding higher efficiencies (up to a maximum of 90% LHV) but did not utilize the latent heat of condensation. The improved efficiency gas boilers were cheaper and easier to install than condensing gas boilers (Gasunie, 1982, Sijbring, 2007, Overdiep, 2007).

To overcome obstacles at the phase of market introduction, (i) training opportunities for installers were initiated, (ii) the reliability of boilers was improved, (iii) governmental subsidy programs were initiates, and (iv) manufacturers used *demand-pull* marketing strategy to stimulate condensing gas boiler sales. Despite subsidies (see next section), the market growth of condensing boilers in the early 1980s was lower than initially expected. Condensing gas boiler sales remained in the range of 20,000-30,000 per year, reaching shares of less than 10% on the gas boiler market in the Netherlands (Figure 11).

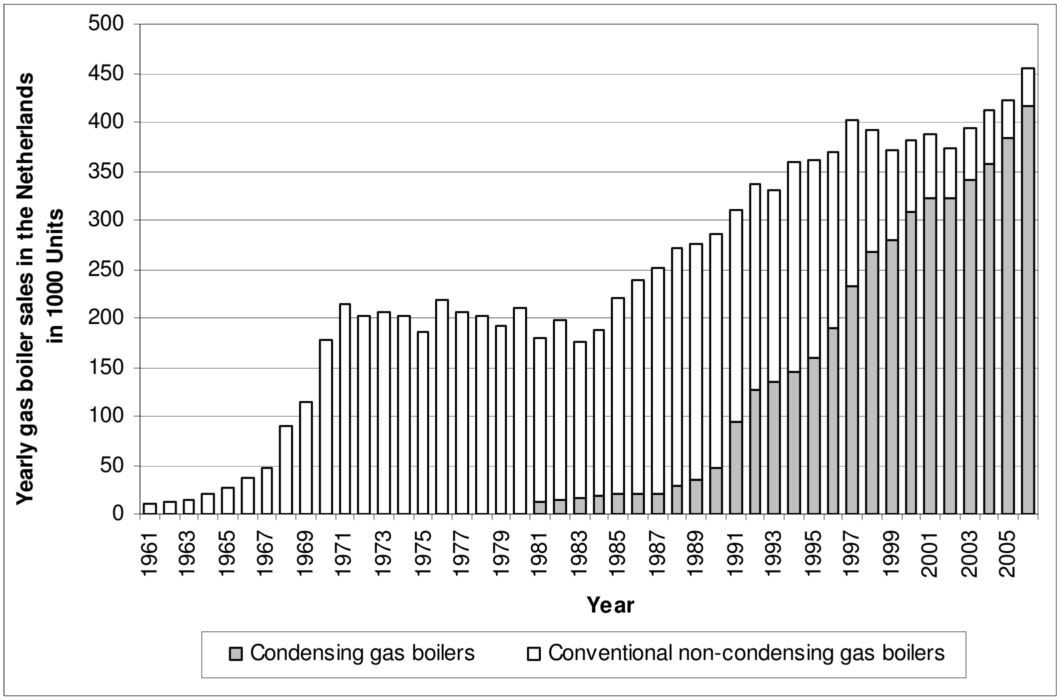

Figure 11: Market development for condensing gas boilers in the Netherlands (Data sources: CBS (2007a), Aptroot and Meijnen (1993), van Maaren (2007), Sjibring (2007))

Aptroot and Meijnen (1993) argue that high prices of condensing gas boilers on the one hand but also natural gas prices that were lower than expected on the other hand, caused unattractively high payback times for condensing gas boilers in the mid and end 1980s (see also results of our analysis in Section 4.1.7). Brezet (1994) found that in 1986, a considerable number of retailers had still problems with the rapid assimilation of condensing gas boilers into their product portfolio because adequate possibilities for staff education were still absent and because gas condensing boilers still showed particularly high susceptibility to failure. By 1986 as little as 5% of installation companies were optimistic about the future of condensing gas boilers in the Netherlands (Brezet, 1994).

In the late 1980s, condensing boilers slowly gained market shares until the early 1990, when mainly three factors caused a drastic increase in condensing gas boiler sales:

- Subsidies and increasing natural gas prices made condensing gas boilers increasingly attractive for the replacement market.
- Technological developments in conventional boiler manufacturing (e.g., the introduction of new generations of modulating burners that require more expensive closed boiler systems[18]) increased the prices of conventional non-condensing gas boilers.
- Production costs as well as additional costs for installation and maintenance of condensing gas boilers continued to decrease compared to standard non-condensing gas boilers.

By 1996, condensing gas boilers reached market shares of 50%. Since the year 2000, their market shares on the total boiler market exceed 80% (Figure 12). This development was also enabled by cost reductions in the manufacturing of condensing gas boilers (e.g., due to upscaling of production, outsourcing of component production, and merging of boiler producers; see Section 4.1.5).

S*ubsidy programs*

After the successful demonstration of the condensing gas boiler technology by manufacturers, the Dutch government set up a subsidy program for the period of 1981-1985, granting subsidies of around 113 EUR per condensing gas boiler. In this period, a total of 28,261 condensing gas boilers were subsidized (Weber et al., 2002). The total sales of condensing boilers in this period are estimated at about 83,000, indicating that a large number of condensing boilers were sold without taking advantage of subsidies. The government did, however, not follow a consistent subsidy policy. As early as in 1985, the initial subsidy programme was incorporated in the National Insulation Programme (NIP), which already started 1978. When the NIP stopped in 1987, the subsidies for condensing boilers were also stopped temporarily (Weber et al., 2002, see Table 2 and Figure 13).
A new programme started in 1990, when the Ministry of Economic Affairs together with the Ministry of Housing, Spatial Planning, and the Environment decided to subsidize one-third of the additional costs for the installation of condensing gas boilers. As a reaction to the presentation of the first Memorandum on Energy Conservation by the Dutch

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[18] Closed boilers receive air via a pipe from outside of the building and not from the room's interior. While condensing gas boilers generally have been always produced as 'closed boilers' this has not been the case for conventional non-condensing boilers, which were in the majority of cases open boilers until the early 1990s (Overdiep, 2007, Sijbring, 2007).

Government in the same year, Dutch energy distribution companies formulated their first Environmental Action Plan (MAP I). The stimulation program for condensing boilers initiated in 1990 by the national government became then a part of MAP I. The MAP I program was financed by a small levy on the energy sales by energy distribution companies. Based on MAP I, half of the total 350 Guilders (160 EUR) subsidies for condensing boilers were paid by the national government (Weber et al., 2002). In June 1993, the national government withdrew from the condensing boiler stimulation programme due to budgetary reasons. EnergieNed immediately stopped the whole subsidy programme. Some distribution companies continued, however, to individually subsidise condensing gas boilers (Weber et al., 2002).

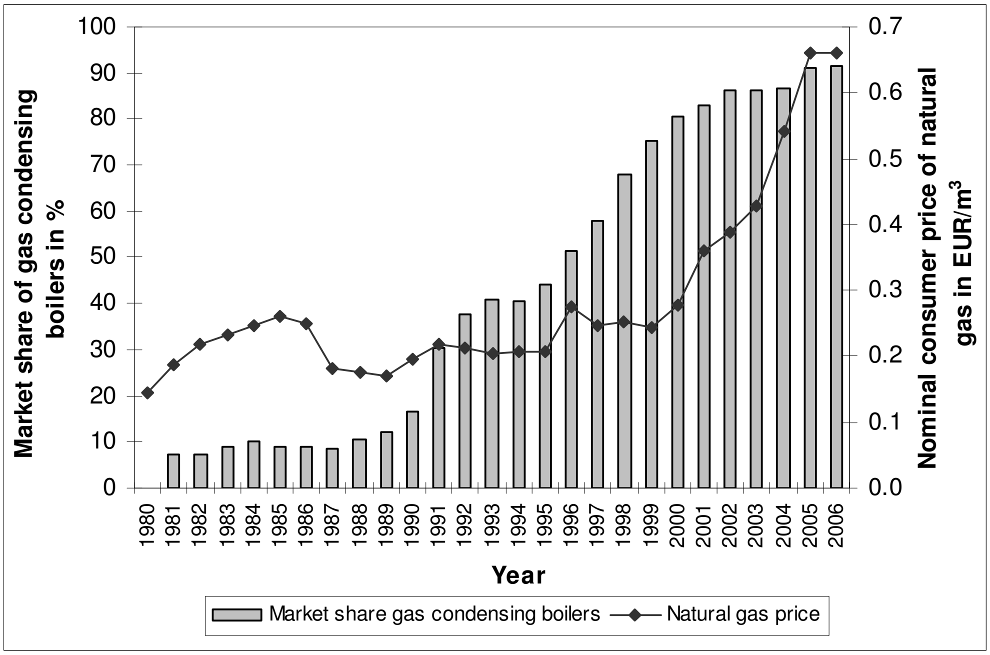

Figure 12: Market share of condensing gas boilers on the total Dutch boiler market and natural gas price in the Netherland (Data sources: CBS (2007a), Aptroot and Meijnen (1993), van Maaren (2007), Sjibring (2007))

In 1994, MAP II was presented with the aim of reducing total CO_2 emissions by 17.1 Mt. A total reduction of 0.57 Mt CO_2 was aimed at by installing condensing gas boilers in the residential sector. Activities to stimulate energy saving under MAP II, led to a new national subsidy scheme for condensing boilers, which was part of the ISO-HR programme; granting 100 Guilders (45 Euro) per boiler and including also subsidies for insulation and other energy efficiency measures. The program ended in 2002. From this time onwards, no subsidies were given to gas condensing boilers anymore (Figure 13). Based on Joosen et al. (2004), Oude Lohuis (2004), Dougle and Oosterheert (1999), Eiff et al. (2001), and own data analysis, we estimate that total *nominal* subsidies of roughly (70 ± 12) million EUR[19] were spent in support of condensing gas boilers between 1981 and 2002 in the Netherlands. This estimate is uncertain because no detailed, complete,

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[19] The estimated amount of subsidies are not inflation-corrected but given as nominal value.

and comprehensive data sources on the subsidies granted in support of condensing gas boilers could be identified.

Table 2: Total yearly subsidies granted for condensing gas boilers in the Netherlands (Data sources: Oude Lohuis (2004), Consumentenbond (various years), Dougle and Oosterheert (1999), and own estimates)

Year	**Number of condensing gas boilers sold with subsidies[1] in 1000 units**	**Subsidy per condensing gas boiler in EUR**	**Subsidies for condensing gas boilers in million EUR[2]**		
			Average	Min	Max
1981	3.9	113	0.45	0.37	0.75
1982	5.1	113	0.58	0.45	0.83
1983	5.5	113	0.63	0.48	0.78
1984	6.7	113	0.75	0.58	0.93
1985	7.0	268	1.87	1.44	2.32
1986	8.9	272	2.42	1.85	3.00
1987	8.9	227	2.02	1.54	2.50
1988	0.0	0	0.00	0.00	0.00
1989	0.0	0	0.00	0.00	0.00
1990	18.8	159	2.53	3.86	6.27
1991	32.9	159	2.61	2.35	2.87
1992	60.0	159	4.76	4.29	5.24
1993	62.9	159	4.99	4.49	5.49
1994	76.8	91	6.97	6.27	7.67
1995	99.8	91	9.06	8.15	9.96
1996	69.6	91	4.74	4.27	5.21
1997	61.9	0	0.00	0.00	0.00
1998	69.6	0	0.00	0.00	0.00
1999	118.0	45	5.31	4.05	6.58
2000	128.6	45	5.79	4.41	7.17
2001	134.8	45	6.07	4.62	7.51
2002	135.4	45	6.10	4.65	7.55
Total			**67.65**	**58.12**	**82.62**

[1] For the periods 1981-1987 and 1999-2002, we assume that (35 ± 10)% of the condensing gas boilers were sold in the Netherlands with subsidies (based on data from Oude Lohuis (2004) for the period 1991-1998).

[2] While Oude Lohuis (2004) mentions a number of 62,862 condensing boilers that are sold in 1993 with subsidies, the Consumentenbond (various years) states that in 1993 no subsidies on condensing gas boilers were granted. Within the scope of this research project, it was not possible to conduct more detailed research to entirely clarify this point; hence the uncertainty interval of 58-83 million EUR.

We have described the development of the Dutch condensing gas boiler market and we estimated the amount of subsidies that have been spent in support of condensing gas boilers in the Netherlands. In the next section, we focus on the empirical data analysis for the construction of experience curve and the calculation of energy savings and consumer costs related to condensing gas boilers.

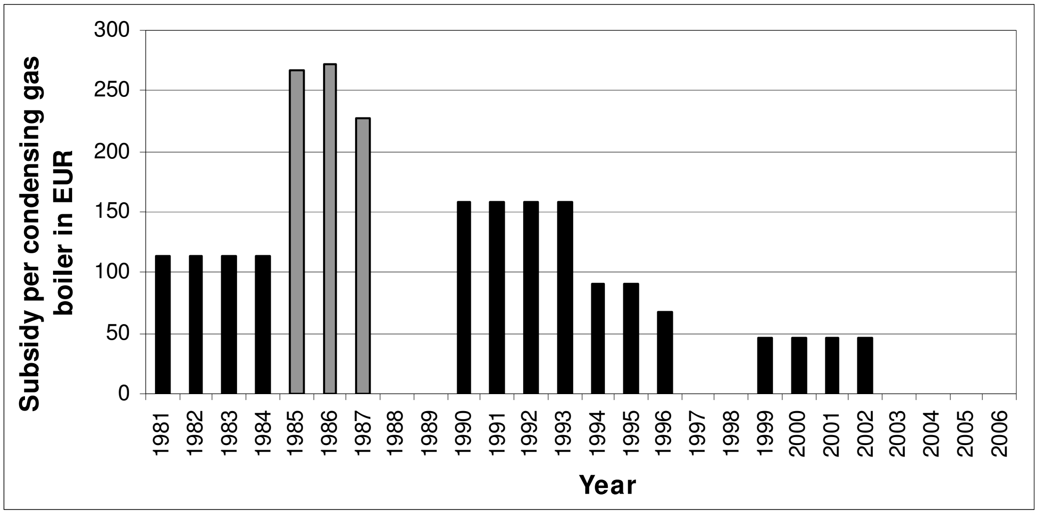

Figure 13: Amount of subsidies[20] paid per condensing gas boiler in the Netherlands; subsidies in the years 1985, 1986, and 1987 cover 33%, 33%, and 40% respectively of additional investment costs (boiler price and installation) for condensing gas boilers compared to conventional gas boilers (Data sources: Consumentenbond (various years), Dougle and Oosterheert (1999))

4.1.4 Approach and data sources

Constructing experience curves

In the first part of our analysis, we develop experience curves for condensing gas boilers in the Netherlands, covering the entire time period in which this technology has been sold at the market, i.e., from 1981 to 2006. For our analysis, we use Dutch boiler prices as a proxy for production costs. This approach is a simplification but nevertheless valid because the Dutch boiler market has been and still is competitive leaving only relatively small and declining profit margins for boiler producers (Sijbring, 2007, Overdiep, 2007, van Maaren, 2007). The Dutch boiler market comprises a large variety of different brands, boiler types and capacities. We restrict our analysis to gas boilers with a capacity lower or equal than 30 kW_{th} because this class of boilers is typically used for individual central heating and hot water production in households. This approach assures as far as possible homogeneity of the analyzed product system. Boiler sales and market penetration rates for the Netherlands were obtained from van Maaren (2007), Aptroot and Meijnen (1993), and Sijbring (2007). Boiler prices were obtained from Consumentenbond (various years) and Warmteservice (2007a,b). These data were supplemented by price data and qualitative information provided by various Dutch boiler manufacturers. The principal source for consumer prices of natural gas, as well as for price indices for total consumer goods is the Dutch statistical bureau CBS (2007a).

Condensing gas boilers were developed in the Netherlands largely independently from technological developments in other countries (van Maaren, 2007, Overdiep, 2007).

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[20] Note that not all of the subsidies received by condensing gas boilers came from the government, i.e., the ministry of economic affairs. Considerable parts of the subsidies were paid (indirectly) by consumers via a levy on energy sales of Dutch utilities.

Technology exchange with other European countries has been minor until the early 1990s. The Dutch boiler market can, therefore, be generally regarded as autonomous (Overdiep, 2007). In the 1990s, trade and technology exchange with other European countries and even with outside Europe increased substantially. Condensing gas boilers sold at the Dutch market were increasingly imported from countries such as Italy or Germany (Overdiep, 2007). To date, we find a global boiler market with condensing gas boilers being exported from and imported to Europe. These market dynamics have to be taken into account when estimating cumulative condensing gas boiler production. In first instance we approximate cumulative condensing gas boiler production by sales data for the Netherlands only, thereby neglecting technology spill over from other European countries and from outside Europe for the entire period of 1981-2006 (Figure 14). To account for technological learning and the accumulation of experience in other European countries, we conduct a sensitivity analysis, in which we extend the system boundary of our initial analysis and estimate cumulative experience in condensing gas boiler manufacturing based on condensing gas boiler sales in the EU-15 (Figure 14). Despite the fact, that in countries like Korea and Japan substantial amounts of condensing gas boilers are sold, we limit our sensitivity analysis to the EU-15 because complete time series data that would allow us to estimate cumulative global condensing gas boiler production were not available.

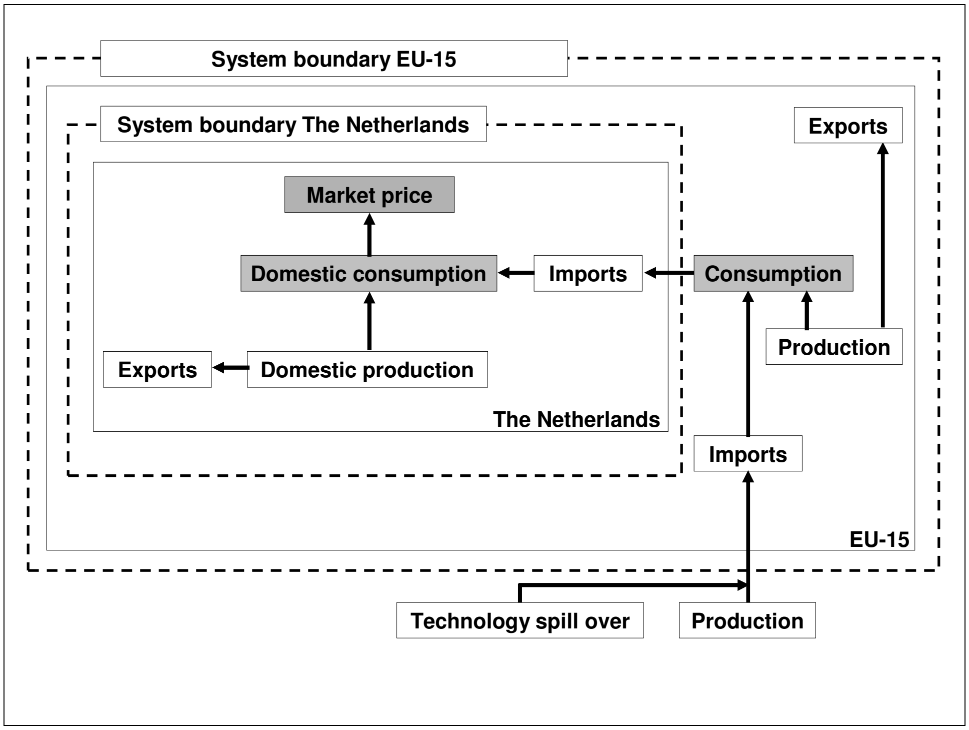

Figure 14: System boundary for the analysis as technological learning in condensing gas boiler manufacturing

Sales data for EU-15 are not available from public literature. We approximate boiler sales based on sales data for France, Germany, the UK, and the Netherlands. These four countries account together for roughly 90% of the market for condensing gas boilers in the EU-15 (see Figure 8). Our analysis thereby neglects technology spill-over from other world regions to boiler manufacturing in the EU-15 or *vice versa*. We estimate boiler capacities in the EU-15 based on *specific* capacity data for Dutch boilers as given by Consumentenbond (various years) and Warmteservice (2007a,b).

Calculating savings of energy, CO_2 emissions, and consumer costs

Next to the construction of experience curves, we calculate in a time series analysis national savings of energy, CO_2 emissions, and consumer costs due to the installation of condensing gas boilers in the Netherlands. For these analyses, we use data from the Consumentenbond (various years), EnergieNed (various years), and CBS (2007a). The basic assumptions for our calculations are summarized in Table 3, Table 4, and Table 5. We calculate yearly energy savings related to condensing gas boilers as:

$$G_{(i)} = C_{ICV(i)} \times M_{(i)} \times EF_{(G)} \times \left[\frac{Y_{ST(i)} n_{ST(i)} + Y_{IE(i)} n_{IE(i)} + Y_{CO(i)} n_{CO(i)}}{\left(\frac{Y_{ST(i)}}{Y_{ST(i)} + Y_{IE(i)}} n_{ST(i)} \right) + \left(\frac{Y_{IE(i)}}{Y_{ST(i)} + Y_{IE(i)}} n_{IE(i)} \right)} - 1 \right] \quad (7)$$

where $G_{(i)}$ [Mt CO_2] stands for the savings of natural gas, $C_{ICV(i)}$ [m^3] for the average natural gas consumption in *individuele centrale verwarming* (*ICV*) dwellings in year *i*, $M_{(i)}$ for the total gas boiler sales in the Netherlands, $EF_{(G)}$ [kg CO_2/m^3] for the emission factor of natural gas, $Y_{ST(i)}$, $Y_{IE(i)}$, and $Y_{CO(i)}$ for the market share, and $n_{ST(i)}$, $n_{IE(i)}$, and $n_{CO(i)}$ for the efficiency of *ST*andard, *I*mproved *E*fficiency, and *CO*ndensing gas boilers in year *i*. The consumer cost savings of condensing gas boilers relative to conventional boilers are calculated as:

$$CS_{(i)} = C_{CO(i)} - C_{ST,IE(i)} \quad (8)$$

where $CS_{(i)}$ refers to the cost savings due to the installation of a condensing gas boiler in year *i*, $C_{CO(i)}$ to the yearly costs related to the condensing gas boiler, and $C_{ST,IE(i)}$ to the yearly costs of a conventional non-condensing gas boiler.

Table 3: Background data used for calculating savings of energy, CO_2 emissions, and consumer costs related to condensing gas boilers

Year	Total number of condensing gas boilers installed in 1000 units	Natural gas consumption in *ICV* dwellings1) in m^3	Natural gas price in EUR/m^3	Standard gas boilers		Improved efficiency gas boilers		Condensing gas boilers	
				Average efficiency (LHV)	Market share	Average efficiency (LHV)	Market share	Average efficiency (LHV)	Market share
				in %					
1981	13	3152	0.19	77	85	82	7	91	7
1982	28	3021	0.22	77	82	82	10	92	7
1983	44	2896	0.23	77	70	83	21	92	9
1984	63	2767	0.25	77	61	83	29	93	10
1985	83	2630	0.26	78	59	84	32	93	9
1986	104	2497	0.25	78	54	84	37	94	9
1987	125	2362	0.18	78	50	84	42	94	8
1988	154	2238	0.18	78	44	85	45	95	11
1989	188	2110	0.17	79	37	85	50	95	12
1990	234	1989	0.20	79	29	86	55	96	16
1991	328	1888	0.22	79	14	86	56	96	30
1992	455	1765	0.21	79	6	86	57	97	38
1993	590	1729	0.20	80	4	87	55	97	41
1994	735	1818	0.21	80	8	87	52	98	40
1995	895	1795	0.21	80	6	88	50	98	44
1996	1084	1913	0.28	80	4	88	45	99	51
1997	1304	1779	0.25	81	5	88	37	99	58
1998	1543	1699	0.25	81	3	89	29	100	68
1999	1780	1733	0.24	81	1	89	24	100	75
2000	2024	1765	0.31	81	1	90	18	101	81
2001	2264	1805	0.38	82	0	90	17	101	83
2002	2482	1763	0.40	82	1	90	13	102	86
2003	2698	1710	0.43	82	1	91	13	102	86
2004	2902	1703	0.44	82	2	91	12	103	87
2005	3099	1648	0.50	83	1	92	8	103	91
2006	3281	1665	0.55	83	2	92	7	104	91

1) Data are estimates based on EnergieNed (various years). The numbers are given as *gross* values, i.e., they deviate from EnergieNed data, which already include the natural gas savings due to the installation of condensing gas boilers.

Table 4: Assumptions used for calculating yearly cost savings of condensing gas boilers (Data sources: Consumentenbond (various years), Warmteservice (2007a,b), Visser (2007))

Year	Nominal price of condensing gas boilers[1] in EUR	Nominal price of non-condensing gas boilers[2] in EUR	Nominal installation costs for condensing gas boilers in EUR	Nominal installation costs for non-condensing gas boilers[2] in EUR	Consumer price index
1981	1066	503	343	250	43
1982	1101	526	343	255	50
1983	1136	550	343	265	52
1984	1134	597	353	275	54
1985	1149	644	353	285	56
1986	1168	691	363	290	52
1987	1186	738	363	295	41
1988	1191	785	372	309	40
1989	1206	831	372	309	38
1990	1221	877	379	327	43
1991	1232	909	393	340	46
1992	1243	940	393	340	45
1993	1254	972	417	372	42
1994	1265	1003	417	372	44
1995	1257	1008	417	386	44
1996	1249	1008	424	397	47
1997	1241	1004	424	420	51
1998	1249	993	488	465	52
1999	1254	978	545	511	52
2000	1236	962	556	556	59
2001	1215	947	635	635	68
2002	1282	931	630	630	72
2003	1284	928	635	635	77
2004	1286	926	655	655	80
2005	1304	923	655	655	91
2006	1323	887	680	680	100

[1] Space heating boilers only

[2] Including standard and improved efficiency boilers for which installation costs are similar.

Table 5: Assumptions used for calculating savings of energy, CO_2 emissions, and costs due to the installation of condensing gas boilers

Emission factor natural gas in kg CO_2/m^3 (Sources: IEA (2007b), IPCC (1995))	1.87
Electricity savings of condensing gas boilers in kWh/a (Vaillant, 2007)[1]	0
Difference in nominal installation costs between condensing and non-condensing gas boilers in EUR[2]	20
Interest rate in %	7
Life time of boilers in years	15

[1] Based on information from Vaillant (2007), we assume average power requirements of 140 W_e for both conventional and condensing gas boilers. This assumption contrasts the estimates from Consumentenbond (various years) according to which condensing gas boiler save 200-300 kWh per year compared to conventional gas boilers. The estimates from Consumentenbond (various years), however, most likely compare condensing gas boilers with outdated boilers that are replaced and not with current closed improved efficiency gas boilers.

[2] Including sales tax.

We do not differentiate between standard and improved efficiency boilers. We calculate yearly costs assuming weighted average energy consumption and boiler prices for these two boiler categories combined based on their market share as presented in Table 3. We calculate $C_{CO(i)}$ as:

$$C_{CO(i)} = \left(GA_{CO(i)} \times P_{NG(i)}\right) + \left(\left(P_{CO(i)} + I_{CO(i)}\right) \times \left(\frac{IR}{1-(1+IR)^{-L}}\right) + M_{CO(i)}\right) \tag{9}$$

where: $GA_{CO(i)}$ - consumption of natural gas
$P_{NG(i)}$ - price of natural gas
$P_{CO(i)}$ - price of condensing gas boiler (space heating only)
$I_{CO(i)}$ - installation costs
IR - interest rate
L - life time of boiler
$M_{CO(i)}$ - maintenance costs

The calculation of $C_{ST,IE(i)}$ follows by analogy. We calculate natural gas consumption based on boiler efficiencies and average natural gas consumption in *ICV* dwellings (see Table 3). We conduct an uncertainty analysis for our results thereby changing input parameters (see Table 6).

Table 6: Sensitivity analysis - calculating consumer cost savings based on various boiler efficiencies

	Standard scenario	High savings scenario	Low savings scenario
Efficiency condensing gas boilers	91-104%	94-107%	90-100%
Efficiency non-condensing gas boilers	77-90%	73-86%	77-90%

Calculating payback time for condensing gas boilers in the Netherlands

To calculate payback times for condensing gas boilers relative to non-condensing boilers, we make use of the Dutch Residential Energy Model (DREM) based on Dittmar et al. (2007). For our calculations, we use a subroutine of DREM that calculates the simple payback times for a set of 16 reference dwellings in the time period of 1981-2005. For each of the reference dwellings *j*, we calculate for year *i* the simple payback time as a function of useful heat demand, boiler efficiencies, gas prices, investment costs (boiler price, installation and maintenance costs), and subsidies (see assumptions above). The calculations can be summarized as:

$$PB_{(i,j)} \frac{P_{CO(i)} + I_{CO} - P_{NCO(i)} - I_{NCO(i)} - S_{(i)}}{\left(\frac{GA_{(i,j)}}{\eta_{NCO(i)}} - \frac{CA_{(i.j)}}{\eta_{CO(i)}}\right) \times P_{NG(i)}} \tag{10}$$

where: $PB_{(i.j)}$ - payback time condensing gas boiler (space heating only)
$P_{NG(i)}$ - price of natural gas
$GA_{(i,j)}$ - useful heat demand
$\eta_{CO(i)}$ - efficiency condensing gas boilers
$\eta_{NCO(i})$ - efficiency non-condensing gas boilers
$P_{EL(i)}$ - price of electricity
$P_{CO(i)}$ - price of condensing gas boiler (space heating only)
$P_{NCO(i)}$ - price of non-condensing gas boiler (space heating only)
$I_{CO(i)}$ - installation costs condensing gas boiler
$I_{NCO(i)}$ - installation costs non-condensing gas boiler
$S_{(i)}$ - subsidies in period t

Given the distribution of dwelling types (see Table 7), we derive the mean payback time across all dwelling types for a given year *i* as:

$$\overline{PB}(i) = \sum_j SH(i,j) \times PB(i,j) \tag{11}$$

where: $\overline{PB}(i)$ - average payback time condensing gas boilers in year *i*
$PB(i,j)$ - payback time condensing gas boiler in year i, reference dwelling *j*
$SH_{(i,j)}$ - share of dwelling type j in year i

The calculations are based on the data as given in Table 3 (natural gas prices and boiler efficiencies) and Table 4 (investment and installation costs), respectively. The useful heat demand of reference dwellings, i.e., before boiler replacement, and the set of reference dwellings are based on Roos and Slot (2001) and Dittmar et al. (2007).

To test the relationship between market penetration and payback time of condensing gas boilers, we apply the concept of the so called *payback acceptance curve* (PAC). A PAC describes the percentage of consumers that would invest in a condensing gas boiler, if it would provide an acceptable payback time. We assume that the PAC is of standard logistic form:

$$MP_{con}(i) = \left\{ 1 - \frac{1}{1 + e^{(-\alpha * (\overline{PB}(i) - PB_{50}))}} \right\} \tag{12}$$

where: $MP_{con}(i)$ - market penetration of condensing gas boilers in year *i*
α - slope of the PAC
PB_{50} - payback at which market penetration is 50%

Table 7: Useful heat demand of reference dwellings (Data source: Dittmar et al. (2007))

	Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Type	Description (in Dutch)	**Useful heat demand in m^3 natural gas equivalents**																
1	<1966 vrijstaand	4808	4597	4397	4209	4034	3872	3724	3589	3467	3356	3258	3171	3093	3025	2964	2912	2866
2	<1966 2/1kap	3700	3542	3393	3254	3124	3004	2894	2795	2704	2623	2551	2486	2429	2379	2335	2296	2262
3	<1946 rijtjeswoning	2233	2142	2057	1978	1906	1840	1782	1729	1683	1643	1608	1577	1551	1529	1511	1495	1482
4	1946–1965 rijtjeswoning	1952	1883	1818	1758	1703	1653	1608	1568	1532	1500	1473	1449	1428	1411	1396	1383	1372
5	<1966 galerijwoning	1211	1193	1179	1169	1161	1158	1157	1160	1165	1173	1182	1194	1206	1220	1234	1248	1263
6	<1966 portiekwoning	1428	1390	1354	1321	1291	1264	1239	1217	1198	1182	1167	1155	1144	1136	1128	1122	1117
7	<1966 bovenwoning	1629	1578	1531	1487	1447	1410	1376	1346	1319	1296	1275	1257	1241	1228	1216	1206	1198
8	1966–1988 vrijstaand	4422	4192	3978	3779	3596	3428	3277	3140	3018	2909	2813	2729	2655	2590	2534	2485	2443
9	1966–1988 2/1kap	3188	3037	2897	2767	2647	2538	2440	2352	2273	2203	2142	2088	2041	2000	1965	1935	1909
10	1966–1976 rijtjeswoning	2009	1924	1846	1775	1710	1651	1600	1554	1514	1480	1450	1426	1405	1387	1373	1361	1352
11	1976–1980 rijtjeswoning	2291	2194	2104	2021	1944	1875	1812	1756	1707	1663	1625	1591	1563	1538	1517	1498	1483
12	1980–1988 rijtjeswoning	2284	2188	2098	2014	1937	1867	1804	1746	1695	1650	1609	1574	1543	1516	1493	1473	1455
13	1966–1988 galerijwoning	1056	1030	1007	987	969	954	941	931	922	916	912	909	907	906	907	908	909
14	1966–1988 portiekwoning	982	962	944	928	915	903	894	886	880	876	873	871	870	870	871	872	873
15	1966–1988 appartement	913	897	884	873	864	857	853	850	850	850	853	856	860	865	870	876	882
16	>1989 woningen	-	-	-	-	-	-	-	-	-	920	920	920	920	920	920	920	920
	Average	2473	2365	2265	2172	2086	2009	1939	1876	1820	1770	1702	1658	1619	1585	1555	1529	1507
		Share in %																
1	<1966 vrijstaand	11.2	11.0	10.8	10.6	10.4	10.2	10.0	9.8	9.6	9.4	9.0	8.8	8.7	8.6	8.4	8.3	8.2
2	<1966 2/1kap	8.5	8.4	8.2	8.0	7.9	7.8	7.6	7.5	7.3	7.2	6.9	6.8	6.7	6.5	6.4	6.3	6.2
3	<1946 rijtjeswoning	11.3	11.1	10.8	10.6	10.3	10.1	9.9	9.7	9.5	9.3	8.9	8.7	8.5	8.4	8.3	8.1	8.0
4	1946–1965 rijtjeswoning	14.0	13.8	13.6	13.3	13.1	12.9	12.7	12.5	12.3	12.1	11.6	11.4	11.3	11.1	10.9	10.8	10.6
5	<1966 galerijwoning	2.6	2.6	2.5	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.1	2.1	2.1	2.1	2.0	2.0
6	<1966 portiekwoning	11.2	11.0	10.8	10.6	10.4	10.2	10.1	9.9	9.7	9.6	9.1	9.0	8.8	8.7	8.6	8.4	8.3
7	<1966 bovenwoning	7.4	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.4	6.3	6.0	5.9	5.8	5.7	5.6	5.6	5.5
8	1966–1988 vrijstaand	4.5	4.6	4.6	4.7	4.8	4.8	4.9	5.0	5.0	5.1	5.0	4.9	4.9	4.8	4.7	4.7	4.6
9	1966–1988 2/1kap	5.0	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.1	5.0	5.0	4.9	4.8	4.8	4.7
10	1966–1976 rijtjeswoning	13.3	13.1	12.9	12.7	12.5	12.3	12.1	12.0	11.8	11.6	11.1	11.0	10.8	10.7	10.6	10.4	10.3
11	1976–1980 rijtjeswoning	3.3	3.3	3.2	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.7	2.7	2.7	2.7	2.6	2.6
12	1980–1988 rijtjeswoning	0.1	1.1	1.9	2.8	3.6	4.5	5.3	6.0	6.8	7.5	7.9	7.8	7.7	7.6	7.6	7.5	7.4
13	1966–1988 galerijwoning	3.0	3.1	3.3	3.4	3.5	3.7	3.8	3.9	4.0	4.1	4.1	4.1	4.0	4.0	3.9	3.9	3.8
14	1966–1988 portiekwoning	2.0	2.1	2.3	2.5	2.7	2.8	3.0	3.1	3.3	3.4	3.5	3.4	3.4	3.4	3.3	3.3	3.2
15	1966–1988 appartement	2.4	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.8	3.9	4.0	3.9	3.9	3.8	3.8	3.7	3.7
16	>1989 woningen	-	-	-	-	-	-	-	-	-	0.0	2.9	4.3	5.7	7.0	8.3	9.6	10.8
	Sum	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 7 (cont.): Useful heat demand of reference dwellings (Data source: Dittmar et al. (2007))

	Year	1998	1999	2000	2001	2002	2003	2004	2005
Type	Description (in Dutch)	**Useful heat demand in m^3 natural gas equivalents**							
1	<1966 vrijstaand	2825	2790	2760	2733	2711	2691	2673	2658
2	<1966 2/1kap	2232	2207	2184	2165	2148	2133	2120	2109
3	<1946 rijtjeswoning	1471	1462	1455	1449	1444	1440	1436	1434
4	1946–1965 rijtjeswoning	1363	1356	1350	1344	1340	1336	1333	1331
5	<1966 galerijwoning	1277	1290	1303	1316	1327	1338	1348	1357
6	<1966 portiekwoning	1113	1110	1108	1106	1104	1103	1102	1101
7	<1966 bovenwoning	1191	1185	1180	1176	1173	1170	1167	1165
8	1966–1988 vrijstaand	2407	2376	2349	2325	2305	2288	2273	2261
9	1966–1988 2/1kap	1886	1867	1851	1837	1825	1815	1806	1799
10	1966–1976 rijtjeswoning	1344	1338	1334	1330	1327	1325	1323	1322
11	1976–1980 rijtjeswoning	1470	1459	1449	1442	1435	1429	1425	1421
12	1980–1988 rijtjeswoning	1440	1427	1416	1407	1399	1392	1385	1380
13	1966–1988 galerijwoning	911	913	916	918	920	923	925	927
14	1966–1988 portiekwoning	875	877	879	881	883	885	887	889
15	1966–1988 appartement	888	894	899	905	910	915	919	923
16	>1989 woningen	920	920	920	920	920	920	920	920
	Average	1487	1469	1453	1444	1431	1420	1411	1403
		Share in %							
1	<1966 vrijstaand	8.0	7.9	7.8	7.8	7.6	7.6	7.5	7.4
2	<1966 2/1kap	6.2	6.1	6.0	5.9	5.8	5.8	5.7	5.6
3	<1946 rijtjeswoning	7.8	7.7	7.6	7.6	7.4	7.4	7.3	7.2
4	1946–1965 rijtjeswoning	10.5	10.3	10.2	10.1	9.9	9.8	9.7	9.6
5	<1966 galerijwoning	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.8
6	<1966 portiekwoning	8.2	8.1	8.0	7.9	7.8	7.7	7.6	7.5
7	<1966 bovenwoning	5.4	5.3	5.2	5.2	5.1	5.1	5.0	5.0
8	1966–1988 vrijstaand	4.6	4.5	4.5	4.5	4.4	4.4	4.3	4.3
9	1966–1988 2/1kap	4.7	4.6	4.6	4.6	4.5	4.5	4.4	4.4
10	1966–1976 rijtjeswoning	10.2	10.0	9.9	9.9	9.8	9.7	9.6	9.5
11	1976–1980 rijtjeswoning	2.6	2.5	2.5	2.5	2.5	2.4	2.4	2.4
12	1980–1988 rijtjeswoning	7.3	7.2	7.1	7.1	7.0	7.0	6.9	6.9
13	1966–1988 galerijwoning	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.6
14	1966–1988 portiekwoning	3.2	3.2	3.1	3.1	3.1	3.1	3.0	3.0
15	1966–1988 appartement	3.6	3.6	3.6	3.6	3.5	3.5	3.5	3.4
16	>1989 woningen	12.1	13.2	14.4	14.8	15.8	16.8	17.6	18.3
	Sum	100	100	100	100	100	100	100	100

The PAC is defined such that condensing gas boilers are adopted in 50% of all cases, if the payback period equals an acceptable value (i.e., PB_{50})[21]. We fit the PAC based on data for market penetration and the calculated average payback time across all dwellings (including subsidies).

4.1.5 Experience curves for condensing gas boilers

We develop two sets of experience curves, one for condensing gas boilers that are exclusively used for space heating (Figure 15 and Figure 17) and another one for condensing gas boilers that are used for space heating and hot tap water production (i.e., so called condensing gas combi boilers) (Figure 16 and Figure 18). The data points in the diagrams represent the average purchasing prices of all boilers included in the analysis for individual years. Installation and maintenance costs are excluded. The uncertainty intervals represent the standard deviation of boiler prices included in the analysis.

Using cumulative boiler sales in the Netherlands as independent variable, we identify learning rates of (7.0 ± 0.9)% for condensing gas boilers (space heating only) and (14.0 ± 1.2)% for condensing gas combi boilers. Extending the system boundary of our analysis and plotting average Dutch boiler prices as a function of cumulative boiler sales in the EU-15 has only minor effects on the results of our analysis. The changes of learning rates remain within the error margins of our results (i.e., we identify learning rates of (6.3 ± 1.0)% for condensing gas boilers (space heating only) and of (14.1 ± 1.0)% for condensing gas combi boilers). The relatively small differences between these results are caused by the fact that cumulative condensing gas boiler sales in the EU-15 increased *not entirely* proportional to the Dutch boiler sales. We nevertheless conclude that the error introduced to our results by narrowing the system boundary of our analysis to the Netherlands (thereby neglecting condensing gas boiler production in other countries) might be negligible.

For conventional non-condensing gas boilers[22], we find learning rates of (15.1 ± 8.4)% (R^2=0.33) for space heating boilers and (26.6 ± 7.7)% (R^2=0.66) for combi boilers (results are not shown in the diagrams). These results suggest that production costs for conventional non-condensing gas boilers decrease at a higher rate than the ones for condensing gas boilers.

By analyzing additional production costs of condensing gas boilers compared to conventional, non-condensing gas boilers, we identify learning rates of (13.2 ± 2.8)% and (26.4 ± 7.4)% for space heating and condensing gas combi boilers, respectively (Figure19).

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[21] We refer to Boonekamp (2005), who applies a similar formulation to estimate cost benefit ratios instead of payback times.

[22] We calculate learning rates based on (i) the average price of all non-condensing gas boilers (standard efficiency and improved efficiency as given by Consumentenbond (various years) and Warmteservice (2007a,b)) and (ii) data on cumulative non-condensing gas boiler sales in the Netherlands.

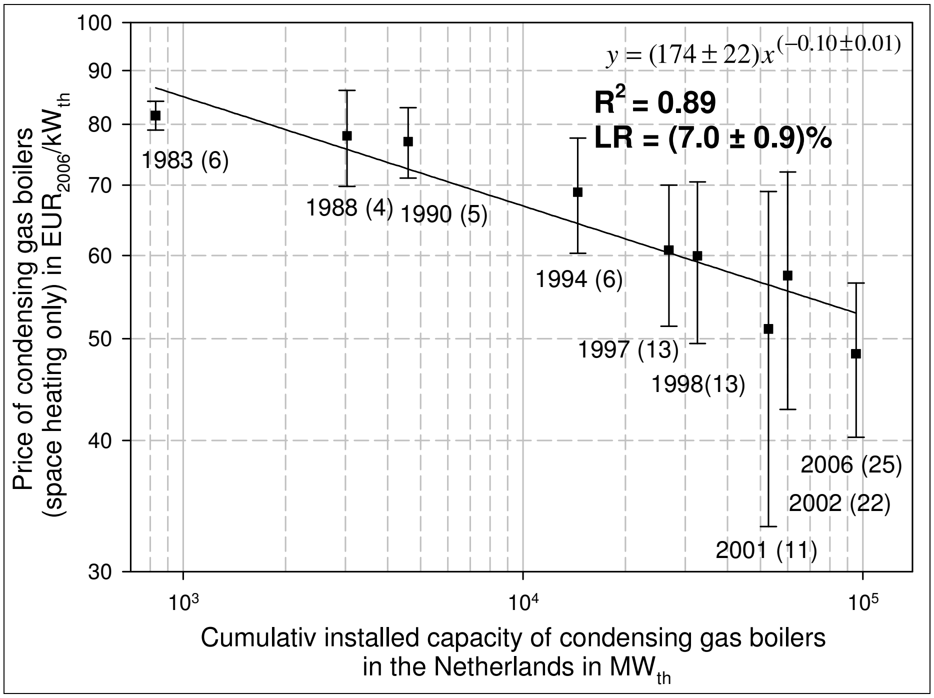

Figure 15: Experience curve for condensing gas boilers (space heating only) in the Netherlands (period of 1983-2007), in brackets number of price data included in the analysis (Data sources: Consumentenbond (various years), Aptroot and Meijnen (1993), CBS (2007a), Sijbring (2007), van Maaren (2007))

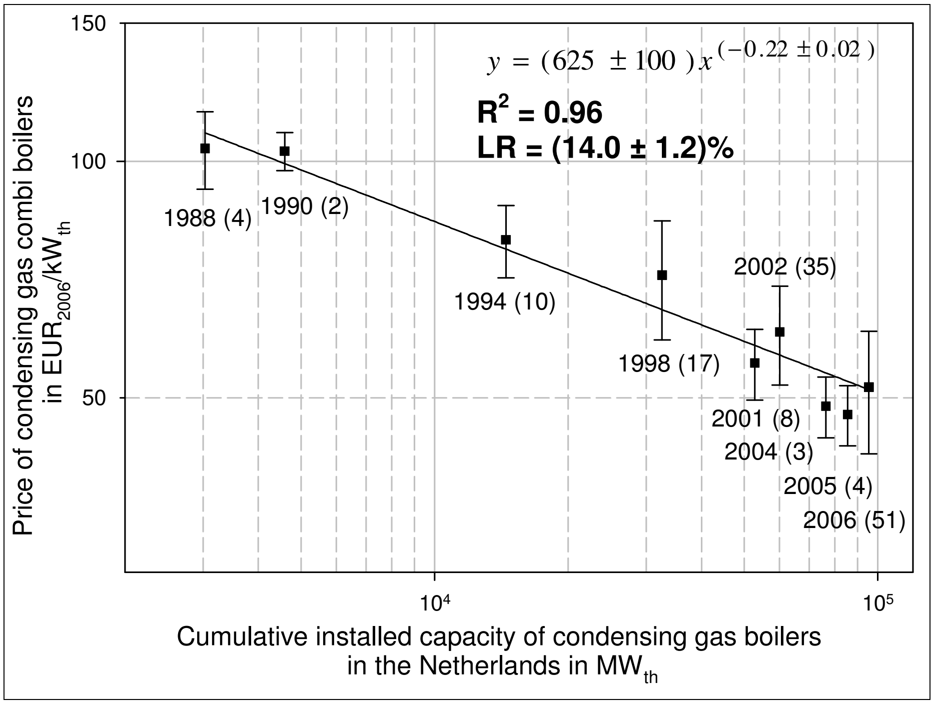

Figure 16: Experience curve for condensing gas combi boilers in the Netherlands (period of 1988-2006), in brackets number of data included in the respective year of analysis (Data sources: Consumentenbond (various years), Aptroot and Meijnen (1993), CBS (2007a), Sijbring (2007), van Maaren (2007))

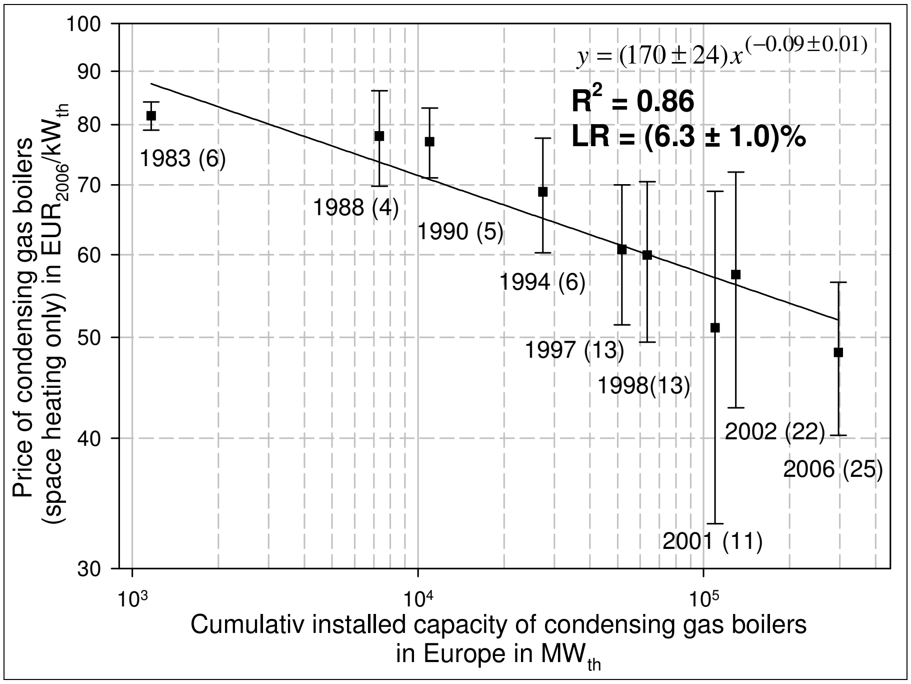

Figure 17: Experience curve for condensing gas boilers (space heating only) in the EU-15 (period of 1983-2007), in brackets number of price data included in the analysis (Data sources: Consumentenbond (various years), Aptroot and Meijnen (1993), CBS (2007a), Sijbring (2007), van Maaren (2007))

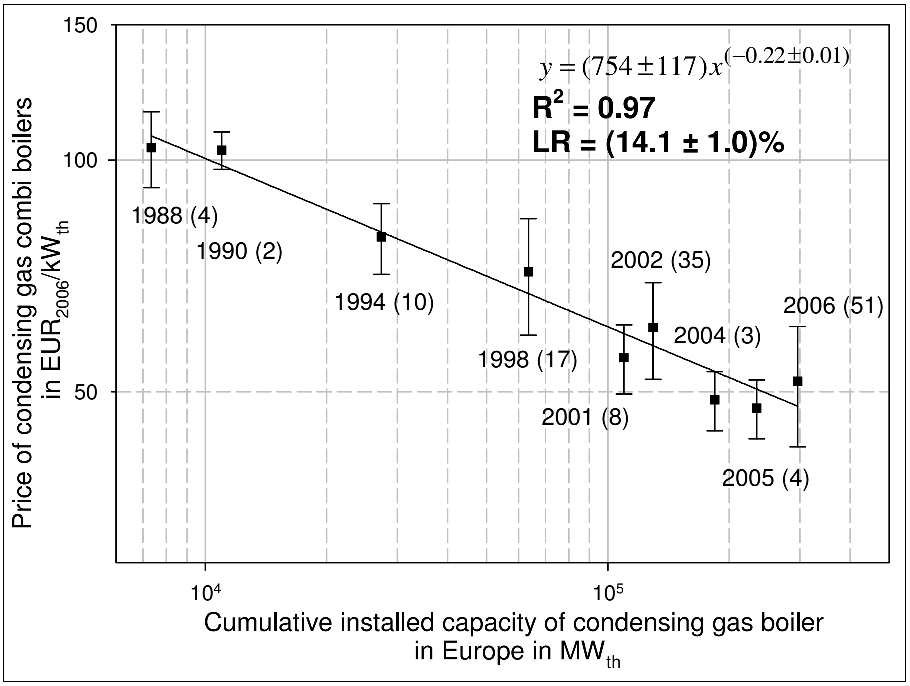

Figure 18: Experience curve for condensing gas combi boilers in the EU-15 (period of 1988-2007), in brackets number of price data included in the analysis (Data sources: Consumentenbond (various years), Aptroot and Meijnen (1993), CBS (2007a), Sijbring (2007), van Maaren (2007))

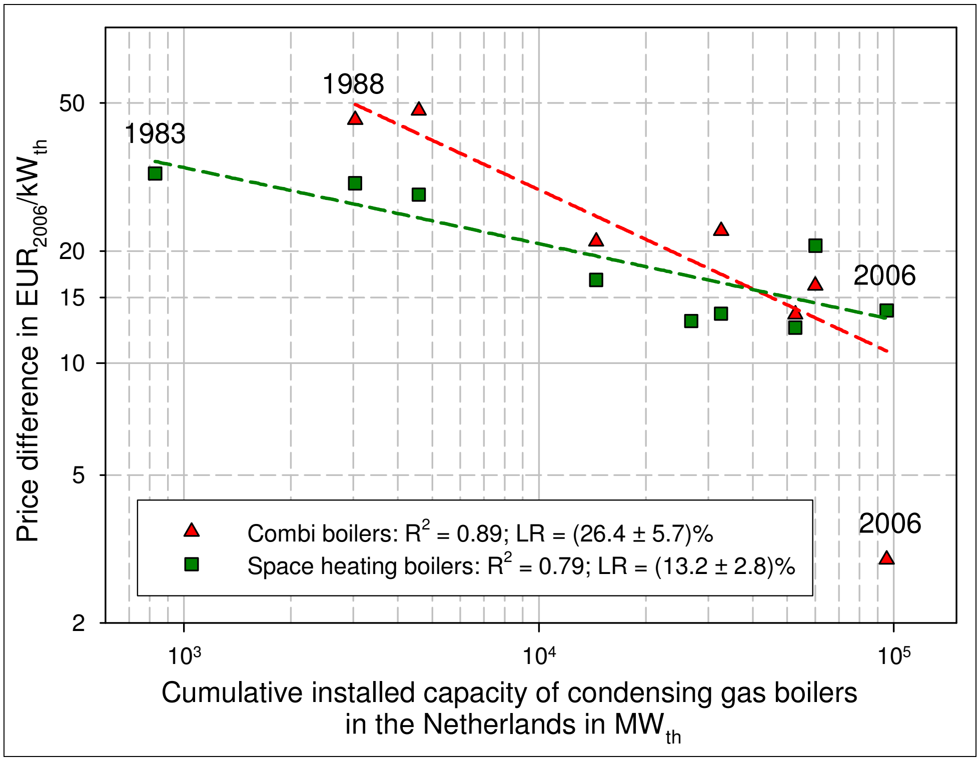

Figure 19: Experience curve for the additional production costs of condensing gas combi and space heating boilers compared to conventional, non-condensing gas boilers in the Netherlands; the numbers in the diagram indicate the years to which the data refer to

Four aspects have to be taken into account when interpreting the presented experience curve results:

- The average additional price of condensing gas combi boilers in the year 2006 is extremely low (Figure 19). Regarding this point as outlier would reduce the learning rate to (23.8 ± 4.9)%.
- The price estimates for conventional non-condensing gas boilers are associated with considerably higher uncertainties than the price estimates for condensing gas boilers. The reason is that the former product category comprises a relatively heterogeneous group of gas boilers (i.e., standard and improved efficiency boilers with open and closed boiler systems). The various non-condensing boiler types differ considerably in price. Furthermore, the share of individual types on the average non-condensing gas boiler price as calculated for individual years vary depending on the availability of price data.
- The actual reduction of prices for non-condensing gas boilers per year (1.6% and 1.4% for space heating and combi boilers in the period 1983/1988-2006, respectively) are much smaller than the one for condensing gas boilers (2.4% for condensing gas space heating boilers (1983-2006) and 4.4% for condensing gas combi boilers (1988-2006)) because the periods in which doublings of cumulative

non-condensing gas boiler sales occur, are much longer (due to the fact that conventional, non-condensing gas boilers are sold in the Netherlands already since the 1960s).

- The price decrease of conventional gas boilers might be to some extent caused by a considerable reduction of profit margins at the producer side, i.e., boiler producers might earn their profits from the mass production of condensing gas boilers and no longer from non-condensing boilers as it was the case until the early 1990s.

The identified learning rates for condensing gas boilers are in line with the results found for other energy technologies (i.e., 15-18% for on-shore wind farms (Junginger, 2005), 22% for photovoltaics (McDonald and Schrattenholzer, 2001), 8% for electricity production from bio-fueled CHP plants (Junginger, 2005), 6% for combined cycle power plants (Claeson Colpier et al., 2002)). Our values are, however, higher than the learning rates as estimated for condensing gas boilers in other studies (Table 8). The observed deviation might be explained by deviations, e.g., in the system boundaries of data and regarding the time periods for which the analyses were conducted. The differences in the learning rates as identified in this study for condensing gas space heating boilers (6.3-7%) and combi boilers (about 14%) is discussed below.

Table 8: Comparison of results with literature data

	Source	Learning rate in %
Condensing gas boilers, space heating only, Dutch sales data, 1983-2006	This study	7.0 ± 0,9
Condensing gas boilers, space heating only, EU-15 sales data, 1983-2006	This study	6.3 ± 1.0
Condensing gas combi boilers, Dutch sales data, 1988-2006	This study	14.0 ± 1.2
Condensing gas combi boilers, EU-15 sales data, 1988-2006	This study	14.1 ± 1.0
Condensing gas boilers, German cost and sales data, 1992-1999	Martinus et al. (2005)	4
Condensing gas boilers, Dutch cost and sales data, 1983-1997	Haug et al. (1998)	4

The observed reductions of condensing gas boiler prices are related to considerable reductions of production costs in the time period studied (Overdiep, 2007). Due to lack of detailed quantitative information, we qualitatively explain reasons and factors leading to the observed decrease in production costs for condensing gas boilers in the Netherlands.

With respect to boiler components, the most important technological changes in the period of 1981-2006 are:

- size reduction (i.e., decrease of material costs) of heat exchangers by roughly 50% between 1981-2007;
- improvements in control electronics (boiler electronics became smaller and at the same time more complex and powerful);
- optimization of internal boiler settings;
- material improvements (e.g., stainless steel is used rather than aluminium for flue gas removal);

- a shift from non-modulating burners (i.e., burners that only work in an *on/off* mode) to modulating ceramic burners (i.e., the power output of burners can be modulated according to the specific heat demand) leading to an improved gas/air management and reduced natural gas consumption.

Major changes regarding individual cost factors for boiler production refer to heat exchangers and control electronics. At the beginning of condensing gas boiler manufacturing in the 1980s, heat exchangers were the single largest cost component in boiler production, accounting for 30% of the total boiler production costs. This share has been reduced drastically in the past 25 years. Nowadays, control electronics are the most important cost component (Overdiep, 2007, van Maaren, 2007, Sijbring, 2007). Looking at the whole time period of 1980-2007, technological developments allowed for reducing the size and mass of condensing gas boilers by a factor of 2-3. Next to improvements in boiler components, major changes in boiler production took place: Cost reductions in manufacturing processes were realized by:

- upscaling of boiler production (i.e., economies of scale);
- improvements of production technology and automation;
- outsourcing of component production.

Outsourcing of component production after the year 2000 to specialized companies was deemed to be a major driver for reducing production costs of condensing gas boilers (Overdiep, 2007, Sijbring, 2007, van Maaren, 2007). In the 1980s, Dutch boiler manufacturers produced the boiler components (e.g., heat exchangers, burners) themselves and only bought control electronics from external suppliers. Nowadays, boiler producers assemble standard components but do not produce these components themselves anymore. Condensing gas boiler manufacturing is also effected by the merging of boiler producers (e.g., Buderus took over Nefit and was itself bought by Bosch). This development offers further potentials for upscaling of production, thereby decreasing purchasing costs of raw materials and components, sales and marketing costs, R&D expenses and other cost items. The differences between the learning rates for condensing gas boilers used for space heating (LR 6.3-7%) and condensing gas combi boilers (about 14%) might be explained by the additional technological learning that occurred due to the integration of a hot water boiler unit into condensing space heating boilers.

Uncertainties of our analysis are related to data on boiler prices. In later years, we use average prices of about 50 condensing gas combi boilers to construct experience curves. For early years, far less data were available (Figure 20). This increases the uncertainties of our results because the impact of each boiler model, which is included in or excluded from our analysis, becomes higher, if the number of boilers that are used for constructing the experience curve is low. The observed changes in average boiler prices might, therefore, to some extent not be caused by technological learning but solely by the composition of the product mix.

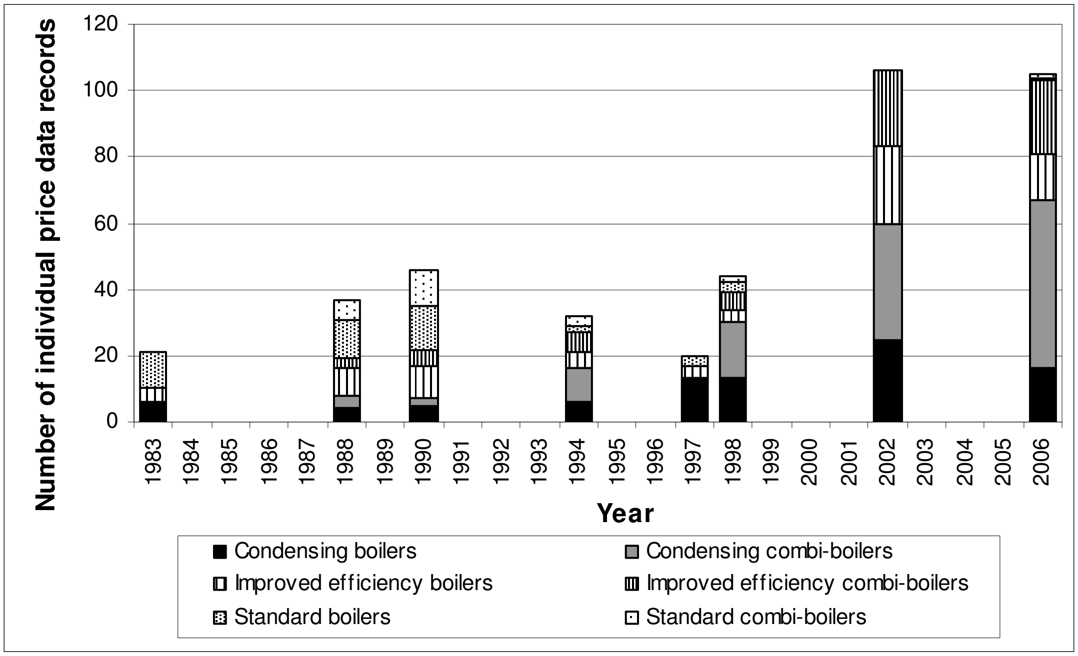

Figure 20: Number of price data records used for constructing experience curves for condensing gas boilers

Finally, our assumptions used for the calculation of cumulative boiler capacities in the EU-15 are uncertain because they are based on typical unit sizes as found on the Dutch boiler market. We do, therefore, not account in our sensitivity analysis for the fact that boilers installed in countries like Germany or France might differ regarding their average capacity from the ones installed in the Netherlands.

4.1.6 National savings of energy, CO_2 emissions, and consumer costs

The replacement of conventional non-condensing gas boilers by condensing gas boilers saves energy and CO_2 emissions (Figure 21). Yearly savings increase mainly as a consequence of the increasing number of installed condensing gas boilers. For the year 1995, we calculate natural gas savings of 410 kt CO_2 equivalents. This estimate is considerably lower than the one calculated by Jeeninga (1999) for the same year (i.e., 820 kt CO_2 equivalents). We explain the deviation with differences regarding assumed boiler efficiencies and reference boiler technology[23]. For the year 2005, we estimate energy savings of roughly 1.47 Mt CO_2. These savings are equivalent to 0.9% of the total fuel use emissions in the Netherlands (UNFCCC, 2007). According to our estimates, over the entire period of 1981-2006, condensing gas boilers contributed to savings of 7.2 billion m^3 natural gas, 13.5 Mt CO_2 emissions, and energy costs of 2.7 billion EUR.

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[23] Jeeninga (1999) calculates energy savings that result from replacing old and outdated boilers by new condensing gas boilers, while we calculate savings that result from the consumer choice in a particular year to buy a condensing gas boiler rather than a non-condensing one. The differences between our estimates and the results from Jeeninga (1999) are to a large extent explained by efficiency improvements of non-condensing gas boilers.

The calculated savings of energy costs can be compared (i) with the total additional costs for consumers due to purchase, installation, and maintenance of condensing gas boilers and (ii) with the subsidies spent by the government in support of condensing gas boilers in the Netherlands. In Table 2, we presented estimates on the total subsidies in support of condensing gas boilers (i.e., 58-83 million EUR). In the period of 1981-2006, consumers paid roughly 1.6 billion EUR in addition to conventional non-condensing boilers for purchase, installation, and maintenance of condensing gas boilers. Together with subsidies and the realized savings of energy costs, this accounts for *net* savings of about 1.0 billion EUR or 75 EUR/t CO_2 avoided emissions (Table 9). This result demonstrates the high cost efficiency of condensing gas boilers for greenhouse gas emission mitigation[24].

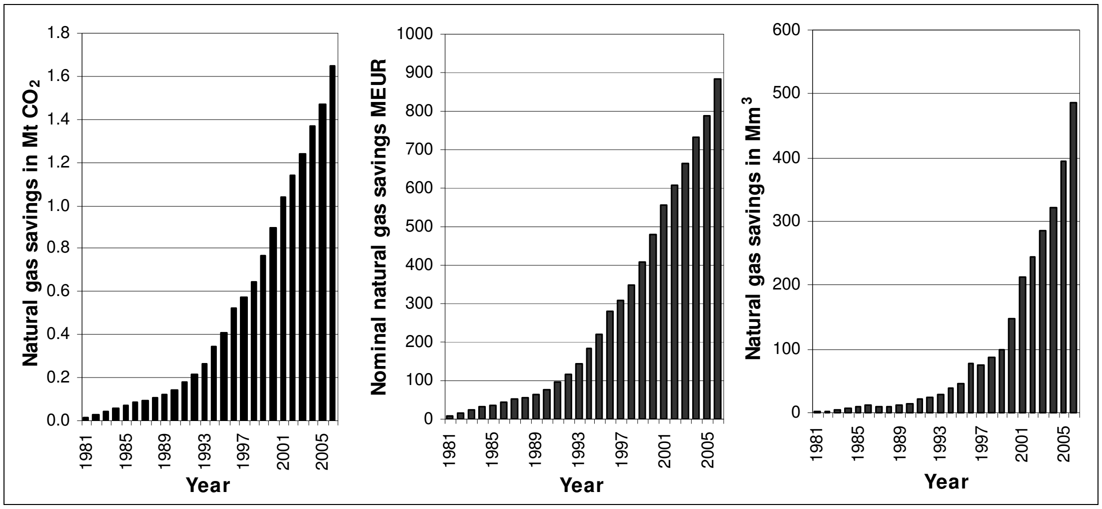

Figure 21: Natural gas savings of condensing gas boilers relative to conventional, non-condensing gas boilers in the Netherlands

Table 9: Total cost-benefit estimates for condensing gas boilers in the Netherlands (period 1981-2006)

Subsidies in million EUR	58-83
Additional consumer costs in million EUR	1597
Savings of primary energy in million EUR	2673
Net savings in million EUR	~1000
Emissions savings in Mt CO_2	13.5
Savings in EUR/t CO_2	~75

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[24] We include as direct costs only subsidies that have been paid in support of condensing gas boilers. However, the introduction of condensing gas boilers resulted also in more indirect costs for the government based on the shortfall of tax revenue in the period of 1981-2006 due to reduced natural gas consumption in the Netherlands. We quantify this effect with roughly 0.9-1.2 billion EUR. Reduced tax earnings between 1981 and 2006 might, however, not be *lost* for the government but might potentially even result in over proportional tax earnings in future years when natural gas is consumed at higher prices than in the period of 1981-2006. This consideration holds especially for the Netherlands, where a large share of the consumed natural gas is produced domestically.

4.1.7 Cost-benefit analysis for condensing gas boilers in Dutch households

Based on boiler prices, installation and maintenance costs, as well as on the yearly consumption of natural gas (see Table 3-5), we calculate yearly savings (in monetary terms) generated by condensing gas boilers relative to conventional non-condensing gas boilers (Figure 22-24)[25]. In the period studied, additional yearly costs for purchase, installation, and maintenance of condensing gas boiler compared to conventional non-condensing boiler declined considerably. Together with savings of natural gas, this adds to *net* yearly savings of condensing gas boilers of up to 70 EUR per boiler in 2006 (standard scenario). Similar savings were reached around the mid 1980s but the lion's share of these cost savings were caused by subsidies. In some years between 1987 and 1995, consumer costs were slightly higher for condensing gas boilers compared to conventional boilers (Figure 22).

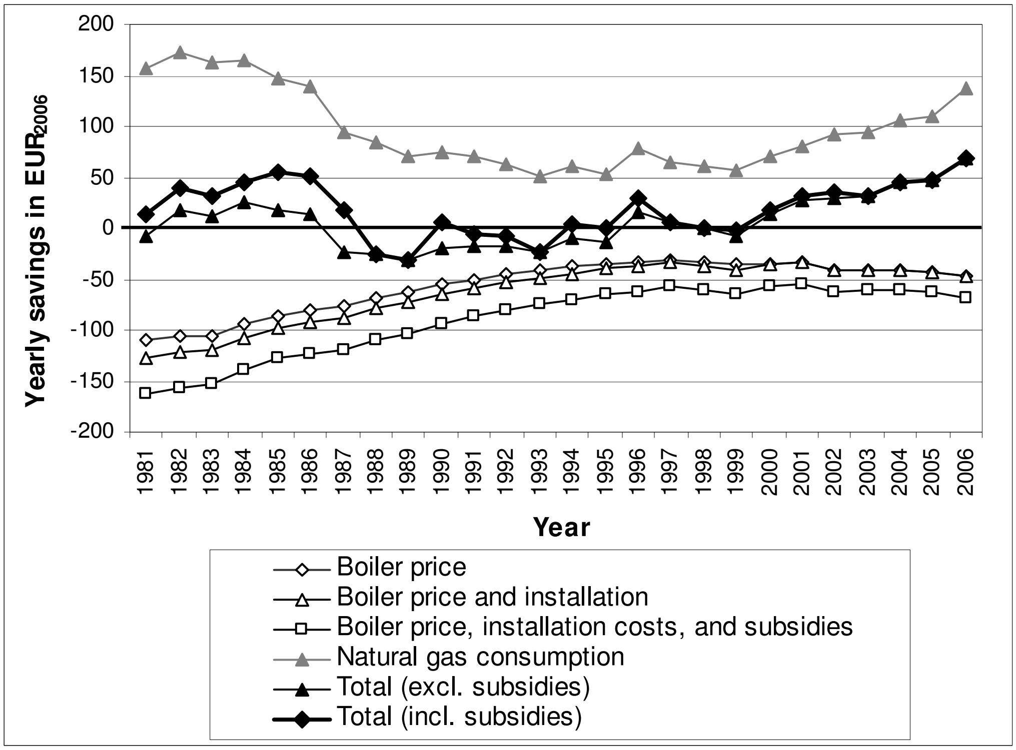

Figure 22: Yearly inflation corrected cost savings of condensing gas boilers in the Netherlands (standard scenario)

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[25] For the yearly savings calculation, we assume constant natural gas savings per year for the entire lifetime of a condensing gas boiler based on the savings in the year of purchase. We thereby assume that consumption and prices of natural remain constant throughout the entire life time of condensing gas boilers.

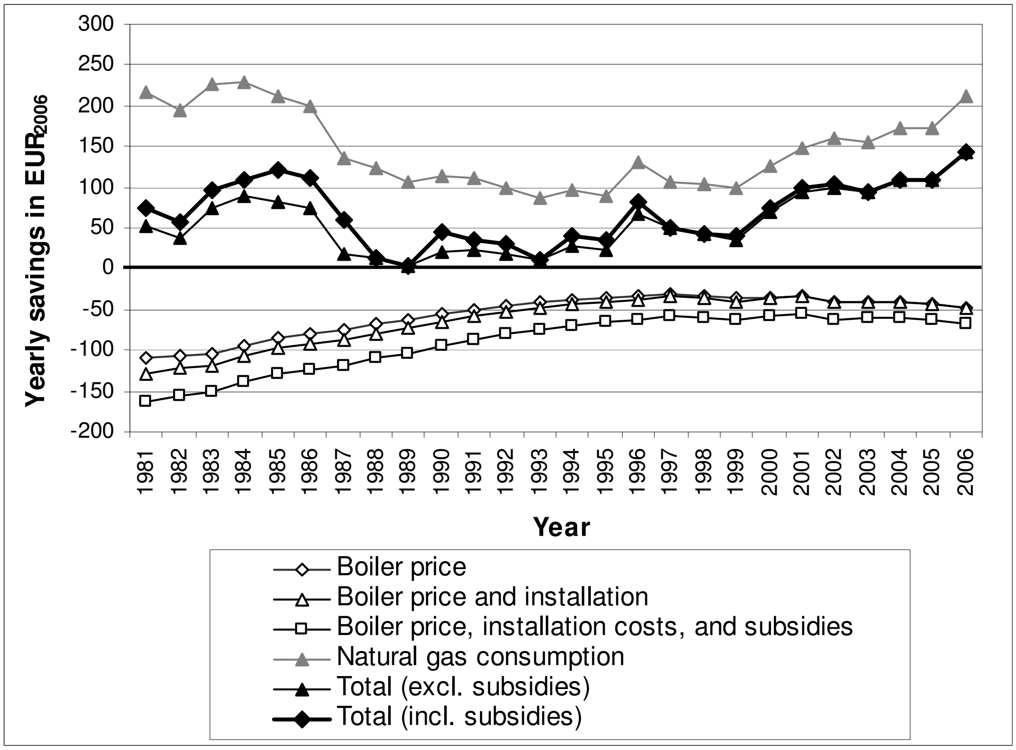

Figure 23: Yearly inflation corrected cost savings of condensing gas boilers in the Netherlands (high savings scenario)

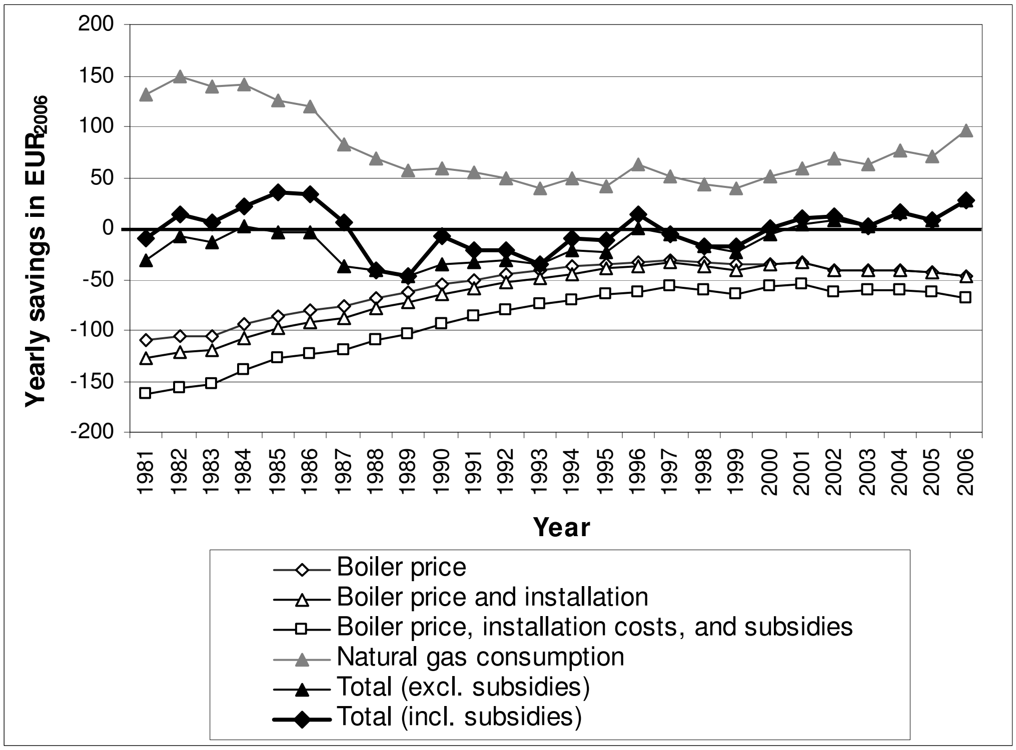

Figure 24: Yearly, inflation corrected cost savings of condensing gas boilers in the Netherlands (low savings scenario)

Based on the calculations presented so far, we can also calculate the costs incurred for CO_2 abatement by condensing gas boilers (Figure 25). The costs for CO_2 emission savings are for many years negative and follow in general the general trend as found in the Figures 22-24[26].

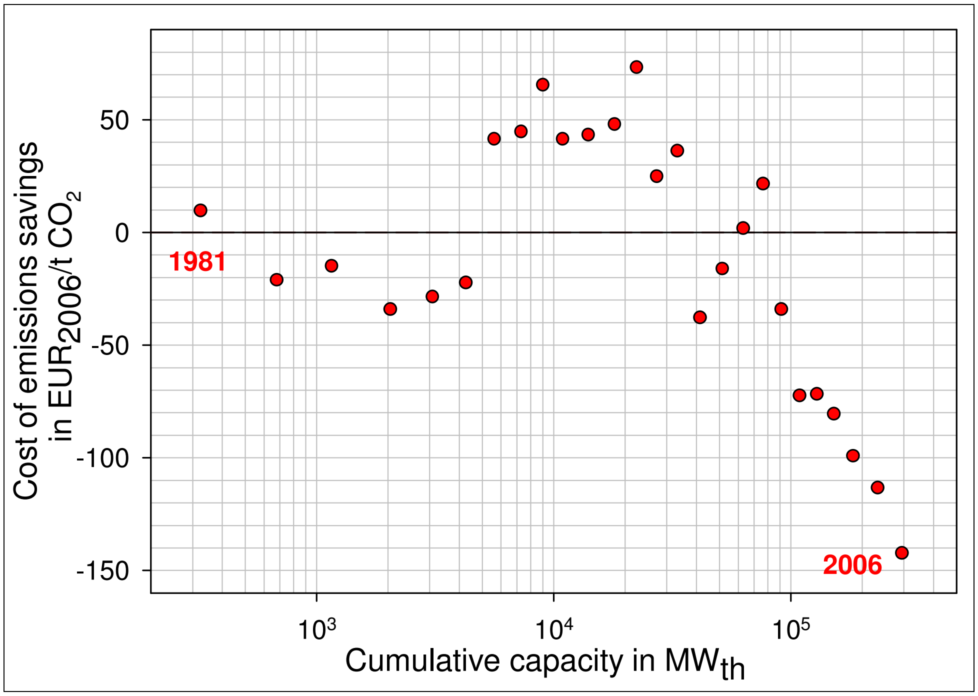

Figure 25: Costs of CO_2 emission savings that have been achieved by condensing gas boilers in the Netherlands[27]

Based on the results presented in Figures 22-25, we draw four conclusions:

- Purchase of a condensing gas boiler has been profitable for consumers in most of the years.
- Natural gas prices and the amount of natural gas consumed per year have a considerable effect on the achieved yearly cost savings of condensing gas boilers.
- Subsidies have been important to make the purchase of a condensing gas boiler profitable for consumers in years (e.g., 1987-1997) where natural gas prices were low and the purchase of a condensing gas boiler would have not been profitable.
- The results of our analysis are subject to uncertainties and sensitive to the underlying assumptions, e.g., boiler efficiencies and average boiler prices.

The sensitivity analysis presented in Figure 23 and Figure 24 indicates that results deviate from the standard scenario, if assumptions are changed, i.e., the assumed average efficiencies of condensing and non-condensing gas boilers (see Table 6). Our results are,

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[26] Note that we plot in Figure 25 the *costs* of CO_2 emission savings, while we show in the Figures 22-24 *cost savings*. Negative *costs* are equivalents to positive *cost savings*.

[27] We include additional costs for purchase, installation, and maintenance of condensing gas boilers relative to conventional, non-condensing boilers as well as subsidies for boilers. We put these *additional* costs in relation to the realized natural gas savings.

furthermore, highly sensitive to the assumed natural gas consumption in households. For average natural gas consumption as assumed in Table 3, it is in general profitable for consumers to install condensing gas boilers. Our results, however, also indicate that yearly savings are not constant but vary and can even be negative (in case of a low natural gas price).

More insight into the cost effectiveness of condensing gas boilers can be gained through the analysis of dwelling stock composition in terms of natural gas demand. Natural gas demand essentially determines the economic viability of condensing gas boilers at given gas prices and boiler efficiencies. We, therefore, calculate payback times for condensing gas boilers differentiating 16 types of dwellings based on a subroutine of the Dutch Residential Model (Dittmar et al., 2007). The basic assumptions and the calculation procedures used for these calculations are described in Section 4.1.4. The results are presented in Figure 26 and Figure 27.

It is conspicuous that dwellings with relatively high a heat demand, namely detached and semi-detached dwellings, show payback times below 5 years almost over the entire period considered (see Figure 26, graph a). Even without subsidies, the payback times for these dwelling types remain sufficiently low, i.e., at maximum 8 years (see Figure 26, graph b).

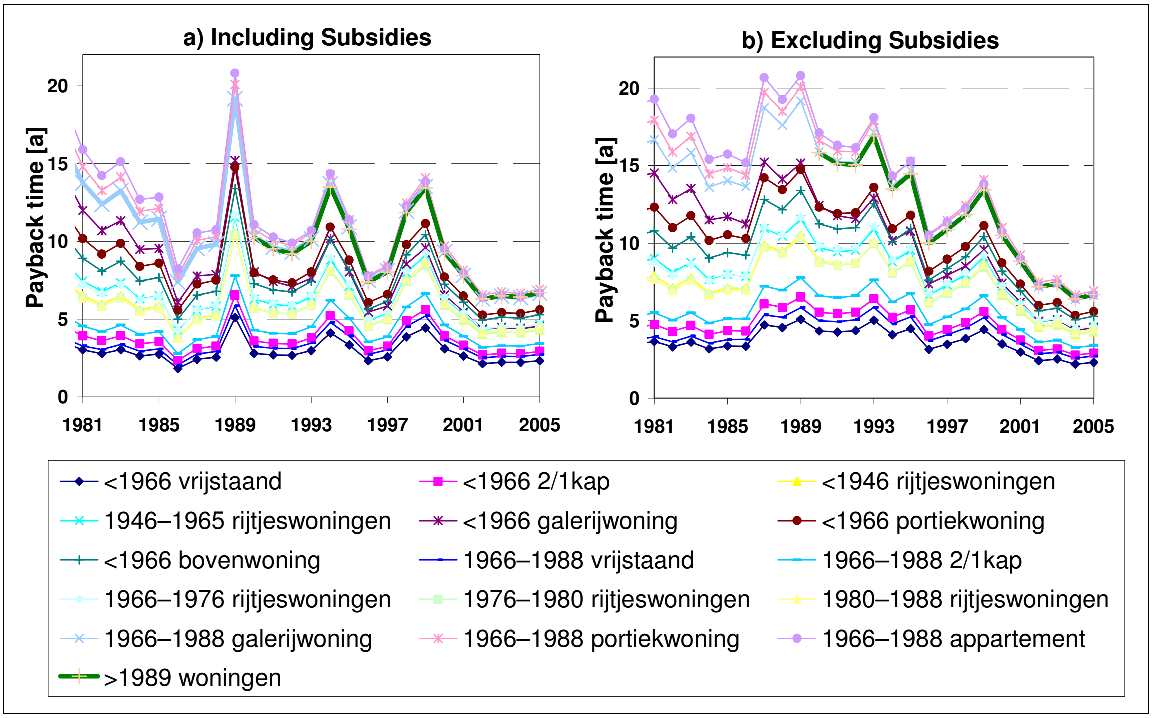

Figure 26: Payback times for condensing gas boilers for 16 different dwelling types in the Netherlands

On the other hand, smaller dwellings (e.g., apartments) show considerably higher payback times, which even exceed the lifetime of condensing gas boilers in some years of our analysis; thereby indicating that condensing gas boilers cannot recover their additional costs within their own lifetime.

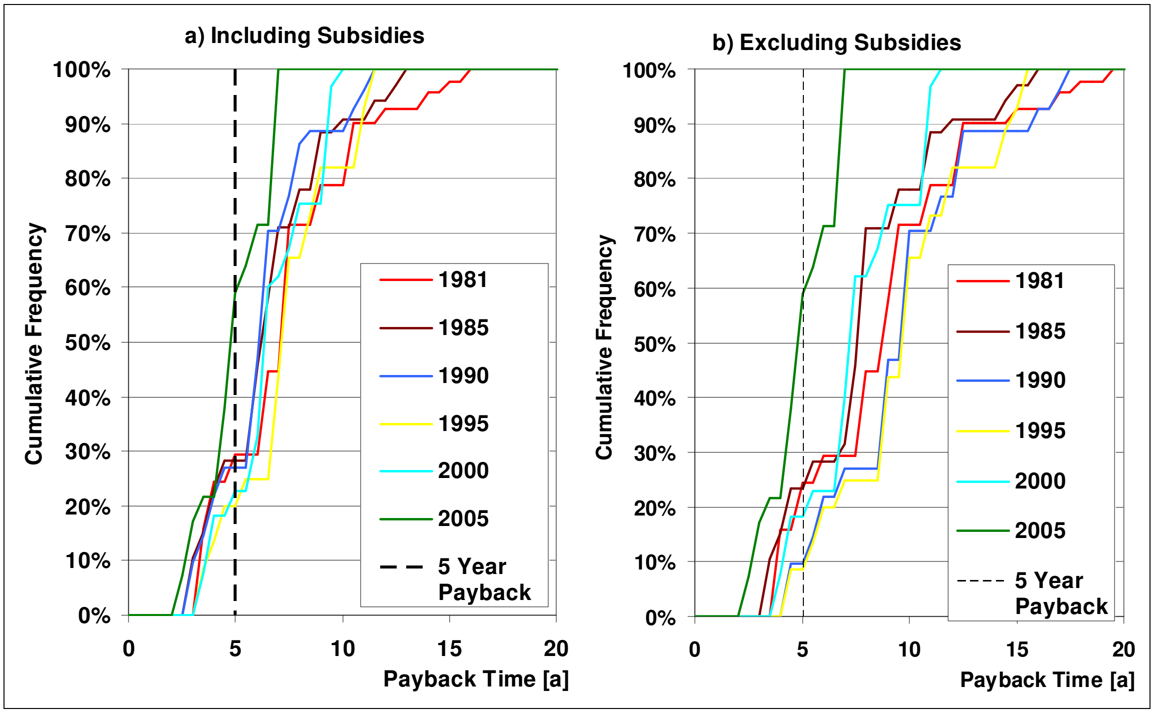

Figure 27: Cumulative frequency curve of payback times for condensing gas boilers in Dutch dwellings for selected years

Furthermore, it is noticeable that payback times realised in dwellings built after 1989 are extraordinarily high (due to relatively low demand for natural gas), i.e., up to 14 years (with subsidies) and even above 15 years without subsidies. Under the simplified assumption that economic profitability, i.e., payback time solely explains the development of the condensing gas boiler market, we may conclude that detached and semi-detached houses were not only potential early adaptors of condensing gas boilers, but also the main target group of condensing gas boiler manufacturers and retailers. This finding can be important when evaluating the market potential for the follow-up technology of condensing gas boilers, i.e., the micro-CHP (see Section 4.2). Economic profitability is, however, not the only relevant criterion that explains the evolution of the condensing gas boiler market in the Netherlands. For example, condensing gas boilers were, among others, installed in newly built dwellings in order to comply with official energy standards, i.e., the *Energie Prestatie Norm* (*EPN*), which was introduced at the end of 1995 (Dougle and Oosterheert, 1999). Beerepoot (2007) observed a significant statistical relationship between the introduction of the *EPN* and the success of condensing gas boilers in newly built dwellings. Nevertheless, we may conclude that the replacement market for semi-detached and detached dwellings had an even stronger influence on condensing gas boiler sales. This hypothesis is confirmed by the cumulative frequency curve of payback times for condensing gas boilers (Figure 27). At the time of market introduction of condensing gas boilers in 1981, the share of dwellings having payback times below 5 years was about 30%. This fraction of the dwelling stock, composed of semi-detached and detached dwellings, might have been the main support pillar for the condensing gas boilers market in the Netherlands.

We fit the *Payback Acceptance Curve* (PAC) against the estimated payback times for the period of 1981-2005 (see Figure 28, curve a). The resulting fit yields values of 4.8 years for PB_{50} and 0.7 for the parameter α at an adjusted coefficient of determination (R^2) of 55%. This result indicates that condensing gas boilers reached a market penetration of 50% at a payback time of roughly 5 years. In Figure 28 it is conspicuous that data for the years 1981-1987 form a cluster, which does not correspond to the overall trend. A reason for this observation could be that the PAC fails to explain the market penetration in the early history of condensing gas boiler market. This result is, however, not surprising because in early years, factors other than economic performance alone determined to a large extend the market penetration of condensing gas boilers in the Netherlands (i.e., training of installers, boiler reliability, and household infrastructure; see also Section 4.1.3 and Brezet (1994)).

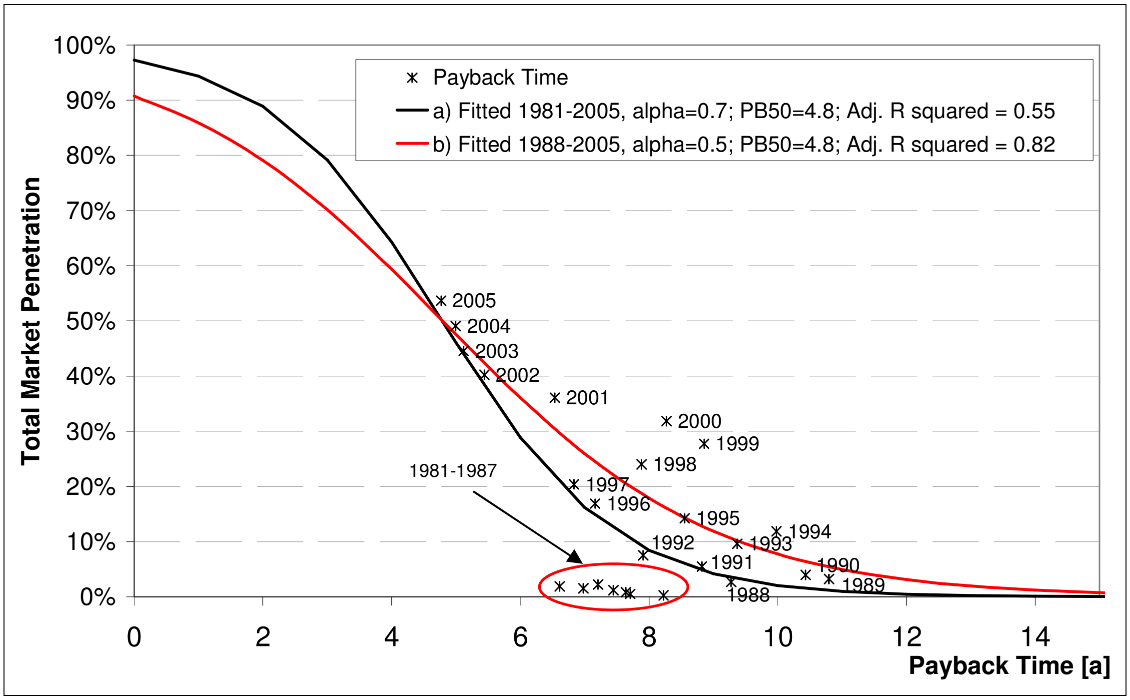

Figure 28: *Payback Acceptance Curve* fitted to data on payback times for the periods of 1981-2005 and 1988-2005; in years coloured red no subsidies were granted

We fit a second curve only to the data for the period of 1988-2005 (Figure 28, curve b). We obtain a PAC with a substantially better fit (adjusted R^2 of 0.82) and with values of 4.8 years for PB_{50} and 0.5 for α. The values for PB_{50} are the same for both fits, implying that in both cases the market penetration reaches 50% at a payback time of roughly 5 years. The parameter α, however, differs. Curve a) is steeper (with an α-value of 0.7) than curve b), where α is only 0.5.

We conclude that the PAC is useful to explain the diffusion of condensing gas boilers in the Netherlands. The PAC, however, fails to explain market diffusion in early years in which the market was to a large extent determined by factors other than payback time. The reduction of payback time for condensing gas boilers in the Netherlands over the years is influenced by a complex set of mutually depend variables such as useful heat demand, natural gas price, boiler efficiencies, boiler price, and installation costs. Technological learning and the gaining of experience in boiler manufacturing, installation, and maintenance contributed a major part to the reduction in payback time and hence to the success of the condensing gas boilers in the Netherlands.

4.1.8 Condensing gas boilers – conclusions and outlook

Condensing gas boilers were invented in the Netherlands and introduced to the market in 1981. In early years, the market success was limited due to, e.g., reliability problems, insufficient training of installers, and high boiler prices. However, condensing gas boilers gained considerable market shares in the late 1980s and early 1990s. Today, condensing gas boilers are the standard household heating technology in the Netherlands with shares of more than 90% on the Dutch boiler market.

We applied the experience curve approach to condensing gas space heating and combi boilers in the Netherlands. The experience curve approach is applicable for condensing gas boilers albeit with the restrictions that production costs had to be approximated by market prices. We find learning rates of (7.0 ± 0.9)% for condensing gas boilers for space heating and (14.2 ± 1.2)% for condensing gas combi boilers. The additional costs for condensing gas space heating and combi boilers relative to equivalent non-condensing gas boilers decline at learning rates of (13.2 ± 2.8)% and (26.4 ± 5.7)%, respectively. The main drivers for the observed cost reductions are economies of scale in boiler manufacturing, improvements of boiler components, and (since the year 2000) the outsourcing of component production from boiler producers to specialized companies.

The experience curve approach is suitable for analyzing condensing gas boilers because the characteristics and components of this technology remained relatively unchanged in the analyzed time period. Moreover, the various boiler models that are included in our analysis are homogenous with regard to technology and product functions. Availability of price data for early years (1981-1987) restricts the application of the experience curve concept to some extent. A major obstacle of our analysis is related to the estimation of cumulative experience. While Dutch boiler sales are readily available, estimates for the EU-15 are attached with considerable uncertainties. The estimation of cumulative global condensing gas boiler sales/production had to be discarded completely from this analysis due to insufficient data availability.

The installation of condensing gas boilers in the Netherlands saved in the period of 1981-2006 around 7.2 billion m^3 natural gas. This adds up to a total of 13.5 Mt CO_2 emissions and 2.7 billion EUR of energy costs that have been saved by Dutch consumers. The calculated energy savings are associated (i) with additional costs at the consumer side of roughly 1.6 billion EUR for purchase, installation, and maintenance of condensing gas boilers and (ii) with 58-83 million EUR subsidies that have been spent between 1981 and 2002 in support of condensing gas boilers. Including the savings of energy costs, we estimate *net* savings of 1.0 billion EUR or 75 EUR/t CO_2 that has not been emitted (win-win-situation for costs and for emissions). This result demonstrates the high cost efficiency of condensing gas boilers for greenhouse gas emission mitigation.

Consequently, we find that condensing gas boilers generate savings of up to 70 EUR per year (value for 2005), if they replace conventional non-condensing gas boilers. The calculated savings depend, however, on the households' natural gas consumption and on the natural gas price. Analyses with the Dutch Residential Model (Dittmar et al., 2007) confirmed that savings can be even negative for both individual years and household types (i.e., indicating *net* additional costs for condensing gas boilers), if gas prices and/or natural gas consumption is considerably lower than the average.

Nowadays, condensing gas boilers are a mature technology. The current focus of Dutch boiler manufacturers is increasingly directed towards micro-CHP systems, which are regarded by many as follow-up technology for condensing gas boilers in the Netherlands.

4.2 Micro-CHP systems (*HRE-Ketels*)

4.2.1 Introduction and objective

Micro-Combined Heat and Power systems (micro-CHP) also referred to as micro-cogeneration is a technology that produces both heat and electricity at small scale, i.e., at the level of individual households. The European Cogeneration Directive defines micro-CHP in a somewhat broader scope as cogeneration units with an electrical capacity of less than 50 kW$_e$ (Cogen Europe, 2004). The gas supplier GasTerra and several boiler manufacturers in the Netherlands regard Micro-CHP systems as the next generation of heating systems for Dutch households, which might replace condensing gas combi boilers (*HR-Ketels*) in the near future (Overdiep, 2007, van den Berg, 2006).

The primary purpose of a combined heat and power system is to utilize waste heat from electricity production. Large- and medium-scale combined heat and power installations (with power outputs ranging up to several Megawatts) are widely used around the world. In the Netherlands, 2,400 MW$_e$ installed CHP capacity accounts for roughly 35% of the total installed electricity production capacity (Figure 29).

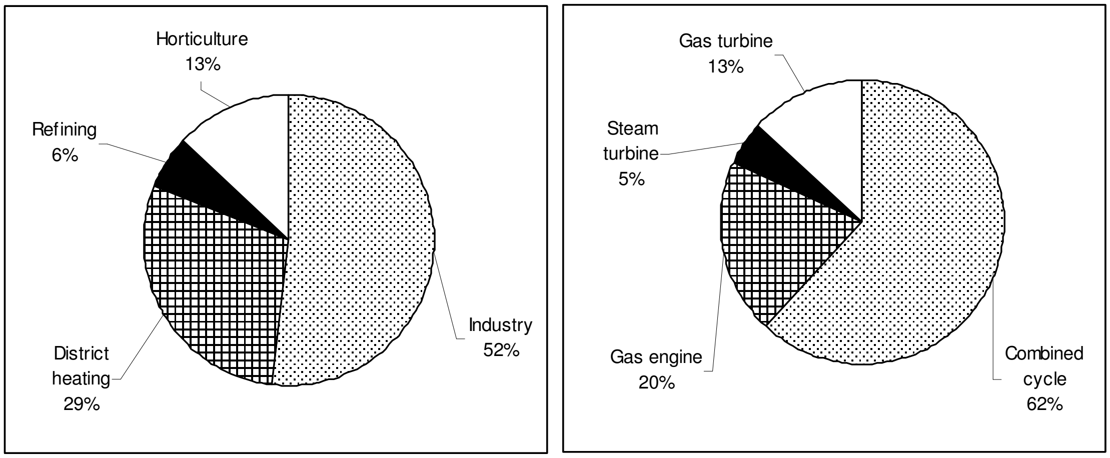

Figure 29: CHP capacity in economic sectors and types of CHP technology (Data source: Cogen Nederland, 2006)

Micro-CHP is, however, a novel technology being currently tested in several pilot projects in the Netherlands. The capacity of micro-CHP systems ranges from around 5 kW$_e$ to 13 kW$_e$ for use in small hotels, swimming pools, or apartment blocks. For application in individual households, electrical capacities of around 1 kW$_e$ and thermal capacities similar to the one of condensing gas combi boilers, i.e., typically in the range of 12-25 kW$_{th}$ are currently developed and tested. The micro-CHP systems that have been developed in the Netherlands use a Sterling engine[28] to produce electricity. The waste heat from electricity generation is then used for space heating. Micro-CHP technology offers several interesting features:

- It is compatible with the Dutch energy infrastructure, i.e., it uses natural gas as primary energy source.

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[28] Gas engines or fuel cells are possible alternatives, see Section 4.2.2.

- It produces electricity more efficiently than average Dutch power plants, if the production of useful heat (that is used for space heating) is taken into account.
- It might potentially replace polluting and carbon intensive fossil fuels such as coal.
- It will mainly produce electricity at times of high demand, i.e., during morning and evening hours, thereby potentially reducing demand for adjusting peak-load electricity supply.
- It contributes to a decentralization of the energy supply system.

Micro-CHP systems are currently very expensive, with (projected) prices ranging from 7,500 EUR to 15,000 EUR (Cogen Europe, 2004, Overdiep, 2007). The high price is associated with relatively low energy saving potentials compared to other technology alternatives (e.g., heat pumps, solar boilers). The actual energy saving potentials might even be smaller than initially projected, if the current trend in Dutch households towards decreasing demand for space heating continues. Also, micro-CHP systems for application in individual households still face institutional barriers such as the regulation of feed-in tariffs for electricity production.

In this chapter, we apply the experience curve approach to micro-CHP systems (for application in individual households) with a capacity of 1 kW$_e$. We thereby aim at analyzing the future price dynamics of this technology in the Netherlands for the period of 2008-2030. Based on this analysis, we evaluate market potentials and we estimate subsidy requirements for micro-CHP systems in the Netherlands. We base our scenario projections on data as published by WGD (2007). We perform a sensitivity analysis based on data given by Ruijg (2006), and MBC (2007).

The analyzed micro-CHP systems are not yet offered at the market. Historical experience curves can thus not be constructed. We continue in the next section with a more detailed description of CHP and micro-CHP technology. In Section 4.2.3, we give a short overview of historical developments and projected market potentials. Our approach and the principal data sources used for our analysis are given in Section 4.2.4. We present our results in Section 4.2.5. In the final section of this chapter, we summarize our findings and we draw final conclusions.

4.2.2 Technology description

Industrial processes and power plants generate waste heat that is usually lost to the environment via flue gas or cooling towers. Combined heat and power installations capture this heat and make it usable for, e.g., space heating or heating boilers in conventional steam power plants. This increases the overall efficiency of power plants to around 70% compared to the 40% of conventional plants. CHP is a mature technology that is widely used in large- and medium-scale industrial installations, power plants, and refineries.

While the primary purpose of industrial CHP installations is to make *use* of waste heat, the primary purpose of micro-CHP systems for household application is to *generate* heat for space heating and hot water production (Figure 30). Electricity is thereby a useful by-product of the heat generation process. Micro-CHP systems are designed to replace conventional, decentralized domestic heating systems. The electricity produced by a micro-CHP unit can be used within the household or delivered to the electricity grid. Micro-CHP systems can achieve thermodynamic heat production efficiencies equivalent to those of condensing gas boilers (around 105-107% LHV). Various technologies for electricity generation can be used in micro-CHP systems. These technologies include external and internal combustion engines as well as fuel cells.

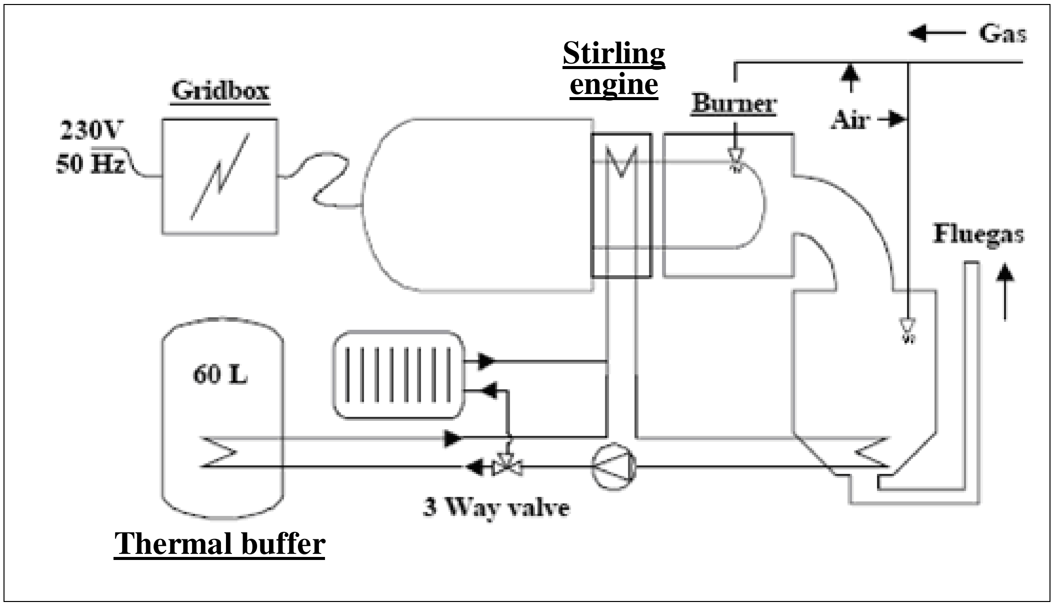

Figure 30: Schematic sketch of a micro-CHP system with thermal buffer; Enatec Stirling Micro-CHP unit (Source: van der Woude et al. (2004))

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Stirling engine (External combustion engine)

Stirling engines are used for electricity generation in the micro-CHP systems, which are currently tested in pilot projects in the Netherlands and in the UK (Overdiep, 2007). Design-wise, the Stirling engine is a rather old and mature technology that was, however, never been used on a large commercial scale. The Sterling engine was developed in 1816 by Robert Stirling. It is an *external* combustion engine in which a working gas is alternately heated and cooled by moving it between a hot and a cold compartment with a displacer piston. The temperature difference between the two pistons causes a pressure gradient, thereby generating mechanical work that is used for electricity generation.

A sterling engine consists of (i) the power piston that is used to pressurize the working gas and (ii) the displacer (leaky) piston that forms a temperature barrier between the hot (upper side) and the cold (lower side) compartment and that is used to move the working gas between the two compartments. The working gas can be helium, nitrogen, hydrogen, or normal air. The entire Stirling cycle can be divided into five phases (Figure 31).

In the first phase, the gas in the cold compartment is compressed by the power piston (power piston in Figure 31 (1) moves up). In the second phase, the gas is moved to the hot compartment by the displacer piston (displacer piston in Figure 31 (2) moves down). In the third phase (3), the gas is heated in the hot compartment by the heat that is continuously supplied by an external source in the surroundings of the hot compartment. The heating of the working gas causes a pressure increase within the compartment. In the fourth step, the power piston is pushed back by the gas to its original position (power piston in Figure 31 (4) moves down). In the fifth phase, the rest of the gas in the hot compartment is pushed to the cold compartment by the displacer piston and cools down (displacer piston in Figure 31 (5) moves up).

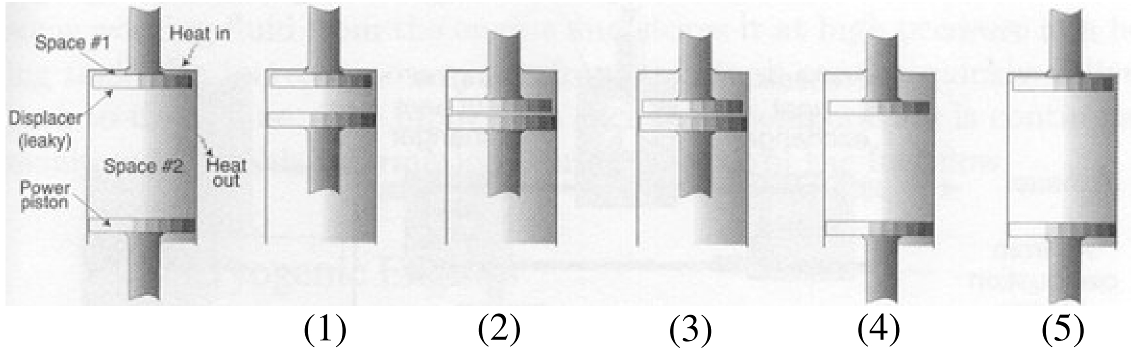

Figure 31: The five phases of a Stirling cycle; beta-type Sterling engine (Source: da Rosa, 2005))

Sterling engines can be constructed as double (alpha) and single (beta) piston systems. The useful energy produced by a Stirling engine is the work performed on the power piston in phase four minus the work performed by the power piston to compress the gas in phase one. Sterling engines are driven continuously by an external heat source, which is most frequently a gas burner. The cold compartment is cooled with water (da Rosa, 2005, van der Hilst, 2005, Wikipedia, 2008a).

In the case of micro-CHP, the cooling water can be used for space heating or as warm tap water. The Stirling micro-CHP systems that are currently developed and tested for the Dutch market have an electrical efficiency (i.e., efficiency of electricity production) of 10-15% and a total efficiency of *useful* energy production of up to 105% LHV.

Micro-CHP systems proposed for use in individual houses have a Sterling engine with an electricity production capacity of 1 kW$_e$ and a resulting heat capacity of 4-5 kW$_{th}$. The heat capacity is, however, not sufficient to meet the average requirements for space heating and hot water production. The problem can be solved by two solutions:

- A thermal buffer unit in the range of 150 l can be installed. Such a measure would require a considerable amount of space but would assure relatively high efficiency gains compared to conventional electricity production.
- An additional peak gas burner can be installed[29]. This solution is currently used in pilot models because of its low requirements for additional space. The installation of a peak gas burner allows keeping the dimension of a micro-CHP system comparable to the one of conventional condensing gas combi boilers. The disadvantage is, however, a reduced electricity production relative to the amount

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[29] The heat produced by the peak gas burner is recovered as efficiently as the heat that is transmitted from the Stirling engine. The additional burner does reduce the share of electricity production per unit of natural gas use but not the overall efficiency (i.e., around 105% LHV) of the entire micro-CHP system.

of natural gas that is consumed, causing thereby lower *relative* efficiency gains and cost savings.

Internal combustion engines

Internal combustion engines compress and burn fuels with atmospheric oxygen in a combustion chamber. The fuel oxidation is an exothermic reaction and leads to an expansion of combustion gases that ultimately perform mechanical work on the piston. Most commonly diesel, gasoline, natural gas, and other hydrocarbons can be used as fuel. The efficiency of internal combustion engines is higher than the one of Sterling engines and ranges around 20%. Internal combustion engines are widely applied and medium in small size CHP systems (e.g., for use in greenhouses, industry, and larger office buildings). However, internal combustion engines require more space and are noisier than Stirling engines. This limits their applicability in micro-CHP systems that can potentially be used for individual household heating.

Fuel cells

Fuel cells are a rather novel technology that still needs development to become competitive with Stirling engines. A fuel cell continuously converts the chemical energy of a fuel (usually hydrogen) in presence of an electrolyte and a catalyst into electricity. The process itself is very quiet and more efficient (i.e., in the range of 30-40%) than fuel combustion in external and internal combustion engines. Fuel cell applications suffer, however, from three main obstacles:

- Hydrogen that is nowadays used as fuel needs to be produced and transported. For production, theoretically renewable electricity can be used but to date mainly natural gas is used as feedstock. The subsequent conversions of natural gas to hydrogen to electricity decrease the overall fuel cell efficiency.
- Methanol-based fuel cells and fuel cells running on other hydrocarbons are still in the R&D phase.
- Fuel cells produce direct current that has to be transformed to alternating current, which in turn causes electricity losses.

Compared to internal combustion engines, fuel cells are still in their infancy. Fuel cells with a capacity of 5 kW_e are used in several pilot CHP systems of Vaillant. They have been installed in multi-family homes and small commercial buildings as part of an European wide field test (Cogen Europe, 2004). Currently, two types of fuel cells are in development for application in micro-CHP systems: PEM (Proton Exchange Membrane) fuel cells and SO (Solid Oxide) fuel cells. Compared to PEM fuel cells, SO technology is still in a relatively early phase of development.

Fuels cells can be used in modular arrangements in so called stacks that allow for adapting the system’s performance to the specific heat/electricity demand. Due to their relatively high efficiencies, fuel cells generate a relative high *electricity to heat ratio* compared to especially Stirling engines, thus producing excess electricity rather than excess heat. The application of fuel cells in micro-CHP systems is still far away from market introduction. Fuel cell micro-CHP systems are hence considered as *second generation* of micro-CHP systems.

From the perspective of the entire heat and electricity demand of households, micro-CHP systems save energy. The savings result from the efficiency gains relative to the average efficiency of electricity production in the Netherlands, which is around 43% (de Jong et al., 2006). De Jong et al. (2006) calculated the energy savings of micro-CHP in a detached house. Assuming a yearly gas use of 1962 m^3 and an electricity consumption from the grid of 4,084 kWh, micro-CHP offers yearly savings of 14 GJ and 1.2 t CO_2 emissions. This is approximately 15% of the total primary energy use and 20% of the total CO_2 emissions of a detached house in the Netherlands (de Jong et al., 2006).

4.2.3 History and market development in the Netherlands

More than a hundred micro-CHP systems with 5 kW_e internal gas combustion engines are installed in the Netherlands (Cogen Europe, 2004). Furthermore, several micro-CHP units with 5 kW_e fuel cells have been installed in a test phase. However, these relatively large installations, are only suitable for small commercial buildings, apartment complexes, swimming pools, hotels, etc.

For the individual housing market, 1 kW_e micro-CHP units with a Sterling engine are currently tested in various pilot projects. Both, Enatec and Gasunie are testing micro-CHP units that are suitable for replacing condensing gas combi boilers in Dutch households. In principle, the Dutch market offers considerable potential for these 1 kW_e micro-CHP units because the majority of Dutch households (i) have access to the natural gas grid and (ii) use individual central heating systems. Micro-CHP systems have the same spatial requirements as condensing gas combi boilers and can hence be used as replacement, requiring only little modifications of the household's energy infrastructure. However, the relatively high projected costs of micro-CHP systems (see text below and in the next sections), the uncertain energy saving potentials, and the unresolved issues related to governmental subsidies and electricity feed-in tariffs, delay the large scale market introduction of this technology in the Netherlands.

For the British market, the energy company Powergen, owned by E.ON, will sell the WhisperGEN micro-CHP system from New Zealand with a four cylinder Stirling engine. This Stirling engine was developed for use on ships, but is now also available in micro-CHP systems for houses. This system has also been tested in the Netherlands (WhisperGEN, 2007, Pehnt et al., 2006). The Magic Boiler Company sells the WhisperGEN system in the Netherlands at prices starting from around 10,000 EUR (MBC, 2007).

For the Dutch market, a one cylinder Stirling engine was designed by Microgen, a subsidiary of British Gas, in cooperation with GasTerra. The Stirling engine is built into a condensing gas combi boiler by the boiler manufacturer Remeha resulting in a micro-CHP system with 1 kW_e, 24 kW_{th} for space heating, and 28kW_{th} for hot water production (Remeha, 2008). However, the activities of Microgen have been terminated by British Gas. It remains therefore uncertain who is going to deliver the Stirling engines for the Remeha micro-CHP systems (Overdiep, 2007, Pehnt et al., 2006). The Smart Power Foundation (SPF, 2007), a cooperation of Dutch boiler manufacturers and the gas company GasTerra aims at providing this micro-CHP system at economically competitive conditions i.e., claiming payback times of no more than five years within five years after market introduction of this system. This means that the additional consumer investment costs for micro-CHP systems should not be higher than 1,500 EUR compared to a conventional condensing gas combi boiler.

Another Stirling CHP system has been developed by Enatec, a cooperation between the energy research institute ECN and the energy company Eneco (Infinia, 2005). This system uses a Stirling engine from the American company Infinia (formerly Stirling Technology Company). These Stirling engines might be produced on a large scale by the Japanese company Rinnai (Infinia, 2005, Pehnt et al., 2006). Both Dutch projects aim at bringing micro-CHP systems to the market by 2008 (Overdiep, 2007, Enatec, 2007). Whether or not the market introduction will be successful, might depend to a large extent on subsidies granted by the government and on the cost reductions that can be achieved by producers in the years ahead.

4.2.4 Approach and data sources

We restrict our analyses to micro-CHP systems that are suitable for installation in individual households, i.e., micro-CHP system with a sterling engine of a capacity of 1 kW_e. To date, price information is only available for the WhisperGen MB2 micro-CHP system (4 piston Sterling engine, 1 kW_e, 7-14 kW_{th}), currently sold at a price of 9,950 EUR (WhisperGEN, 2007). The micro-CHP system from Remeha is extensively tested but not yet sold at the market. The Smart Power Foundation plans to sell 1.6 million of these micro-CHP units until 2020 in the Netherlands (Overdiep 2007; Energietransitie 2007; Hendriks 2006). Overdiep (2007) provided us with a document from the *Werkgroep Decentraal* that projects *targeted* future costs and requested subsidies for micro-CHP systems in the Netherlands (WGD, 2007). The basic assumptions and predictions made in this document are presented in Table 10.

Table 10: Projected market price, energy savings, and requested subsidies for 1 kW_e micro-CHP systems in the Netherlands (Source: WGD (2007))

Year	Yearly micro-CHP sales	Cumulative micro-CHP sales	Projected additional costs in EUR	Acceptable additional costs in EUR[1)]	Subsidy per micro-CHP system in EUR	Total yearly subsidies in million EUR
2008	6,000	-	4500	3000	1500	9.0
2009	12,000		3750	2550	1200	14.4
2010	20,000	38,000	3000	2075	925	18.5
2011	45,000	-	2400	1800	600	27.0
2012	75,000	-	1800	1500	300	22.5
2015	140,000	498,000	-	-	-	-
2020	300,000	1,658,000	-	-	-	-
2030	-	4,140,000	-	-	-	-

1) Estimates for acceptable additional costs of 1,500 EUR (compared to condensing gas combi boilers) base on the assumption of a payback time of 5 years, excluding costs for installation. For the time period of 2008-2012 acceptable additional costs are considerably higher than 1,500 EUR because it is assumed that micro-CHP systems will be dominantly installed (i) by early adopters who are willing to accept longer payback times and (ii) in houses with above-average heat demand.

Subsidies from the government are required to bridge the gap between *projected* and *acceptable* additional costs of micro-CHP systems in the Netherlands. As projected by WGD (2007), micro-CHP systems will need subsidies of 91.4 million EUR in the period of 2008-2012. This demand for subsidies can, however, be substantially higher, if:

- Micro-CHP systems are more expensive at the point of market introduction than the additional cost estimates in Table 10 suggest. Such a scenario is not unlikely, given an average price of condensing gas combi boilers of around 1,300 EUR in 2007 and a price of 9,950 EUR for the WhisperGen MB2 micro-CHP system (i.e., resulting in additional consumer costs of 8,650 EUR).
- The projected cost reductions are too optimistic, i.e., the prices of micro-CHP systems decrease at a slower rate than predicted in Table 10.
- The energy and the energy cost savings are too optimistic. This refers to the efficiency of micro-CHP systems, but specifically to the natural gas price and the revenue for electricity sold to the grid. A scheme for compensating excess electricity that is sold to the grid is still under debate. Uncertainties also relate to the future natural gas prices that may increase faster than prices of electricity.

We therefore aim to analyze various scenarios for price, i.e., cost reductions of micro-CHP systems until the year 2030. For these analyses we make use of the data presented in Table 10 and the learning rates as identified for condensing gas combi boilers in the previous chapter of this report. We do not calculate own estimates on energy saving potentials of micro-CHP systems because (i) several studies already addressed this point in detail (the most recent ones being Ruijg (2005) and de Jong et al. (2006)) and (ii) such analyses would go clearly beyond the scope of this research project.

Based on the information given by Ruijg (2005) and MBC (2007), the assumptions in Table 10 can be regarded as 'low-cost' scenario. We therefore perform a sensitivity analysis by assuming cost savings of only 180 EUR/a, which translates (under the assumption of an acceptable payback time of 5 a) into maximum acceptable additional cost of 900 EUR (Ruijg, 2005). In our sensitivity analysis, we furthermore assume that the initial price of micro-CHP systems is 10,000 EUR, which is similar to the price of the micro-CHP system offered by the Magic Boiler Company (MBC, 2007). The results of this sensitivity analysis can be somewhat regarded as 'high-cost' scenario.

4.2.5 Experience curves for micro-CHP systems

We first take a closer look at the rate at which cost reductions are expected to occur for micro-CHP systems, and to what learning rates this would correspond to (Section 4.2.5.1). Next, we compare the projected market diffusion rates for micro-CHP with the historic rates of condensing natural gas (space heating and combi) boilers (Section 4.2.5.2). Finally, we scrutinize the assumptions on required governmental subsidy to successfully introduce micro-CHP in the Netherlands (Section 4.2.5.3).

4.2.5.1 Analysis of cost reductions and corresponding learning rates

We first plot the projected *additional* price for micro-CHP systems (Column 4 in Table 10 as a function of cumulative production (estimates based on data in Column 2 and 3 in Table 10. We identify a learning rate of (16.1 ± 1.9)% for the projected additional price of micro-CHP systems (Figure 32).

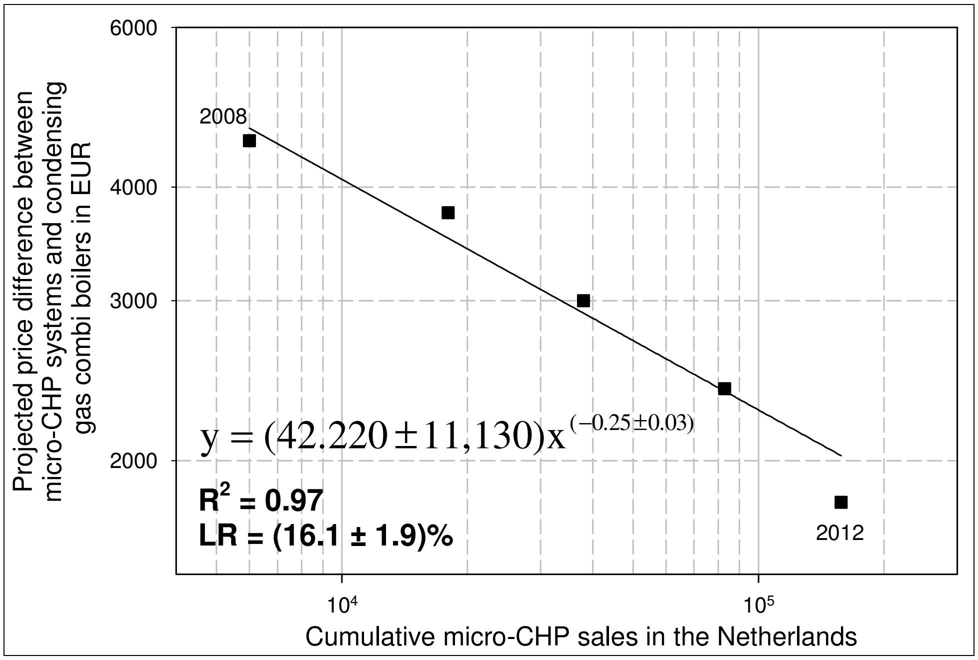

Figure 32: Experience curve for the additional price of micro-CHP systems compared to average condensing gas combi boilers; numbers in the diagram indicate the year, which the data refer to; market growth as assumed in Table 10 (Data source: WGD (2007))

The identified learning rate refers to the additional price of micro-CHP systems, i.e., the costs related to the Stirling engine, and its integration into a *more or less* conventional condensing gas combi boiler. The resulting learning rate is in range with:

- the learning rates as identified for the additional costs of condensing gas combi and space heating boilers, i.e., (26.4 ± 5.7)% and (13.2 ± 2.8)%, respectively (see Figure 19);
- the learning rate that we identified for condensing gas combi boilers (see Figure 16).

Although Sterling engines have never been produced on a large scale, the technology is relatively mature and does not involve revolutionary technological solutions or materials (e.g., as it is the case for photovoltaics and other products of the semi conductor industry). We therefore regard the assumed learning of (16.1 ± 1.9)% reasonable. However, as the example of comparable technologies show, learning rates could potentially be lower or higher. We therefore conduct a first sensitivity analysis by introducing an error range of ± 5% into the identified learning rate of 16%. This range was deemed appropriate based on:

- our results for condensing gas boilers;
- the average range of learning rates of modular technologies that typically ranges between 10% and 20% (Junginger, 2005, Junginger et al. 2008, Neij, 1999).

The results in Figure 33 indicate that a deviation of learning rates from the projected 16% has a considerable effect on the achieved reduction of additional costs for micro-CHP systems:

- Assuming a learning rate of 21% will lead to additional costs that are as low as 1,518 EUR by 2012 and therefore in range of the projected acceptable price difference of 1,500 EUR.
- Assuming a learning rate of 11% will lead to additional costs that are as high as 2,026 EUR by 2012 and therefore considerably above the projections for an acceptable price difference of 1,500 EUR. By assuming a learning rate of 11% for the costs of the Sterling engine and its integration into the boiler system, additional costs will still be in the range of 1,532 EUR by 2030. This would indicate demand for governmental subsidies for 22 years instead of only 4-5 years.

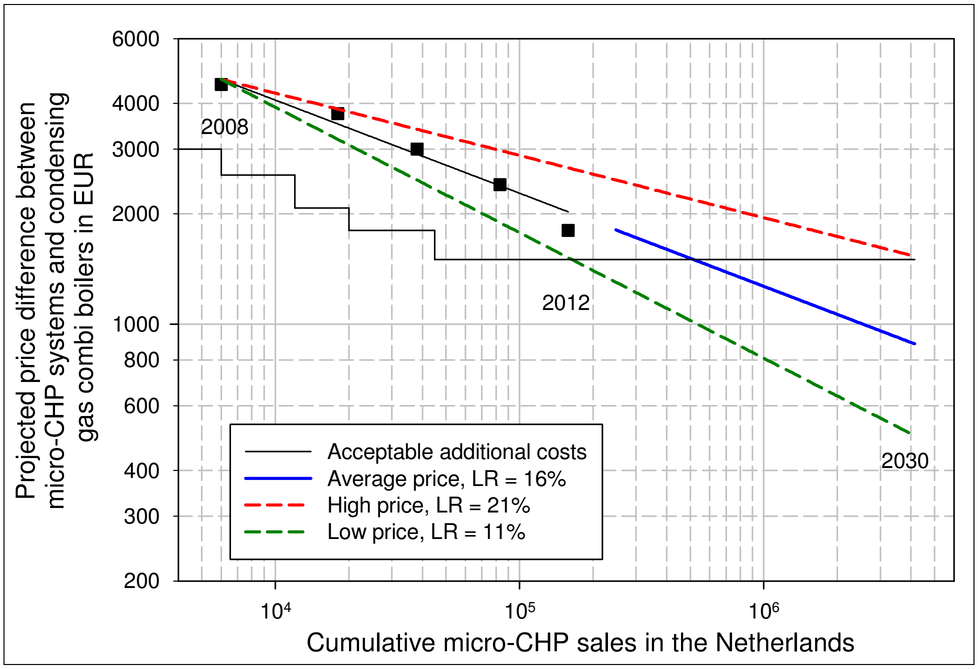

Figure 33: Sensitivity analysis - experience curve for the additional price of micro-CHP systems compared to average condensing gas combi boilers (low-cost scenario); numbers in the diagram indicate the year, which the data refer to; we assume here market growth and acceptable additional costs as given in Table 10; the area between the acceptable additional cost line and the projected price difference indicates the required subsidies for micro-CHP systems (Data source: WGD (2007))

For the second sensitivity analysis (high-cost scenario), we use similar learning rates as in Figure 33. We, however, now assume (i) that the first micro-CHP systems will be sold at prices of 10,000 EUR, which translates into initial additional costs of around 8,750 EUR and (ii) that the final level of acceptable additional cost is 900 EUR rather than 1,500 EUR. The results in Figure 34 indicate that such a high-cost scenario inevitably means that the amount of subsidies required for micro-CHP systems increase substantially. Even under the relatively optimistic assumption of a 21% learning rate, micro-CHP systems require governmental subsidies beyond the year 2030.

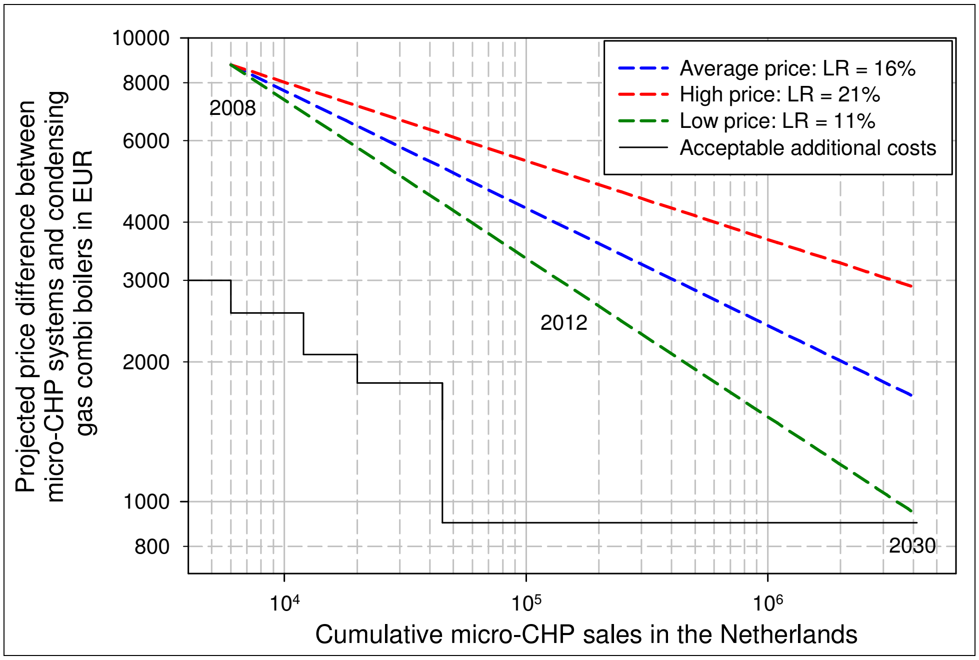

Figure 34: Sensitivity analysis - experience curve for the additional price of micro-CHP systems compared to average condensing gas combi boilers (high-cost scenario); numbers in the diagram indicate the year, which the data refer to; we assume here market growth as given in Table 10, acceptable additional costs of 900 EUR and an initial additional price of 8,750 EUR; the area between the acceptable additional cost line and the projected price difference indicates the required subsidies for micro-CHP systems (Data sources: WGD (2007), Ruijg (2007), MBC (2007))

So far, we have analyzed the additional costs of a micro-CHP system relative to a condensing gas combi boiler. We now analyze the cost reductions of the entire micro-CHP system. For this analysis, we use data on additional costs (see Table 10), recent price estimates for average condensing gas combi boilers (i.e., 1,240 EUR in 2008), and the assumption of a 14% learning rate for condensing gas combi boilers (see Figure 16).

We estimate a learning rate of (12.2 ± 1.1)% for the price of the entire micro-CHP system (Figure 35). The result presented in Figure 35 is (in first sight) counter-intuitive because the learning rate of the entire system is lower than the learning rate of its components. This finding can be explained by the fact that each doubling of micro-CHP production/sales is not equivalent with a doubling of condensing gas boiler sales. The cost component of roughly 1,200 EUR for the conventional gas condensing combi boiler decreases therefore much more slowly than the additional costs of 4,500 EUR for the Sterling engine and its integration into the micro-CHP system.

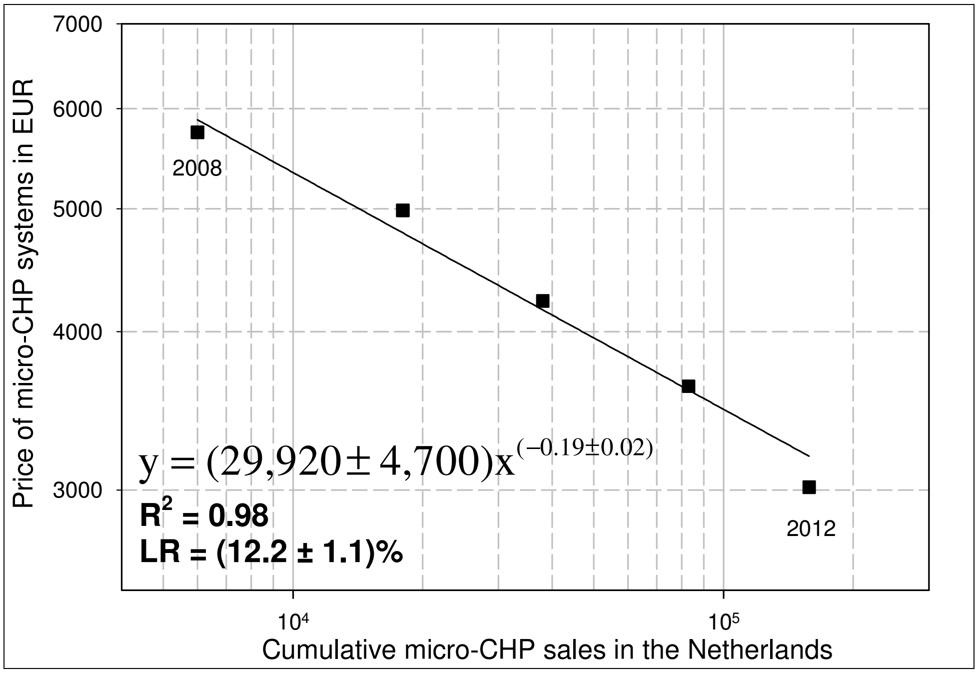

Figure 35: Experience curve for entire micro-CHP systems; numbers in the diagram indicate the year, which the data refer to, market growth as assumed in Table 10 (Data source: WGD (2007))

We conduct a sensitivity analysis (low-cost scenario) for the costs of an entire micro-CHP system, assuming (i) a learning rate for condensing gas combi boilers of 14% and (ii) a learning rate for Stirling engine and system integration of (16 ± 5)%. Based on this scenario, we estimate the learning rate for the entire micro-CHP system to be within the interval of 8.5% to 13.7% (Figure 36).

In the high-cost scenario (assuming similar learning rates as in the low-cost scenario but an initial price of micro-CHP systems of 10,000 EUR), we find learning rates of 9-16% (Figure 37). The higher learning rates compared to the low-cost scenario are explained by the fact the additional costs of micro-CHP systems constitute in the high-cost scenario a higher share on the total micro-CHP price. Cost reductions that occur for the sterling engine and its integration into the boiler system have, therefore, a higher impact on the price of the entire system than in the low-cost scenario. In the high-cost scenario, micro-CHP systems are by 2030 in absolute terms roughly 450-1,350 EUR more expensive than in the low-cost scenario.

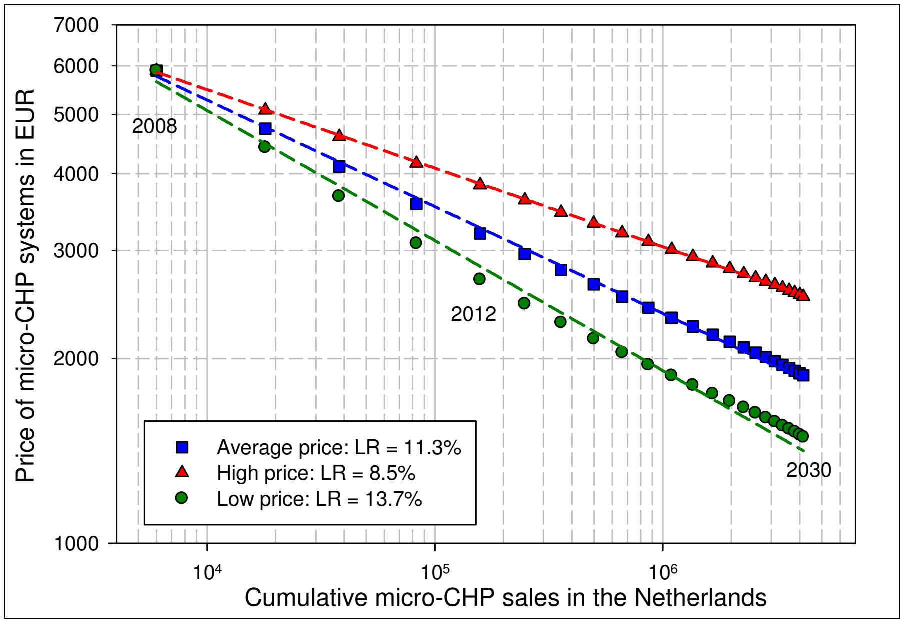

Figure 36: Sensitivity analysis – low-cost scenario: Experience curve for entire micro-CHP systems; numbers in the diagram indicate the year, which the data refer to (Data source: WGD (2007))[30]

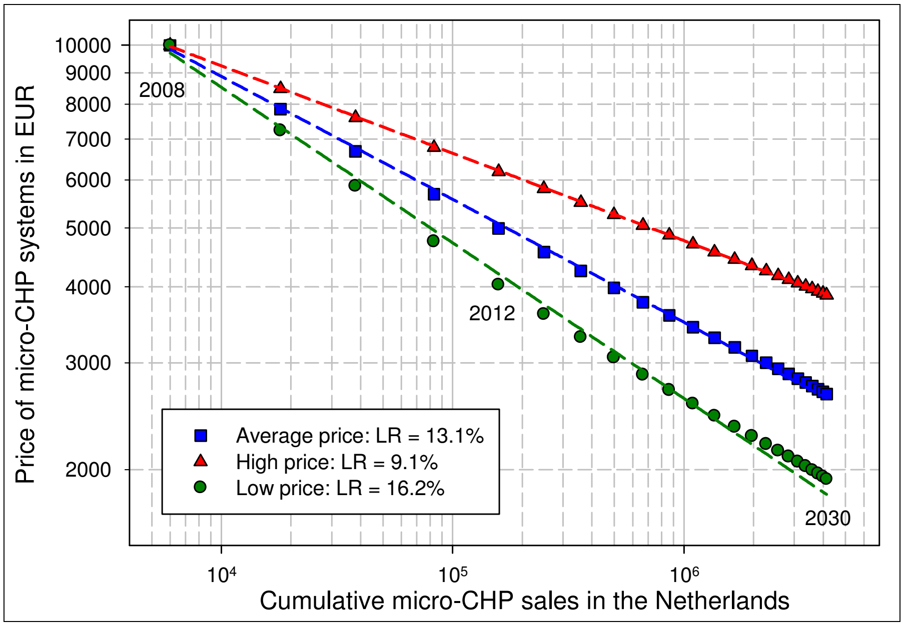

Figure 37: Sensitivity analysis – high-cost scenario: Experience curve for entire micro-CHP systems; numbers in the diagram indicate the year, which the data refer to (Data sources: WGD (2007), Ruijg (2007), MBC (2007))

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[30] The deviation between the learning rates estimated in Figure 35 and the ones based on the average price curve in Figure 36 are caused by the fact that we use additional price data as given in Table 10 for estimating the learning rate in Figure 35, while the learning rate in Figure 36 is base on the assumption that additional costs reduce at a learning rate of 16% while costs for the condensing gas boiler component reduce at a rate of 14%. The differences between the two learning rates are within the uncertainty ranges of the results.

The analyses presented so far investigate the relationship between prices and cumulative sales of micro-CHP systems. However, depending on the dynamics of, e.g., prices, energy costs, and subsidies provided, yearly micro-CHP sales can vary considerably from the predictions made in Table 10. In other words: Micro-CHP systems can *ride down* the experience curve faster or slower, depending on how much systems are sold per year in the Netherlands. While the *absolute* amount of required subsidies depends on both, the assumed learning rate and the acceptable additional costs[31], the amount of *yearly* subsidies depend also on the yearly micro-CHP sales. In the next section, we will have a closer look on the market diffusion projected for micro-CHP systems in the Netherland.

4.2.5.2 Analysis of projected market diffusion rates

In this part of our analysis, we compare the projected market diffusion for micro-CHP systems (see Table 10) with the historic market diffusion of condensing gas (space heating and combi) boilers in the Netherlands (Figure 38 and Figure 39).

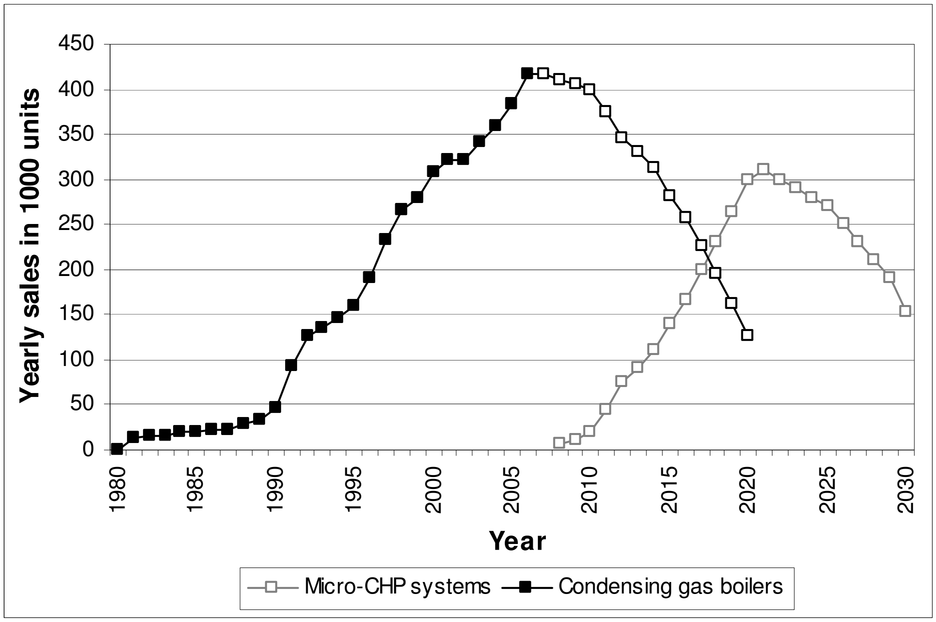

Figure 38: Projected sales of micro-CHP systems and historic sales of condensing gas boilers in the Netherlands (filled symbols indicate historic data, white symbols indicate projections)

The market projections assume that micro-CHP systems are bought in the first years after market introduction by early adopters who are willing to pay a relatively high additional price compared to condensing gas boilers. It is furthermore assumed that micro-CHP systems will first diffuse the replacement market for detached houses as well

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[31] The acceptable additional costs depend themselves on parameters such as natural gas price, the feed-in tariff for electricity, the amount of natural gas consumed and electricity produced, as well as on the discount rate of consumers.

as the market for relatively large newly built houses with above average heat demand. By shortly after the year 2012, additional prices are expected to have fallen to a level of around 1,500 EUR. Micro-CHP technology is expected to gain substantial market shares in the boiler replacement market for houses with medium and low natural gas demand (Overdiep, 2007). By 2020, micro-CHP systems are projected to almost entirely displace condensing boilers as standard household heating technology in the Netherlands. Based on market projections for 2020 and 2030 (see Table 10), a reduction of sales is expected for years after 2020 (WGD, 2007). Whether or not such a development is likely to happen will depend on a variety of factors among them the development of alternative energy efficient household heating technologies.

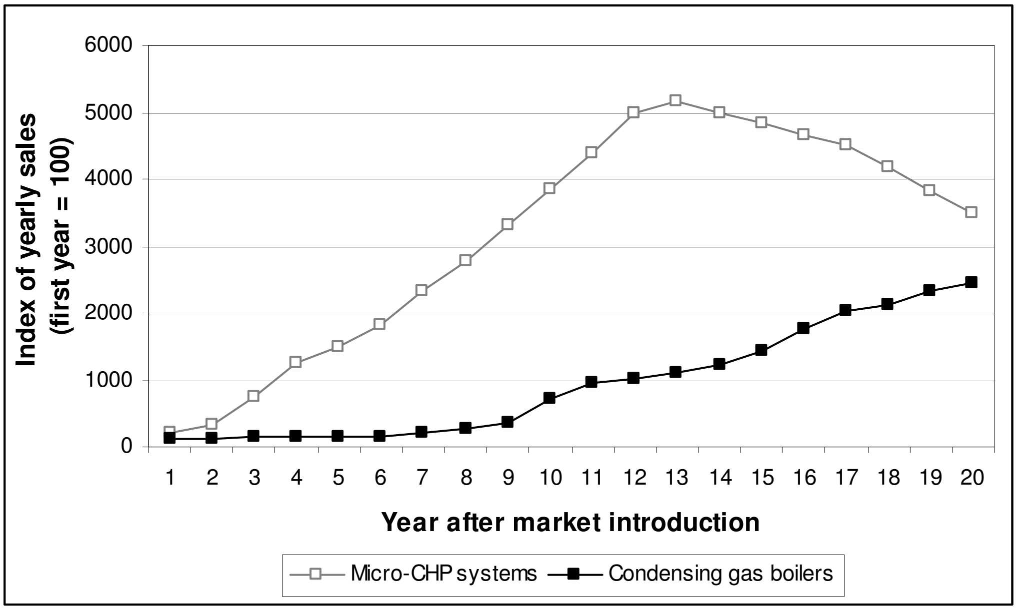

Figure 39: Index of projected micro-CHP sales and historic development of condensing gas boiler sales in the Netherlands

Due to poor reliability, high prices, and insufficient training of installers, condensing gas boiler sales remained low during the first ten years after market introduction (see also discussion in Section 4.1.3). Comparing the historic market diffusion for condensing gas boilers with the scenario projection for micro-CHP systems, the latter appear very optimistic. It is doubtful, though not impossible, that micro-CHP sales will increase in the years after market introduction as fast as anticipated by WGD (2007) (see Table 10). The yearly growth rates as projected for micro-CHP systems are comparable to the ones observed for condensing gas boilers in the years after 1990. These growth rates were, however, only reached due to exceptionally favourable market conditions for condensing gas boilers (i.e., relative price increase for conventional non-condensing boilers, increasing energy prices, declining prices for condensing gas boilers, and almost ten years experience of boiler manufacturers and installation companies; see Section 4.1.3).

One major difference between micro-CHP systems and condensing gas boilers is that condensing gas boilers became first standard in new dwellings with high demand. New and well insulated dwellings are however not the preferred option for micro-CHP systems due to the relatively low heat demand of these dwellings. Micro-CHP diffusion might therefore be restricted to some extent to the replacement market. This might be an obstacle to high and rapid market diffusion of micro-CHP systems. We therefore argue that the very optimistic market projections for micro-CHP systems only hold, if

- boundary conditions are very favourable (e.g., high energy prices, high reliability of technology, high consumer awareness);
- the projected payback time of 5 years can be reached.

The market projections as shown in Figure 38 and Figure 39 should therefore be regarded as *high market growth scenario*. To obtain more detailed insight into the actual market potential of micro-CHP systems, we recommend more detailed analyses using models that differentiate various dwelling types such as the Dutch Residential Model (Dittmar et al., 2007) (see also our analysis for condensing gas boilers in Section 4.1.7)

4.2.5.3 Assessment of required governmental subsidies

Based on projected market sales and price reductions for micro-CHP systems (see Table 10), we also analyze requirements for governmental subsidies. Requirements for subsidies are calculated as the difference between *actual* additional costs and *acceptable* additional costs as depicted in Figure 33 and Figure 34. The calculated subsidy requirements are thereby equivalent to *learning investments* as they have been discussed in Text Box 1.

Relatively small deviation of learning rates can cause considerable changes in the required subsidies (Figure 40). If the additional costs for micro-CHP systems decline at a rate smaller than 12% for each doubling of cumulative production, subsidies need to be paid well beyond the year 2030 (under the assumption that 1,500 EUR additional cost for micro-CHP are acceptable for consumers). Assuming considerably higher learning rates of 16-20% reduces the amount of required subsidies to 50-160 million EUR.

Next to the calculations presented in Figure 40, we calculate also a ‘high-cost’ scenario; thereby assuming an initial price for micro-CHP systems of 10,000 EUR and acceptable additional costs of only 900 EUR. The results of these calculations in Figure 41 indicate that the required subsidies would be a factor five to more than a magnitude higher than projected by WGD (2007). Assuming an average learning rate of 16% would result in subsidy requirements of more than 3 billion EUR (compared to the initial estimate of 156 million EUR. This result indicates that next to the assumed learning rate (i) the initial price level of micro-CHP systems at the point of market introduction and (ii) the achievable energy cost savings are highly important parameters determining the amount of subsidies required. Figure 41 indicates furthermore that subsidies might need to be paid well beyond the year 2030, even if a learning rate of 20% can be achieved. This result seriously questions the economic feasibility of micro-CHP systems, if the assumptions made for our calculations hold in reality.

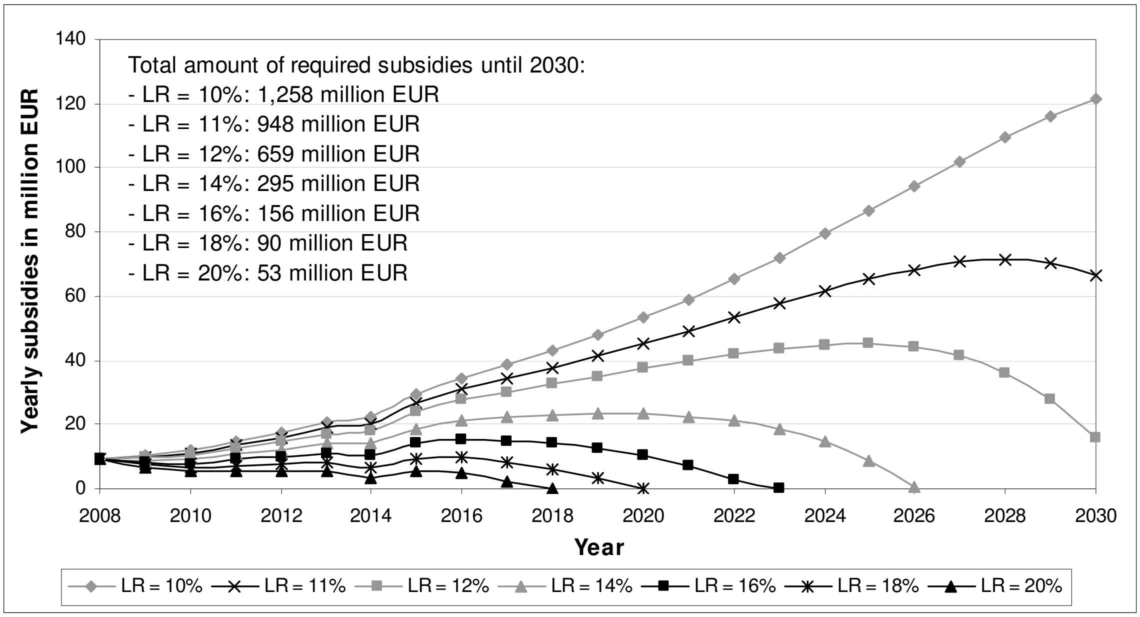

Figure 40: Sensitivity analysis – low-cost scenario: Required subsidies for micro-CHP systems depending on the assumed learning rates for additional costs relative to condensing gas combi boilers; assuming micro-CHP sales as shown in Figure 38

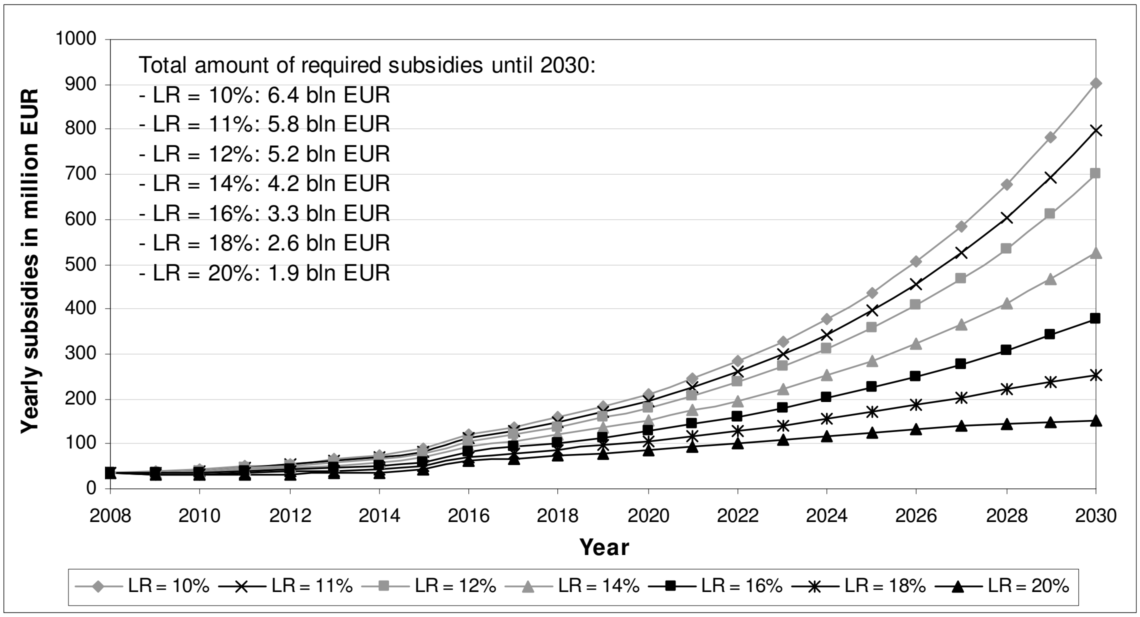

Figure 41: Sensitivity analysis – high-cost scenario: Required subsidies for micro-CHP systems depending on assumed learning rates for the additional costs compared to condensing gas combi boilers; assuming micro-CHP sales as shown in Figure 38

Assuming a learning rate of 16% for the additional costs of micro-CHP systems, we calculate in the low-cost scenario total requirements for governmental subsidies of 120-160 million EUR[32]. The deviations between this estimate and the 91.4 million EUR that are published by WGD (2007) result from the fact that the additional price of micro-CHP systems as estimated by WGD (2007) (see Table 10) for 2012 is considerably lower than the price would be assuming average cost reduction based on all data points (see fitted experience curve in Figure 32)[33]. The time period, over which these subsidies might have to be paid, depends on the yearly sales of micro-CHP systems (Figure 42).

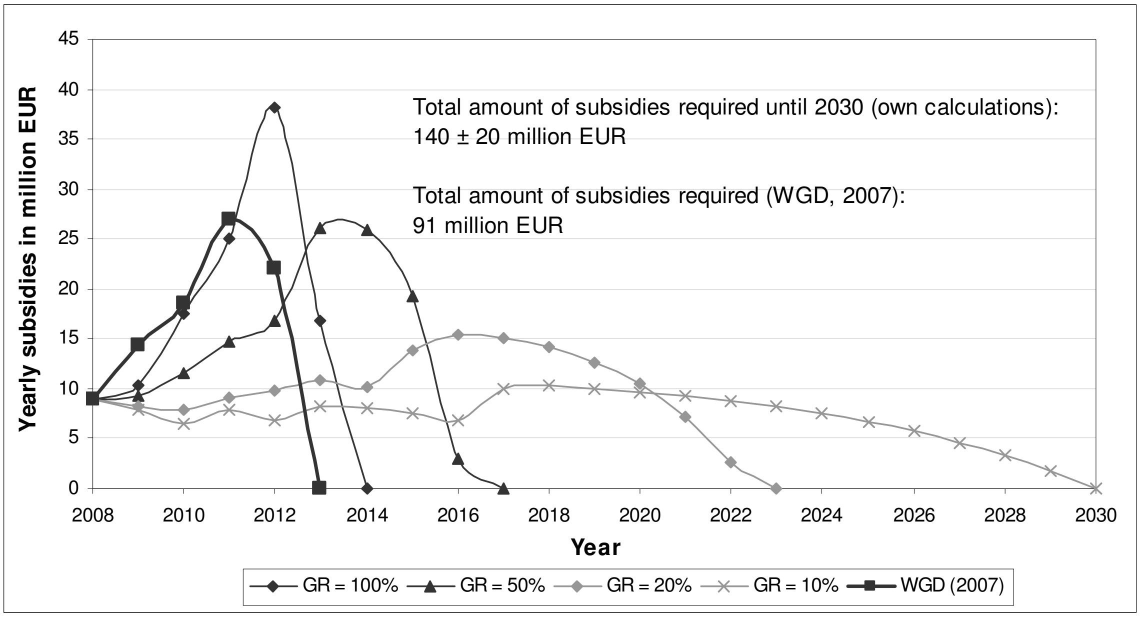

Figure 42: Sensitivity analysis – low cost scenario: Required subsidies for micro-CHP systems for various market growth scenarios; assuming market growth rates (GR) of 10% - 100% and a learning rate of 16% for the additional costs of micro-CHP systems compared to condensing gas combi boilers

Depending on *yearly* micro-CHP sales, the requirements for *yearly* subsidies vary. Under the assumption that (i) additional costs of micro-CHP systems decline at a rate of 16% with each doubling of cumulative production and that (ii) market growth as projected in Table 10 can be realized, yearly subsidies of up to 27 million EUR will be required in the years directly after market introduction. Depending on the actual market growth, yearly subsidies can be substantially higher (almost 38 million EUR in 2012 at market growth rates of 100%) or smaller (around 10 million EUR per year at market growth rates of 10%).

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[32] As mentioned earlier, the amount of subsidies does not only depend on the assumed learning rate but also on the level of acceptable additional costs.

[33] According to WGD (2007), the additional costs for the year 2012 are 1,800 EUR (see Table 10). This estimate is considerably lower than the value resulting from the fitted regression line. The observed deviation causes substantial differences in the estimate for total subsidies due to substantial micro-CHP sales in the year 2012.

The results presented in the sensitivity analysis above indicate that estimates for the required *total* and *yearly* subsidies strongly depend on four factors:

- the initial price of micro-CHP systems at the point of market introduction;
- the rate at which the additional price for micro-CHP systems decline, i.e., the learning rate for sterling engine and its integration into the boiler system;
- the yearly growth rate of micro-CHP sales;
- the profitability of micro-CHP systems for consumers (i.e., realized energy savings, gas and electricity prices).

4.2.6 Micro-CHP – conclusions and outlook

Using market and cost projections for micro-CHP systems as published by WGD (2007), we project learning rates of:

- 16% for the additional costs (i.e., costs associated with the sterling engine and its integration into the boiler system);
- 12% for the total price of micro-CHP systems.

In view of the results for other technologies (e.g., condensing gas boilers), we regard the identified learning rates reasonable. We performed an uncertainty analysis by introducing error margins of ± 5% to the identified learning rates. The results of this analysis show that only small changes in learning rates have considerable effect on the additional costs for micro-CHP systems, i.e., limiting the period in which subsidies are required until 2012 or extending the period until 2030 (Figure 33).

While the learning rate projected by WGD (2007) for additional costs of micro-CHP systems is in range with our findings for condensing gas boilers, the assumed market penetration rate, i.e., the growth of yearly micro-CHP sales, seems over optimistic. The history of condensing gas boilers in the Netherlands but also of other novel and efficiency technologies show that market growth is generally much slower than predicted by WGD (2007) for micro-CHP systems.

The assumptions shown in Table 10 result in a decrease of additional prices for micro-CHP systems by 60% and in a decrease of prices for total micro-CHP systems (assuming a learning rate of 14% for the boiler component) by almost 50% in only 4 years after market introduction. A similar price decline in an equally short time period has not been observed for any of the other energy demand technologies analyzed in this report. For example, condensing gas combi boilers show a price decline of only 23% in a period of high market growth between 1990 and 1994.

Given these findings, we regard it likely that the total amount of subsidies required for micro-CHP systems might be in the range of 120-160 million EUR (low-cost scenario based on assumptions from Table 10). Considerable deviations from this average are possible, if:

- the additional costs of micro-CHP systems compared to condensing gas combi boilers decline slower than projected, i.e., if the learning rate is lower than the projected 16%;
- the initial additional price of micro-CHP systems at the point of market introduction is higher than the projected 6,000 EUR;

- the savings of energy and energy related costs are lower than projected, i.e., the *acceptable* additional costs are lower than 1,500 EUR.

The period for which subsidies are required might be substantially longer than initially predicted (even beyond 2030), if the extremely optimistic parameter projections of WGD (2007) do not hold. In our high-cost scenario, we calculate subsidy requirements of well beyond one billion EUR for the case that the initial micro-CHP price is 10,000 EUR at the point of market introduction and that the acceptable additional price is only 900 EUR instead of 1,500 EUR. Based on this discussion, we draw the following conclusions:

- The projected diffusion rate, i.e., the projected yearly micro-CHP sales are considered extremely optimistic. Projected yearly sales of 140,000 only 7 years after market introduction would equal a market growth roughly twice as fast as for condensing gas boilers.
- The projected learning rates for micro-CHP systems seem to be realistic, albeit subject to uncertainties due to (i) possible increases in material and energy prices and (ii) the fact that learning rates for condensing boilers can only give some indication for a possible rate of cost reductions for micro-CHP systems.
- Additional uncertainty results from assumptions underlying the data presented in Table 10, i.e., low-cost scenario projection for initial additional costs of 6,000 EUR, acceptable additional costs of 1,500 EUR, acceptable payback times of 5 years, energy prices and energy savings.
- The estimated yearly and absolute subsidy requirements are subject to major uncertainties; already small deviation from the assumptions presented in Table 10 can result in major changes in the required subsidies.
- Under the condition that the assumptions in Table 10 hold, we regard it realistic that the total subsidy requirements amount to 120-160 million EUR. These subsidies have to be spend most likely over a time period of 10-15 years with total yearly subsidy requirements of maximum 10-15 million EUR.
- The *absolute* amount of required subsidies might thereby be substantially higher than the predicted 91.4 million EUR (WGD, 2007); the *yearly* requirements for subsidies can, however, also be substantially lower than predicted by WGD (2007).

The results presented in this chapter base on a relatively simple sensitivity analysis, using the assumptions presented in Table 10. Assumptions with respect to the acceptable additional costs are directly related to achievable energy savings, energy prices, and the assumed consumer discount rates. A more detailed uncertainty analysis that includes these factors can give a more comprehensive projection for the required subsidies. Such an analysis could also differentiate different household types in the Netherlands, thereby generating more detailed and reliable projections on the market potential of micro-CHP systems.

4.3 Heat pumps (*Warmtepompen*)

4.3.1 Introduction and objective

Heat pumps upgrade heat from a lower to a higher temperature level by means of mechanical work. The most common applications of heat pump technology are (i) the supply of process heat for industrial processes, (ii) refrigerators, and (iii) air conditioning systems. The history of heat pumps dates back until the mid of the 19th century, when the first heat pump based refrigerator was developed. For several decades, heat pumps have been commercially available for space heating as energy efficient (albeit expensive) alternative to conventional heating systems.

The concept of using the underground as heat source and sink for both space heating and cooling dates back until the 1940's, when the first ground source heat pump was installed in the USA (Martinus et al., 2005). Today, various different types of heat pumps are used in industry, greenhouses, in other commercial applications, and in the residential and commercial building sector (Figure 43). Heat pumps used in industry typically make use of high-temperature waste heat while heat pumps used for space heating and cooling utilize low-temperature heat mainly provided by the natural environment, i.e., soil, ambient air, or ground water. The capacity of heat pumps that are used for industrial applications typically range between 2 kW_{th} and 200 kW_{th}. Heat pump systems for residential use are generally smaller with capacities ranging between 5-20 kW_{th}.

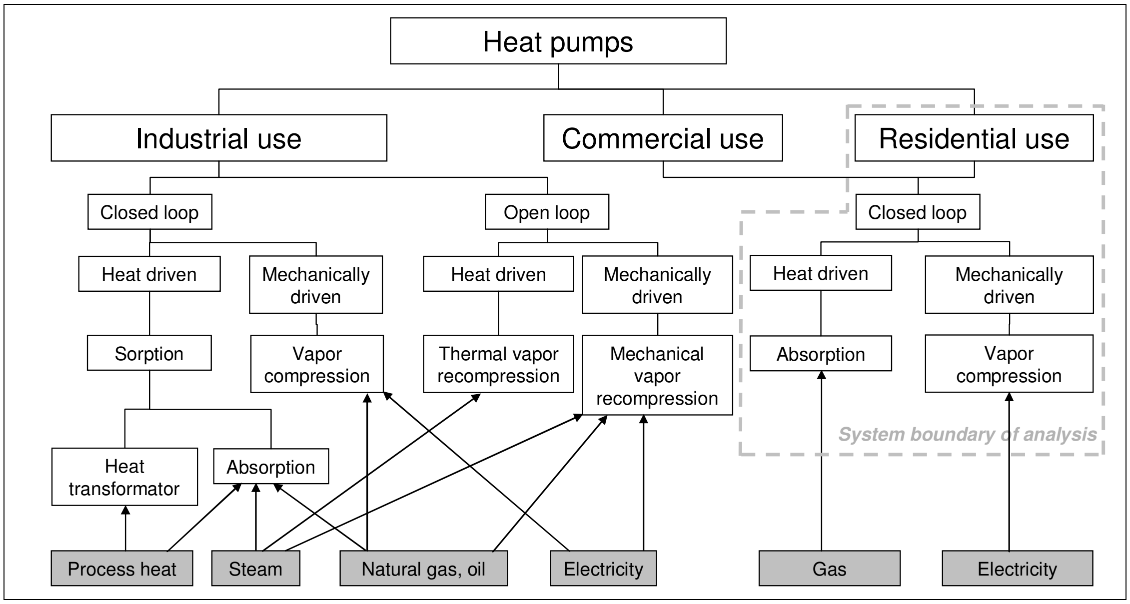

Figure 43: Types and applications of heat pumps (adapted from Boot et al. (1998); the grey dotted line indicates the system boundary of our analysis[34]

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[34] In the most common case of a closed-loop system, a working fluid is circulated in a closed loop between areas of high and low temperature for heat exchange. There occurs only heat transfer but no active movement of matter (e.g., water or air) from the environment. In an open-loop systems matter (i.e., most commonly water) is first extracted from the environments and transported via, e.g., a well to the heat pump where heat is either extracted or added. After use, the water is discharged to a drainage field or another well.

The number of heat pump installations in greenhouses and in the residential and commercial buildings sector of the Netherlands increased from 553 in 1995 to 12,300 in 2006 (Figure 44). Heat pump installations for space heating and cooling had in 2006 a combined capacity of around 830 MW_{th} and saved in the same year roughly 2.9 PJ of primary fossil energy, which is equivalent to almost 200 kt CO_2 emissions (CBS, 2007b). Due to the relatively high energy prices, the number of heat pump installations has increased rapidly in recent years.

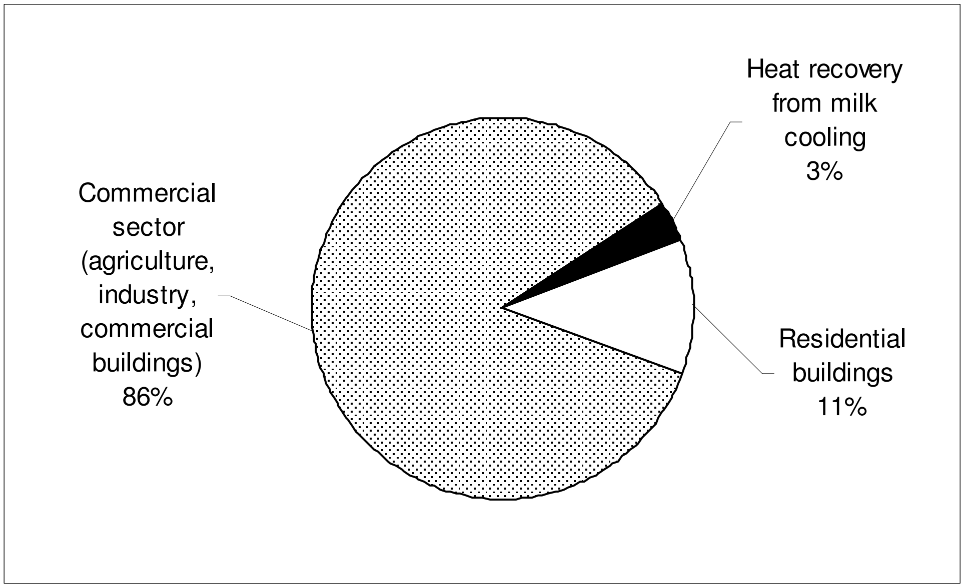

Figure 44: Sector shares on the total installed heat pump capacity in the Netherlands (Data source: CBS (2007b))

Future heat pump applications might include conventional energy demand technologies, e.g., heating boilers and household appliances. Although heat pumps are generally regarded as technology that improves the efficiency of energy functions, their environmental performance has to be evaluated in each case specifically because:

- Fuel mix and conversion losses for electricity generation have a considerable effect on the overall energy performance of electricity driven heat pump systems. Depending on the electricity mix in a country, conventional gas heating systems may be more energy efficient than electrical heat pumps.
- Heat pump systems often contain refrigerants as working fluid that have a high greenhouse gas potential. Already small amounts of refrigerants leaking from the system or being released to the atmosphere during end-of-life disposal of heat pumps can lead to emissions with a considerable greenhouse gas potential (Quaschning, 2006).

In this chapter, we aim at analyzing the cost dynamics of 7.6 kW_{th} *heat pump systems that are used for space heating in the residential sector. Due to limited data availability, we base our analysis on a time series of purchasing price data for Switzerland and on cumulative sales of residential heat pumps in Switzerland and in Western Europe. In a second step of our analysis, we extend the conventional experience* *curve approach by modelling the energy performance of Swiss heat pumps (i.e., COP) and the energy production costs of 7.6 kW$_{th}$ heat pumps as a function of cumulative Swiss heat pump sales.*

We continue with a description of heat pump technology and an overview of market dynamics for heat pumps used for space heating in the residential sector. We explain the principal data sources used for our analysis in Section 4.3.4). We present, discuss, and summarize our results in the last two sections of this chapter, i.e., in Section 4.3.5 and Section 4.3.6.

4.3.2 Technology description

Heat pump systems transfer heat from a low-temperature reservoir to a high-temperature reservoir by adding work to the system. The mechanism of a heat pump can be described in physical terms as an inverse Carnot cycle: A working fluid (in gaseous form) is compressed by applying work in an adiabatic process. The compression causes a temperature increase within the working fluid. The excess heat can be extracted from the high-temperature working fluid via heat exchangers. The working fluid cools and condenses. The pressure of the working fluid is afterwards decreased in an adiabatic process, which causes the temperature of the fluid to drop further. In this stage, the cold working fluid can extract heat from an external source (e.g., ambient air, soil, or water), it thereby evaporates, and the cycle starts from the beginning with the compression of the evaporated working fluid (Figure 45).

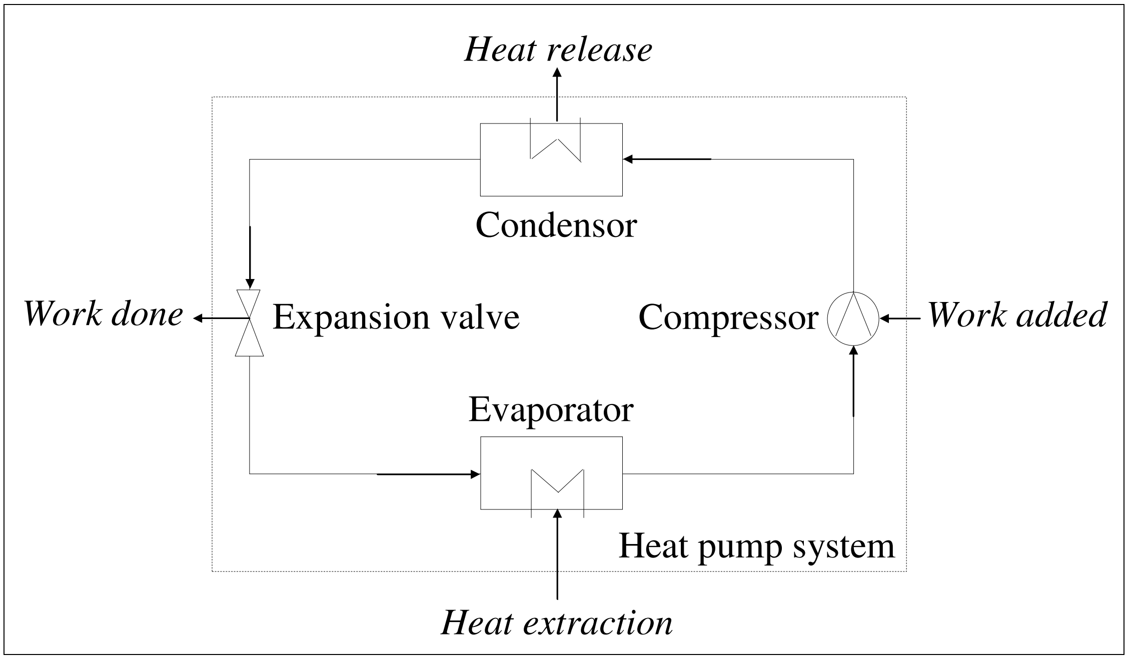

Figure 45: Working cycle and major components of a vapour compression heat pump system (adapted from Martinus et al. (2005))

The efficiency of a heat pump cycle can be expressed as coefficient of performance (COP) or primary energy ratio (PER). The COP is defined as the ratio of the output of useful heat and the input of mechanical work. In the ideal case, the COP only depends on the temperature difference between the low-temperature and the high-temperature reservoir:

$$COP = \frac{T_H}{T_H - T_L} \tag{13}$$

where T_H stands for the temperature of the high-temperature reservoir and T_L for the temperature of the low-temperature reservoir. The PER is calculated as the ratio of the overall output of useful heat (H_U) and the input of fuel (I_F):

$$PER = \frac{H_U}{I_F} \tag{14}$$

The seasonal performance factor (SPF) is used for calculating the heat pump performance over one year. It is defined as:

$$SPF = \frac{TH_U}{TI_F} \tag{15}$$

where TH_U stands for the overall output of useful heat per year and TI_F for the overall energy input per year.

The performance of heat pumps is influenced by source temperature, output temperature, source type, seasonal source temperature variability, and user behaviour. Heat pumps that are used for residential space heating make typically use of a low-temperature heat reservoir (i.e., soil, air) and can reach a maximum temperature of 150 °C at the output side (Martinus et al., 2005). In past decades, heat pumps made considerable progress with regard to their energy efficiency. The COP of small heat pumps used in the residential sector increased from, e.g., 1.5 in the 1970s to 3.2 in 2000 (Martinus et al., 2005).

A wide range of different heat pump technologies are used in industry (absorption and adsorption heat pumps). However, in the residential sector, predominantly *vapour compression* heat pumps are installed. Vapour compression heat pumps work according to the principles outlined in Figure 45 and can be considered as mature technology. The compressor in a vapour compression heat pump can principally be driven by an electric motor, by a gas or a diesel engine. The energy efficiency of gas or diesel fired compression heat pumps is in theory better than the efficiency of electricity driven heat pumps (assuming average European electricity mix) because the excess heat from the gas or diesel engine can be used directly for heating purposes whereas the heat resulting from public electricity generation facilities, which generate only power, is generally lost to the environment. Gas-driven heat pumps might become important for applications in the retrofit market of countries with a dense natural gas grid, like the Netherlands or the UK.

In heat pump systems, typically working fluids with low boiling points are used, i.e., CFCs until the early 1990s and ammonia, CO_2, propane, and other hydrocarbons in recent years. Research and development focuses on CO_2 as working fluid. Carbon dioxide is non-toxic, non-flammable, and compatible with common heat pump materials. However, the COP of CO_2 systems is low. It is, therefore, not clear, to what extent CO_2 as working fluid can penetrate the heat pump market. Furthermore, current research in heat pump technology focuses on the use of natural refrigerants, the integration of smart control systems, and the reduction of production costs.

The choice of the heat source is very important for the efficiency of heat pump systems (Table 11). Ideally, the heat source should have a high temperature and should show relatively little temperature variations. Various sources can be utilized as heat reservoir for heat pumps that are used for residential space heating:

- Soil – At a depth of roughly 1.5 meters, the underground has a stable temperature, equivalent to the average yearly surface temperature (e.g., 5-12 ºC in Central Europe). However, the heat conductivity of soil is lower than the one of groundwater.
- Ground and surface water – Groundwater can be used as heat source in places where the groundwater table is high. While the groundwater temperature is relatively constant, surface waters show considerable seasonal temperature variability. Water has very high heat conductivity.
- Air – Air is easily accessible but shows large seasonal temperature variability. Especially in colder climates an auxiliary heating system will be needed when outside temperatures are low during winter. The seasonal temperature variations cause air-source heat pumps to have lower COPs than ground source heat pumps.

Table 11: Overview on heat pump performance (Data sources: ODEV (2006), FWS (2007), Keller (2003), Sanner (2003), Sijpheer and Strootman (2004))

Heat source	COP	SPF
Ground (Soil)	4.0-5.5	3.0-4.5
Air	3.0-4.0	2.6-3.3
Water	-	3.6-4.9

The PER of electric heat pumps depends on the efficiency of electricity generation. Sijpheer and Strootman (2004) calculated PERs of 1.2-1.6 for ten ground source heat pump installations in the Netherlands (based on a SPF of 3.0-4.0). NEFIT gas absorption heat pumps showed a PER in the range 1.2-1.5, which indicates that gas absorption heat pumps can compete with electrical vapour compression heat pumps in terms of energy efficiency (Blom, 2000).

4.3.3 History and market development in Europe

The idea to use a thermodynamic cycle to transfer heat from a lower to a higher temperature level dates back to the 19th century and led to the development of first vapour compression cycles for use in refrigerators. The application of heat pumps for space heating was, however, for a long time not economically feasible. After the First World War, efforts were made to use vapour compression cycle technology for heating. In 1928, the first heat pump for space heating was installed in the UK. After the Second World War, air-to-air heat pumps used for air conditioning had a market break-through in the USA. Heat pumps for use in residential heating remained in their infancy, reaching only marginal sales in the years before the first oil crisis in 1973. In the years afterwards, sales of heat pumps for space heating increased drastically in several European countries (Figure 46). While heat pump sales decreased in the years after the second oil crisis in France and Germany due to low oil prices and reliability problems, they experienced slow but steady growth in Switzerland. With increasing energy prices and discussions about anthropogenic greenhouse gas emissions, heat pumps experienced a renaissance at the end of the 1990s. Since this time, sales have grown drastically.

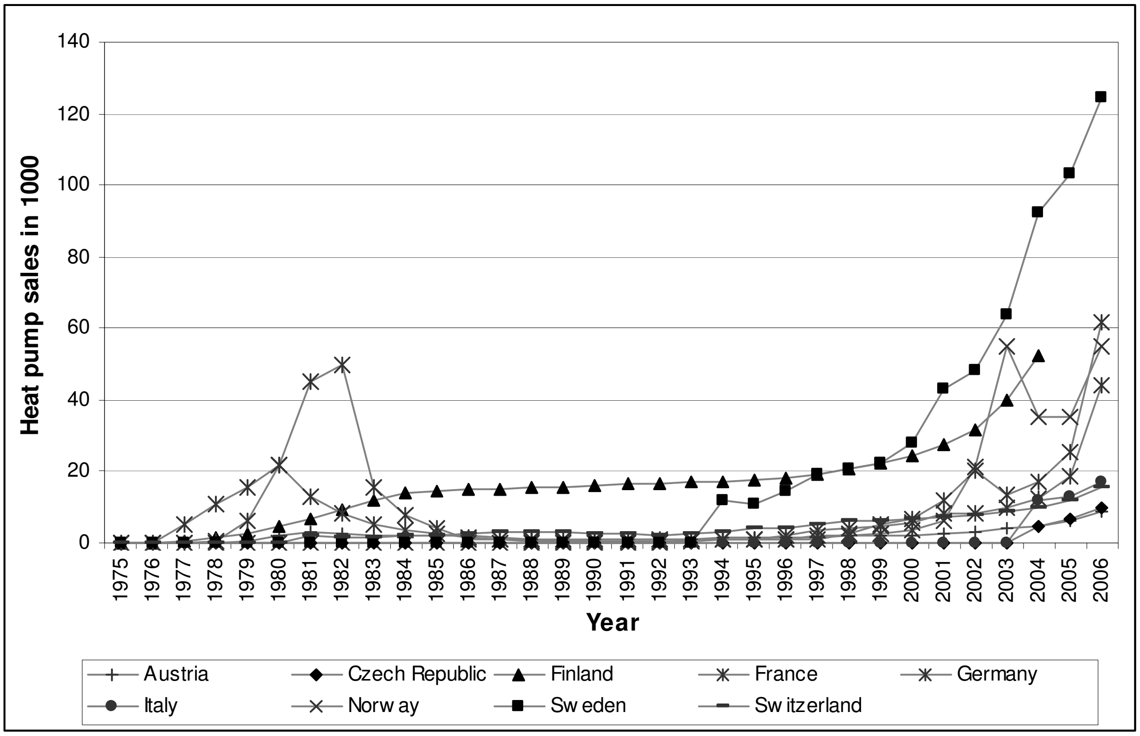

Figure 46: Heat pump sales in selected European countries (Data sources: Martinus (2005), FWS (2007))

The Western European heat pump market can be divided according to three geographical regions:

- In Scandinavia and Switzerland electricity has been the main energy source for generating space heat in households. The reasons are the availability of relatively cheap electricity from domestic resources and the absence of an extended natural gas grid. In these countries, ground source heat pumps replace inefficient resistance heating. The market penetration of heat pumps that are used for space heating is relatively high.
- Southern Europe is characterized by a large market for electricity-driven air-to-air heat pumps that are used for air conditioning. A large portion of the air conditioning units can be operated in reverse and thereby be used for space cooling and heating.

- Central and Western Europe are characterized by large natural gas grids (e.g., in the UK, the Netherlands, and Germany). In these countries, the market shares of heat pumps on the total heating market are still marginal mainly due to (i) the relatively high purchasing prices of natural gas-driven but also electricity-driven heat pumps compared to conventional natural gas based heating technologies.

Heat pumps installed in commercial buildings (e.g., offices, hotels, hospitals) contribute the majority to the country-wide heat pump related energy savings in the building sector of the Netherlands (Figure 47). Research and development has considerably improved the quality of heat pumps in the past decade. By 2006, the installed heat pump capacity in the Netherlands (commercial and residential heat pumps) amounted to 831 MW_{th}, which saved in total 2.6 PJ primary energy and 68 kt CO_2 emissions (CBS, 2007b) (Figure 47).

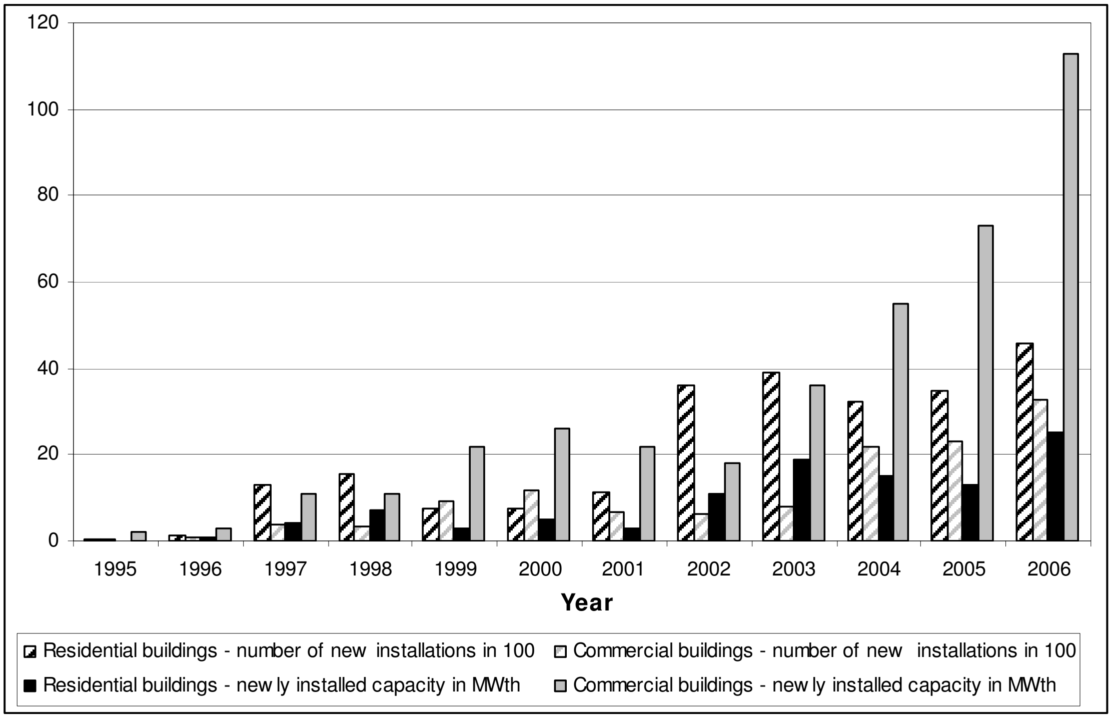

Figure 47: Yearly heat pump installations in commercial and residential buildings in the Netherlands (Data source: CBS (2007a,b))

The history of heat pumps in the residential sector of the Netherlands dates back until 1983, when the first heat pump water heaters were introduced. The COP of these heat pumps varied between 1.5 and 2.9. The first heat pumps for space heating were driven by gas engines, which encountered technical problems. In combination with other factors such as low oil price and a lack of policy support, this caused a decrease in the interest for heat pumps. Spurred by increasing energy prices and the discussions about anthropogenic climate change, electricity-driven heat pumps began to receive attention in the early to mid 1990s. With the introduction of energy standards for newly built houses (EPN) in 1995, the demand for heat pumps increased. In the Netherlands residential heat pumps are primarily installed in new dwellings.

Several projects were initiated to promote heat pumps in the Dutch residential sector. By 2004, 78 of such projects were realized, with roughly 7200 apartments (mainly newly built houses) being involved. The yearly number of residential heat pump installations increased substantially since the year 2001 (Figure 48). By 2006, the capacity of residential heat pump installations amounted to 110 MW_{th}. The majority of these heat pumps are ground source heat pumps that are used for space heating, hot water production, and cooling. Heat pumps used in individual, free standing houses are more abundant than collective systems (Braber et al., 2004). Residential heat pumps are supported by several governmental programs and organizations in the Netherlands (e.g., SenterNovem, Stichting Warmtepompen, Convenant Warmtepompen, Stichting Kwaliteitskeur Warmtepompen).

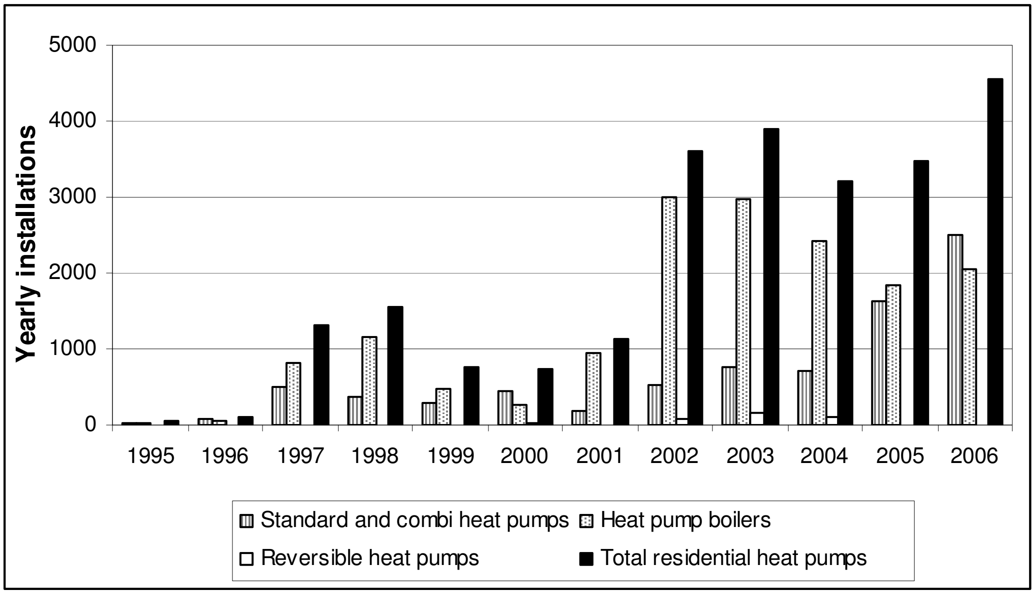

Figure 48: Yearly heat pump installations in the Dutch residential sector (CBS, 2007a,b)

Heat pump systems for residential use in the Netherlands face several problems (Braber et al., 2004, Inventum, 2008):

- Heat pumps have to compete with high efficiency condensing gas boilers, which are reliable, cheap, and which have considerably lower spatial requirements than heat pumps. Condensing gas boilers and the potential follow-up technology of micro-CHP systems are supported by a powerful gas lobby.
- Installation companies are specialized in gas boilers and have only limited experience with heat pumps. These companies have, however, a large influence on the decision of consumers.
- Suitable heat pump systems are available for newly-built houses but generally not for the replacement market of the existing building stock.
- The costs for heat pumps related to purchase and energy use are roughly 330-500 EUR per year higher (3,700-5,600 EUR over a life time of 15 years) compared to comparable solar heating systems. Both systems are suitable to reach an EPC of 0.8 in newly build houses.

- Heat pumps are economically competitive, if there is demand for both space heating and cooling, but so far there is hardly any market for residential space cooling in the Netherlands.

Several factors are important for the success of heat pump technology in the Dutch residential sector:

- the potential for future cost reductions;
- the potential for system adaptations to make heat pumps also suitable for the replacement market;
- the development of gas driven heat pumps to make use of the existing natural gas grid infrastructure.

4.3.4 Approach and data sources

The data for our experience curve analysis are based on information from open literature, producer associations, and materials provided by individual producers. While data for heat pump sales (in the past 15 years) are readily available for many European countries, price data (let alone cost data) are scarce. In the course of this research project, we could identify time series price and COP data for Swiss heat pumps, covering the period of 1980-2004 (FWS, 2007, WPZ, 2008). Time series of price data for more than 10 years could neither be organized for the Netherlands nor for Germany or Sweden. The reasons for the encountered difficulties might be found in the competitiveness of the heat pump market that makes producers and installation companies very reluctant to reveal any potentially sensitive information.

Based on the time series of price data provided for Switzerland, we differentiate between three individual components of heat pump systems, i.e., (i) heat pump, (ii) ground probe, and (iii) piping and connections. Using the available data on Swiss and Western European heat pump sales (e.g., Martinus et al., 2005, FWS, 2007)), we conduct a sensitivity analysis for various experience parameters. For calculating cumulative Swiss heat pump sales [MW], we assume an average capacity of 7 kW_{th} per heat pump for the entire period of 1980-2004.

For modelling the COP of heat pumps with the experience curve approach, we use Swiss data for the period of 1993-2007 (WPZ, 2008). We combine Swiss cost and COP data to model the dynamics of costs per kW heat produced. We include in this calculation the costs for heat pump, ground probe, and piping. We differentiate a base case as well as a low and high cost scenario (Table 12). We assume a constant electricity price of 0.22 EUR/kWh_e and a constant COP to SPF ratio of 0.8 as determined by Sijpheer and Strootman (2004).

Table 12: Assumptions used for calculating energy related heat pump costs

	Base case scenario	Low cost scenario	High cost scenario	Source
Lifetime heat pump [a]	15	20	15	Braber et al. (2004)
Capacity [kW_{th}]	7.6	7.6	7.6	FWS (2007)
Max load operation [h/a]	2000	2400	1600	Inventum (2008)
Yearly maintenance cost [EUR/a]	50	40	60	Inventum (2008)
Interest rate [%]	7	7	7	

4.3.5 Experience curves for heat pumps

We first plot the prices of the three components of a 7.6 kW_{th} heat pump system as a function of cumulative heat pump sales [MW_{th}] in Switzerland (Figure 49).

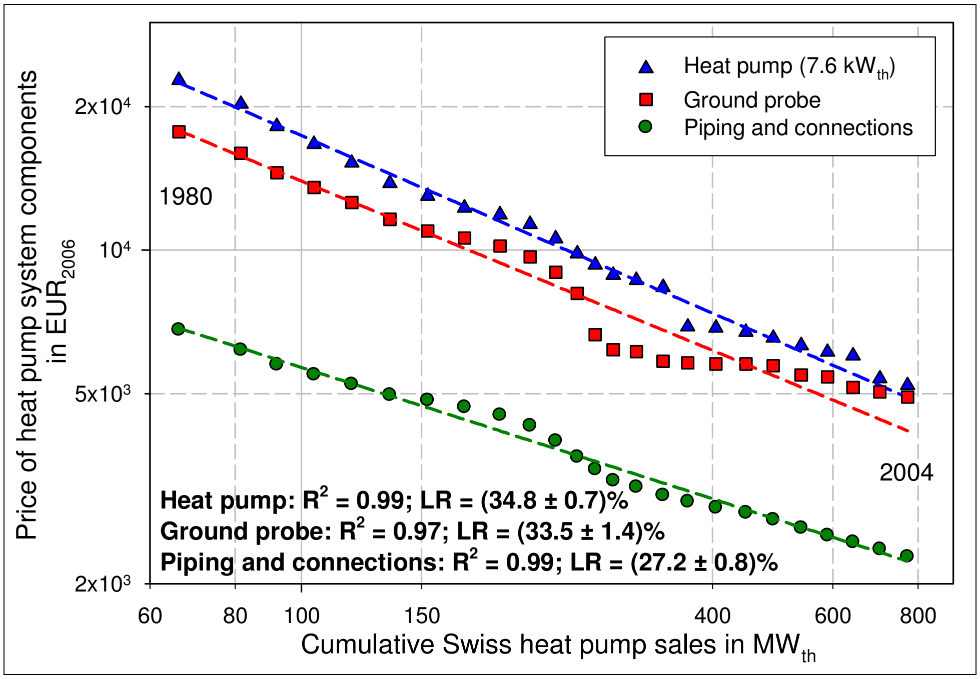

Figure 49: Experience curve for components of heat pump systems in Switzerland covering the period of 1980-2004 – Scenario I: Prices as function of cumulative Swiss heat pump sales (Data source: FWS (2007))

We identify a learning rate of (34.8 ± 0.7)% for 7.6 kW_{th} heat pumps in Switzerland. This finding indicates a considerable cost decline in the past decades. The price reductions for ground probes and piping and connections are in the same range as for the heat pump itself. Plotting the same component prices as a function of cumulative installed Swiss heat pump capacity, yields an even higher learning rate, i.e., (41.6 ± 2.0)% (Figure 50). The deviations in the results presented in Figure 49 and Figure 50 might be caused by three factors:

- errors that have been introduced in the results presented in Figure 49 by assuming a constant average heat pump capacity of 7 kW_{th}; it is likely that that the average heat pump capacity decreased in the period 1980-2004;
- underestimation of cumulative *produced* heat pump capacity by using data on cumulative *installed* heat pump capacity in Figure 50, i.e., disregarding possible replacement of heat pumps that have been installed in early years;
- disregarding in Figure 49 and Figure 50 possible *net* exports of heat pumps, which would lead to an underestimation of cumulative production and an overestimation of actual learning rates.

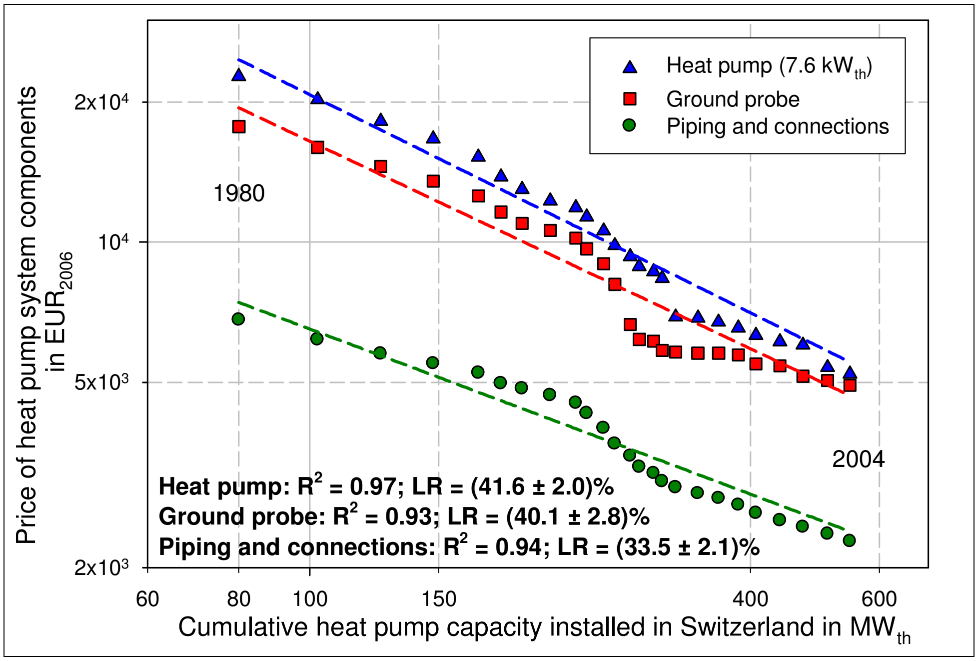

Figure 50: Experience curve for components of heat pump systems in Switzerland covering the period of 1980-2004 – Scenario II: Prices as function of installed heat pump capacity in Switzerland (Data source: FWS (2007))

Using cumulative Western European heat pump sales [million units] as independent variable of our experience curve analysis yields considerably lower learning rates than estimated previously (Figure 51). Under the assumption that prices are an adequate approximation of production costs, we find cost reductions of (24.5 ± 1.0)% for 7.6 kW_{th} heat pumps in Switzerland with each doubling of Western European heat pump sales. The observed deviations might be caused by several factors, including considerable uncertainties that are related to our estimates on (i) cumulative Western European heat pump sales.

The total costs for entire heat pump systems (i.e., cumulative costs for heat pump, ground probe, and piping and connections) reduce at rates of 23%, 33%, and 40% depending on the use of Western European sales data, Swiss sales data, or Swiss installation data, respectively.

The presented experience curve analyses indicate that costs for piping and connections decrease considerably slower than costs for heat pumps and ground probe.

This finding is in line with expectations because piping systems are basically a part of a much larger and more mature learning system. Our results indicate a considerable cost decline for heat pumps in the past decades. This result is supported by the findings of Martinus et al. (2005), who identified a learning rate of 30% for industrial heat pumps in Germany.

Despite the relatively good compliance of our results with literature, we emphasize that the price data, which are used for our analyses (FWS, 2007) are subject to uncertainties. The exceptionally good fit of data to the regression line (i.e., coefficient of determination of 0.93-0.99) raises questions whether data represent actual observations or only estimates by FWS (2007) based on data available for a few years only. Contacting FWS could not clarify this point.

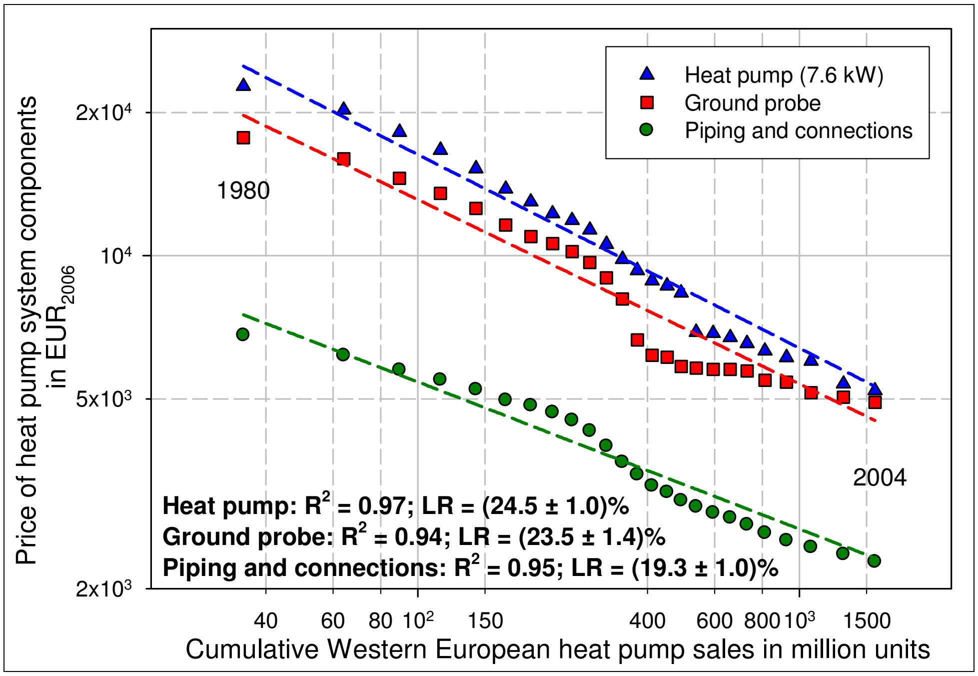

Figure 51: Experience curve for components of heat pump systems in Switzerland covering the period of 1980-2004 – Scenario III: Prices as function of cumulative Western European heat pump sales (Data source: FWS (2007), Martinus (2005), CBS (2007a,b)

The observed cost reductions can be attributed to technological learning in the manufacturing and installation of both heat pumps and related system components. The change of refrigerants in the early 1990 might have temporarily increased production costs. However, in the past decades, heat exchangers became both smaller and cheaper. Heat pumps use mainly components (e.g., the vapour compression cycle, heat exchangers) that are delivered by the cooling industry. We might therefore conclude that the major driver for cost reductions in the manufacturing of heat pumps was technological learning in heat pump assembling and system integration. Cost reductions were also achieved by economies of scale (this includes manufacturing costs, purchasing costs, sales costs, and possibly other cost items). The prospective of the future heat pump market has led also to a growing interest of traditional boiler manufacturers in this technology (e.g., Vaillant, Bosch, and Daalderop). The dynamics regarding experience and technological learning that have been observed for boiler manufacturing hold to some extent also for heat pump producers. In the past 3-4 years, however, market prices for heat pumps have increased. This phenomenon is caused by increasing resource and material prices (e.g., steel price) and a demand-driven heat pump market that allows producers to increase their profit margins.

In the second part of our analysis, we extend the conventional experience curve approach and model the energy performance, i.e., the COP of Swiss heat pumps as a function of the cumulative sold Swiss heat pump capacity. To account for the fact that COP improvements are limited by laws of physics, we introduce as additional term the thermodynamic maximum COP of 8.8 (1/COP = 0.11) into our experience curve model.

We identify a learning rate of (13.8 ± 1.8)% (Figure 52). This finding indicates an increase in the energy efficiency of heat pumps. The data deviate, however, considerably from the fitted exponential function. The relatively low coefficient of determination ($R^2 = 0.58$) indicates substantial uncertainties related to the applicability of the experience curve approach for modelling and projecting the energy efficiency dynamics of heat pumps.

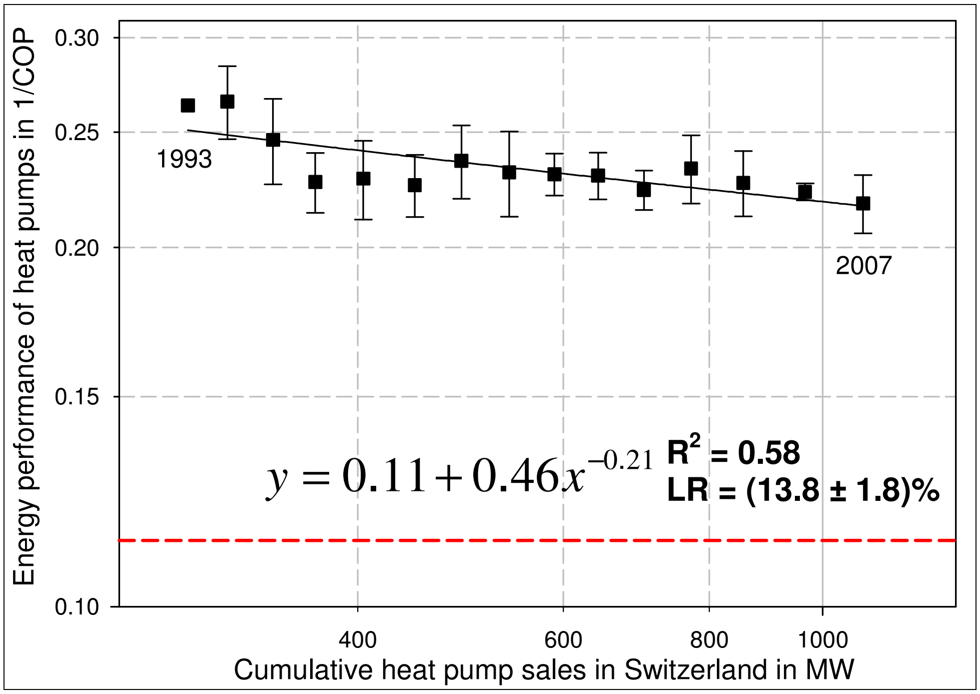

Figure 52: Experience curve for the COP of Swiss heat pumps; period of 1993-2007, the dotted red line indicates the thermodynamic maximum COP at given test conditions (Data source: FWS (2007), WPZ (2008))

Combining cost experience curve (Figure 49) and COP experience curve (Figure 52), we construct an experience curve for costs per kWh heat produced by Swiss heat pumps (Figure 53). We find an average learning rate of (27.7 ± 0.8)%. This finding indicates a considerable drop in consumer costs of heat pumps per unit of heat produced. However, consumer costs per kWh heat produced reduce at a lower rate than the specific costs for heat pump capacity (28% compared to 35%, see Figure 49 and Figure 53).

A comparison of the costs of roughly (0.14 ± 0.02) EUR/kWh$_{th}$ in 2007 with the consumer costs of Dutch condensing gas boilers shows, however, that heat pumps are not yet cost competitive in the Netherlands (Figure 53). Our finding support thereby the results of Braber et al. (2004), who came to similar conclusion when analyzing the competitiveness of heat pumps in the Netherlands.

It is important to note that the learning rate identified for costs per kWh$_{th}$ refer to electricity driven heat pumps and depends on the assumed electricity price. A high electricity price results in high costs per kWh heat. In that respect, it is important to note that high total costs result in a lower learning rate because the change of cost components related to heat pump price and COP are independent from the electricity price and constitute under a high-electricity price scenario only a smaller share on the total energy related costs.

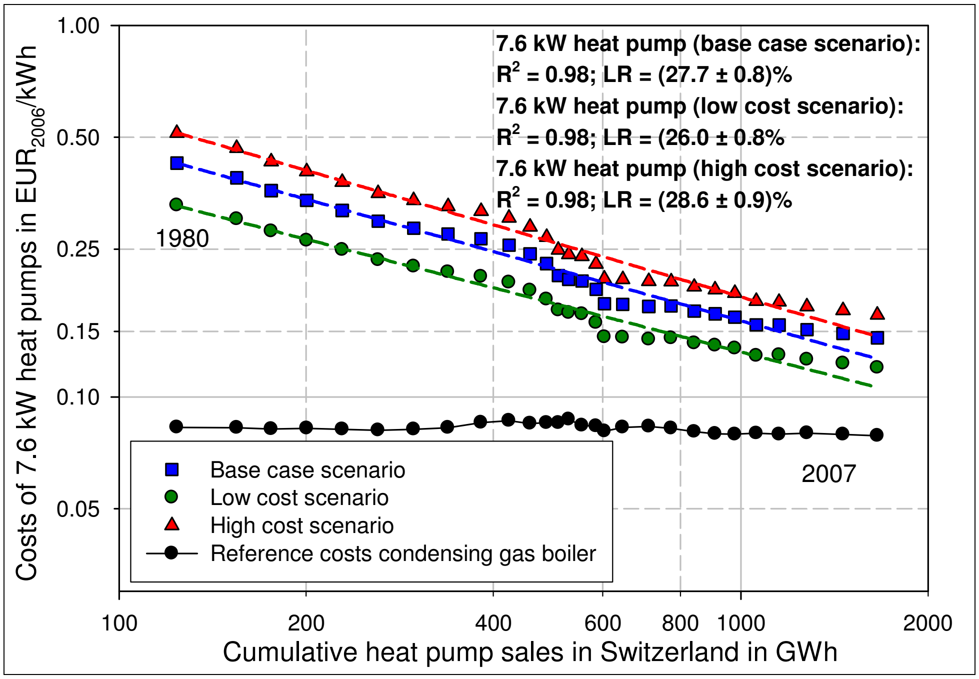

Figure 53: Experience curve for energy related costs of Swiss heat pumps; period of 1980-2007 (Principal data sources: FWS (2007), WPZ (2008))

4.3.6 Heat pumps – conclusions and outlook

In several European countries (e.g., Sweden and Switzerland), electrical vapour compression heat pumps are a standard space heating technology. The residential and commercial heat pump market in the Netherlands is growing but still in its infancy - mainly due to relatively high technology costs and spatial constraints in many households.

The experience curve concept is applicable for heat pumps but limited by poor availability and quality of price (let alone cost) data. Assuming that production costs follow prices adequately, we find a general trend towards cost reductions for heat pumps in the range of 25-42% with each doubling of cumulative heat pump capacity/sales based on price data for Switzerland. The learning rates for ground probes and piping and connections are in the range of 24-40% and 19-34%, respectively. While the general trend towards reducing production costs is confirmed by Marinus et al. (2005), our results are subject to considerable uncertainties. Due to a recently increasing demand for heat pumps, prices are currently increasing in Germany and in the Netherlands (Inventum, 2008). This deviation from the empirically observed trend is caused by increasing profit margins for producers.

By extending the conventional experience curve approach to physical energy efficiency, we find a trend towards COP improvements at a rate of (13.8 ± 1.8)% with each doubling of the cumulative capacity of Swiss heat pump sales. Combining the results of cost and COP experience curves, we identify an average learning rate of (27.7 ± 0.8)% for the total costs per kWh heat produced by heat pumps. Identifying costs of roughly (0.14 ± 0.02) EUR/kWh_{th} for 2007 indicates that heat pumps are still not cost-competitive relative to condensing gas boilers (0.08 EUR/kWh_{th}) in the Netherlands. Our results are subject to uncertainties because individual data points (mainly for COP) show considerable deviation from the fitted exponential regression line.

Interesting options for research and development are gas driven heat pumps that might potentially be more energy efficient than electrical ones and that would comply with the existing heating infrastructure in the Netherlands. Spatial constraints and the abundance of individual rather than district heating in the current building stock might, however, limit the applicability of heat pumps in the Netherlands to mainly newly-built large and free-standing houses.

4.4 Hot and cold storage systems (*Warmte en koude opslag*)

4.4.1 Introduction and objective

Hot and cold storage (warmte en koude-opslag) also referred to as aquifer thermal energy storage is a technology that uses the thermal capacity of groundwater bodies to store heat, i.e., thermal energy[35]. Hot and cold storage systems are commonly used for heating and cooling of large commercial buildings, e.g., office buildings or hospitals. Hot and cold storage offers considerable savings of energy, energy related costs, and CO_2 emissions. Novem (1998a) estimates that hot and cold storage technology saves of up to 80% of final energy relative to conventional cooling installations and improves the total energy performance of buildings by 15-20%. Van Aarssen (2006) quantifies total primary energy savings compared to conventional heating and cooling in commercial buildings with 40%.

Until the end of 2006, around 500 hot and cold storage projects with a total capacity of 743 MW_{th} have been realized in the Netherlands (Figure 54) contributing to yearly savings of 625 TJ primary energy and 43 kt CO_2 emissions (CBS, 2007b).

Figure 54: Geographical map of hot and cold storage installations in the Netherlands (van Aarssen, 2006)

The installation of hot and cold storage systems requires suitable geological conditions (see Section 4.4.2). Hot and cold storage technology is relatively expensive and usually only profitable for large buildings with a considerable energy demand for heating and cooling (e.g., office buildings, hotels, or hospitals). Novem (1998a) estimated for the year 1998 minimum cooling requirements of 250 kW_{th} for newly built houses being equivalent to a floor space of 5000 m^2 to make the installation of a hot and cold storage system profitable. Increasing energy prices and decreasing installation costs

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[35] Aquifer thermal energy storage is indeed by far the most common type of hot and cold storage. However, also other technological solutions for hot and cold storage systems are possible and have been tested such as energy storage in, e.g., artificial water tanks.

improve, however, the profitability of hot and cold storage installations in more recent years also for smaller houses (Figure 55; van Aarssen 2006).

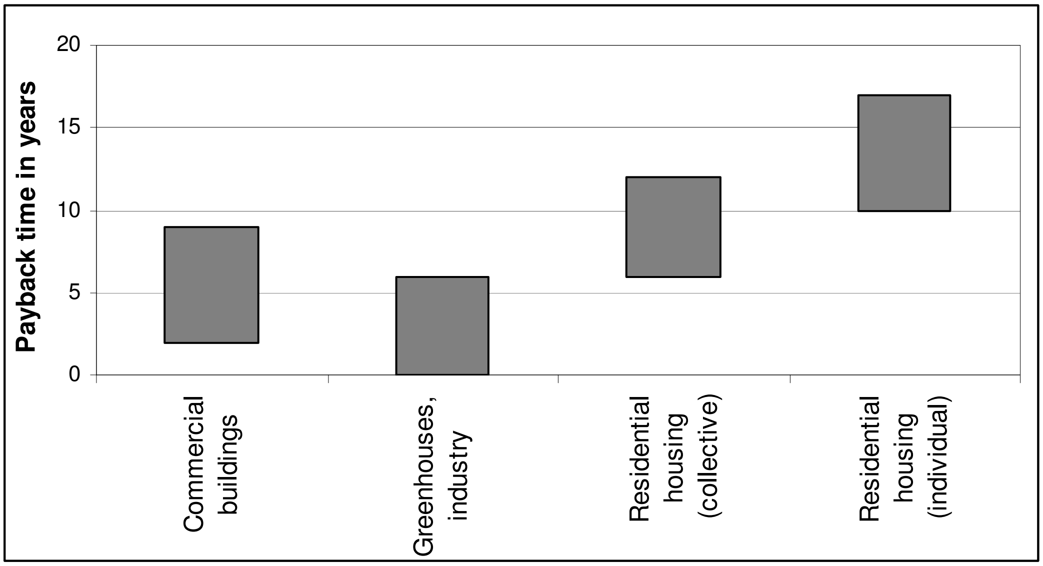

Figure 55: Recent payback times for hot and cold storage installations (Data source: van Aarssen (2006))

To assess potentials for contributing to energy and emission savings, it is important to obtain a more detailed insight into the cost dynamics of hot and cold storage systems in the Netherlands. *In this chapter, we apply the experience curve approach to hot and cold storage systems. We limit the scope of our analysis to the Netherlands. This approach is justified because due to its geological condition, the Netherlands is the country with by far the largest installed hot and cold storage capacity in the world.*

We start out with a short description of technology and historical background (Section 4.4.2 and Section 4.4.3). We explain approach and data sources used for our analysis in Section 4.4.4. We present and discuss our results in Section 4.4.5. We summarize our findings on hot and cold storage systems in Section 4.4.6.

4.4.2 Technology description

Hot and cold storage systems consist of a groundwater reservoir, one or more wells for water exchange, pumps, and a heat exchange system. In its most simple form, a hot and cold storage system has two wells (doublet system), a *hot* and a *cold* one. In case of demand for space cooling, water is extracted from the cold groundwater reservoir and pumped to a heat exchanger. The heat exchanger transfers heat originating from the building to the water that has been extracted from the aquifer. The heated water is then discharged via the second well to the aquifer. In winter, or in case of demand for space heating, the cycle can be reversed (Figure 56).

The hot and cold storage system is not an isolated installation. It is always connected via the heat-exchanger to the heating/cooling system of a building, greenhouse, or industrial installation. This *secondary* system can be a cooling battery, floor heating and cooling, a central climate control system, or a system for industrial process cooling. The components of hot and cold storage systems that are within the system boundary of our analysis (see Figure 56), are referred to as the *primary* system. All components of the heating system outside of the system boundary in Figure 56 are referred to as the *secondary* system. There are several possible configurations of hot and cold storage systems, differing both in number and arrangement of wells. Examples are:

- doublet systems with one hot and one cold well;
- doublet reservoir mono-well systems in which the wells are separated vertically from each other, using an impermeable layer (aquiclude) as barrier between the hot and the cold groundwater bodies;
- doublet recirculation systems in which the secondary system has only a demand for cooling.

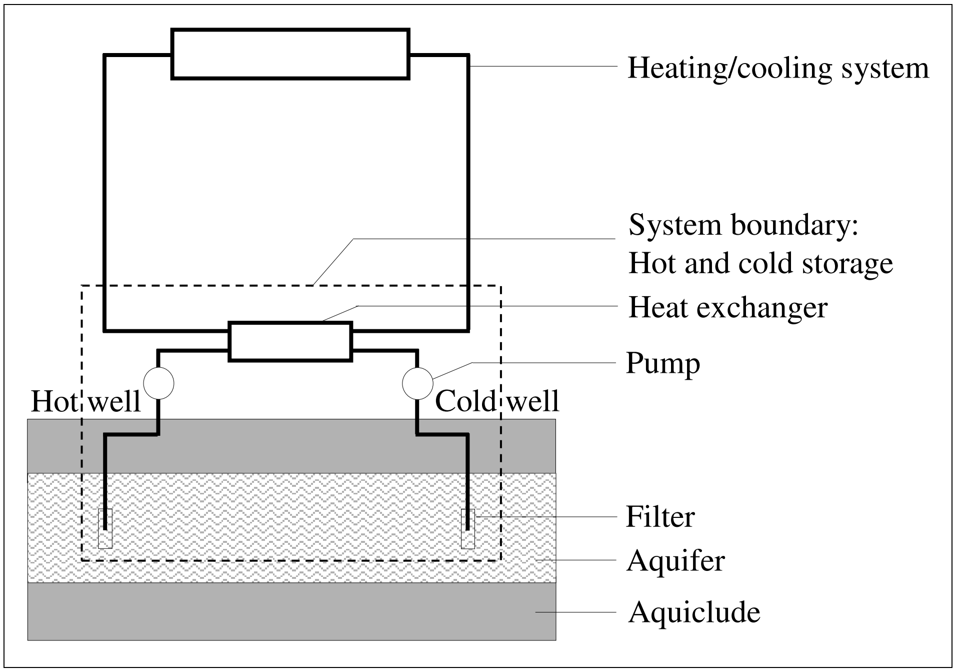

Figure 56: Simplified scheme of a hot and cold storage system; the dotted line represents the system boundary of our analysis

Hot and cold storage systems require favourable geological conditions. These include suitable depth, thickness, size, permeability, and spatial orientation of aquifer layers in the underground as well as suitable groundwater quality (Figure 57).

The geology of the Netherlands is characterized by deltaic, coastal, and eolian sediments that have been deposited during Pleistocene glacial and interglacial periods. The western part of the Netherlands is composed almost exclusively of river estuaries and alluvial deposits close to or below see level. Especially this part of the country offers very suitable conditions for the installation of hot and cold storage systems (Figure 58). Typically three sand layers ranging in depth between 15 m and 250 m can be used as aquifers for hot and cold storage installations. Most commonly, the middle aquifer layer (at 30-80 m depth) is used as heat reservoir for hot and cold storage installations because it generally provides more favourable structure, permeability, and water flow conditions than the first aquifer layer and it is more easily accessible than deeper aquifer layers (DWA, 2007).

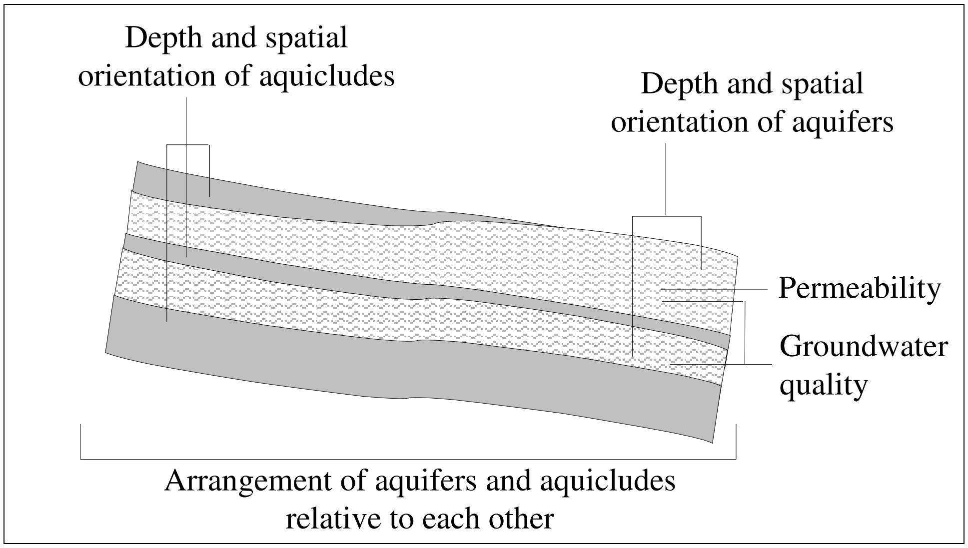

Figure 57: Schematic sketch of geological characteristics determining the suitability of the underground for the installation of hot and cold storage systems

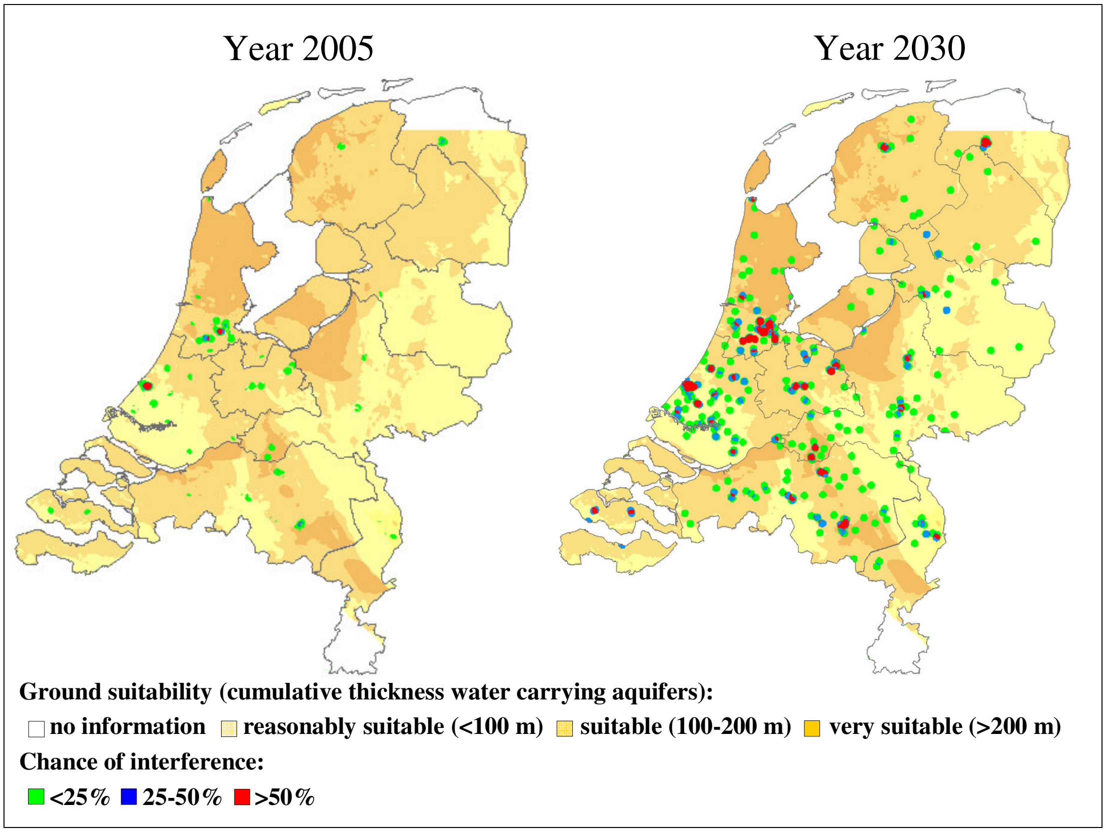

Figure 58: Underground suitability for hot and cold storage systems in the Netherlands (Source: van Aarssen, 2006)

Due to their relative large grain size, the sandy aquifers around Amsterdam offer the best conditions for hot and cold storage systems in the Netherlands (IF Technology, 2007). The eastern part of the Netherlands is partly shaped by moraine deposits of the last ice age. Higher relief energy and lower groundwater tables make the underground in this region less suitable for hot and cold storage installations.

Today, the Netherlands are international leader in hot and cold storage technology. No other country in the world has realized as many hot and cold storage installations as the Netherlands (Willemsen and van Harlingen, 2002; see also Section 4.4.3). As Figure 58 indicates, the potentials for hot and cold storage installations are, however, exhaustible (i.e., increasing chance of interference between neighbouring systems). In several areas of the Netherlands, we already find today interference of hot and cold storage systems with each other. This situation will potentially increase, if the number of installations continues to increase as projected until the year 2030 (Figure 58). On the other hand, the development and implementation of contained systems may be an option to overcome this problem. Hot-cold storage systems must meet several legal requirements before getting permission:

- The *net* heat balance must remain zero, i.e., the amount of heat transferred to the aquifer must be equal to the amount of heat extracted from the aquifer over the course of one year.
- The installation should not induce a risk to the drinking water system.
- New hot and cold storage systems should not interfere with existing nearby located storage systems.

4.4.3 History of hot and cold storage technology in the Netherlands

The development of first hot and cold storage projects in the Netherlands started in the early 1980s. The primary aim of these projects was to use the ground as heat source for space heating in winter. Research and development activities for the first demonstration projects were conducted under the National Research Program Sun Energy (Nationaal Onderzoek Programma Zonne-energie). Based on the positive experiences with the first installations, this technology was further developed (Snijders, 2002). In the period of 1985-1995 research was carried out, partly financed by national research programs and by the IEA Storage Program. Until the mid 1990s, the number of hot and cold storage installations remained low (Figure 59).

Reasons for the relatively low growth of hot and cold storage in the years between 1985 and 1995 were (i) that the technology was new and both installation companies and civil engineers were relatively inexperienced and (ii) that during the mid 1980s, energy prices were still too low to make this relatively expensive technology cost competitive. Both factors made investments in this energy efficient heating and cooling technology relatively unattractive. After 1995, the number of hot and cold storage installations increased steadily. In recent years, hot and cold storage became a standard and mature technology. Increasing energy prices led to a market boom in the last 3 years, making also smaller hot and cold storage installations profitable for investors. Today, drilling and installation companies offer standardized *turn-key* hot and cold storage systems in a wide range of capacities. In 2006, a total of roughly 500 hot and cold storage systems (mainly mono-well and doublet systems) have been installed in the Netherlands. Since 1985, hot and cold storage saved a total of 3.2 PJ primary energy resources and roughly 0.2 Mt CO_2 emissions in the Netherlands (Figure 59). Around 50% of hot and cold storage systems are installed in office buildings (Figure 60).

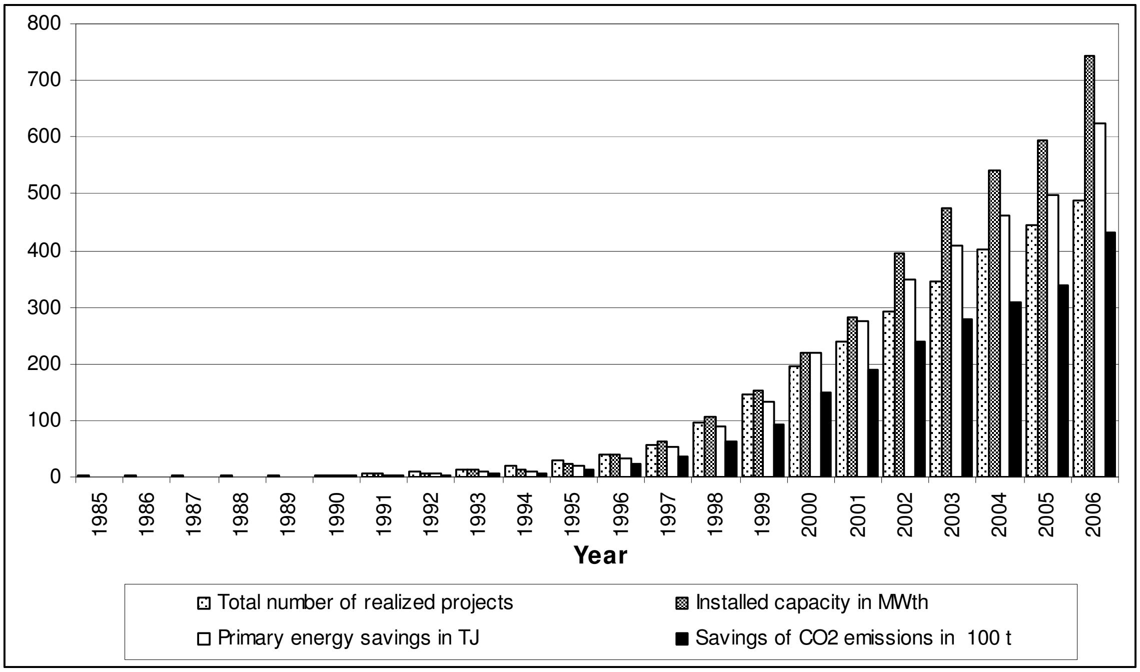

Figure 59: Hot and cold storage in the Netherlands – number of systems, installed capacity, yearly primary energy savings, and yearly savings of CO_2 emissions (Data sources: Graus and van der Meer (2003), CBS (2007b), Segers et al. (2006))

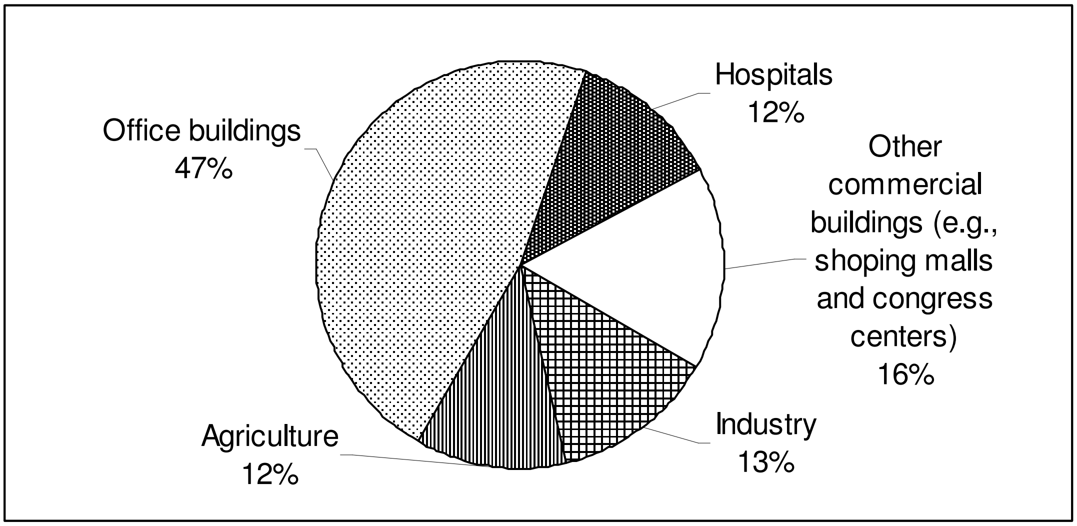

Figure 60: Share of the various economic sectors on the total number of hot and cold storage systems installed in the Netherlands (Data source: Snijders (2002))

Hot and cold storage systems were supported by various governmental subsidy schemes, e.g., BSE-MEA (Besluit Subsidies Energieprogramma's – Programma Marktimplementatie Energieopslag in Aquifers), EINP (Subsidieregeling Energie

Investeringen Non-profit Sector), EIA (Energie-investeringsaftrek), VAMIL (Vrije Afschrijving Milieu-investeringen, and EB-fonds (Energiebesparingfonds, Energiedistributiebedrijven). After 2001, most subsidy schemes were terminated. However, investors can still receive dedicated tax deduction and subsidies from various different regional and national sources.

Apart from the Netherlands, only Sweden has a considerable number of hot and cold storage systems installed (>10 in the year 2002). In all other countries, hot and cold storage is still at the level of pilot projects (Willemsen and van Harlingen, 2002).

4.4.4 Approach and data sources

We base our experience curve analysis exclusively on data for the Netherlands. This approach is justified because the Netherlands are internationally the technology leader and the Dutch market for hot and cold storage systems can be regarded as largely autonomous. For the analysis of system-related costs, we draw the system boundary according to Figure 56 around the *primary* hot and cold storage system. We approximate actual costs by price data that include all costs related to the *turn-key* installation of the *primary* system, i.e., planning, purchase, and installation of heat exchanger, electronic control system, underground piping, and piping from the aquifer to the heat exchanger (in contrast, the *secondary* system is excluded, i.e. the cooling battery, floor heating and cooling, a central climate control system etc.). Price data are obtained from open literature, expert interviews, and various internet sources, e.g., Novem (1998a,b, 1999a,b), SW (2007), Geocomfort (2007). Data on the cumulative number and capacity of hot and cold storage installations in the Netherlands are estimated based on CBS (2007b), Segers et al. (2006), and Graus and van der Meer (2003).

Furthermore, we collect information on capacity, water flux density, depth of the aquifer layers, number of wells, as well as on the specific type of hot and cold storage systems (Novem, 1998a,b, 1999a,b, SW, 2007, Geocomfort, 2007). From our analysis, we exclude:

- underground heat-exchangers (i.e., closed systems, which exchange heat by making use of the temperature differences between the water in the heating/cooling cycle and the groundwater);
- geothermal heating;
- other systems for heat exchange (i.e., systems that use asphalt for heat collection or surface water for cooling);
- energy poles (i.e., foundation poles or pillars of buildings that are used for heat exchange).

We exclude all those systems from our analysis, for which the year of completion was unclear. In total, we include data for 202 hot and cold storage systems in our analysis, covering the period of 1992-2007. By our experience curve analysis, we cover roughly 40% of the Dutch hot and cold storage installations. The choice of an appropriate functional unit for analyzing cost dynamics of hot and cold storage systems is complicated as various different system configurations are possible. Furthermore, the geological properties of the underground determine to a large extent costs and performance of hot and cold storage systems. We choose the following indicators (with different functional units) to analyze hot and cold storage systems:

- costs per hot and cold storage systems [EUR_{2006}]
- cost per well [EUR_{2006}/n]
- costs per capacity [EUR_{2006}/kW], costs per capacity and number of wells [EUR_{2006}/(kW*n)]
- costs per flux density [$EUR_{2006}/m^3/h$], costs per flux density and number of wells [$EUR_{2006}/(m^3*n)/h$]

4.4.5 Experience curves for hot and cold storage systems

The data overview in Figure 61 indicates relatively large differences between the price of hot and cold storage systems in individual years. The data span from 8,000 EUR_{2006} for the cheapest system up to almost 3,000,000 EUR_{2006} for the most expensive one with average prices over all years being roughly 270,000 EUR_{2006}. Visual inspection of data presented in Figure 61 does not allow identifying a general trend towards either reducing or increasing absolute prices.

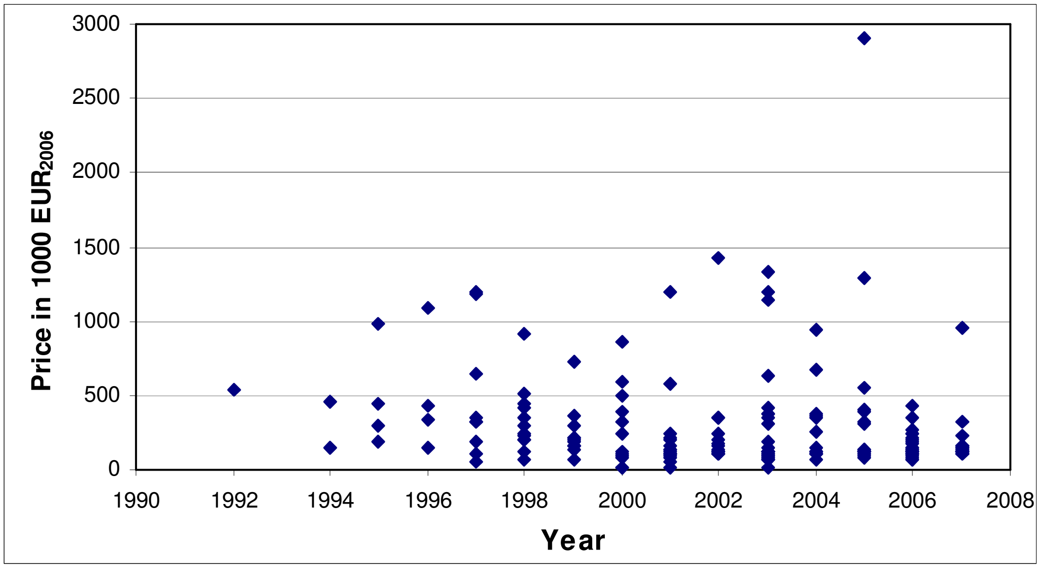

Figure 61: Overview of prices for hot and cold storage systems in the Netherlands (Data sources: Novem (1998a,b, 1999a,b), SW (2007), Geocomfort (2007), CBS (2007b), Segers et al. (2006), Graus and van der Meer (2003))

The total price of a hot and cold storage system depend on its capacity [kW] and water flux density [m^3/h]. In the first step of data analysis, we normalize price data with these parameters (Figure 62 and Figure 63). In both cases, the specific prices show large variations and do not allow identifying a general trend towards reducing or increasing costs.

The reasons for the relatively scattered data can be explained by the fact that costs for hot and cold storage systems are not solely determined by system capacity and flux density but also by other parameters such as:

- the number and depth of wells;
- underground characteristics, i.e., spatial orientation, depth, and permeability of aquifer layers.

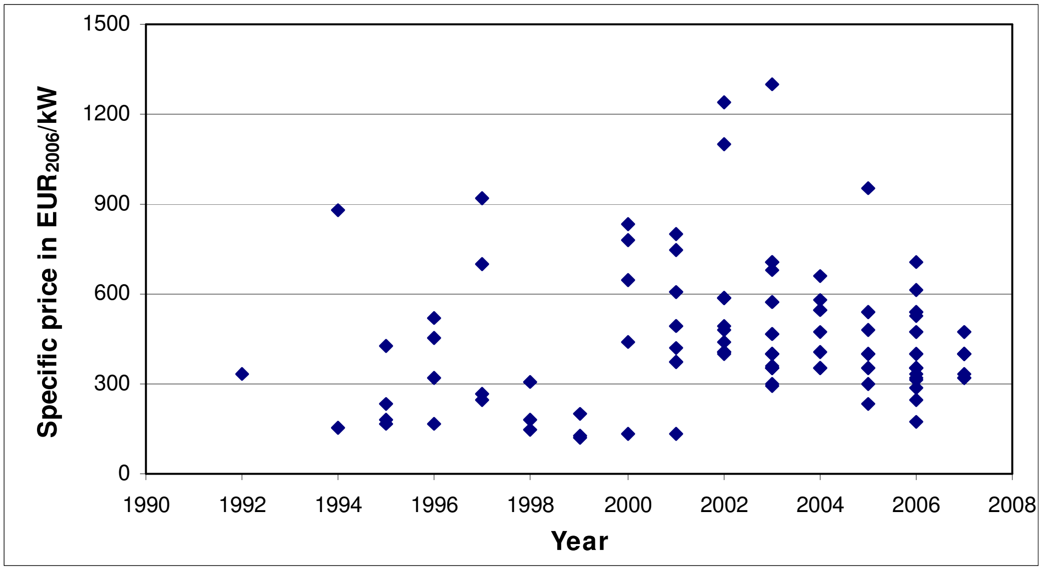

Figure 62: Overview of specific price [EUR_{2006}/kW] for hot and cold storage systems in the Netherlands

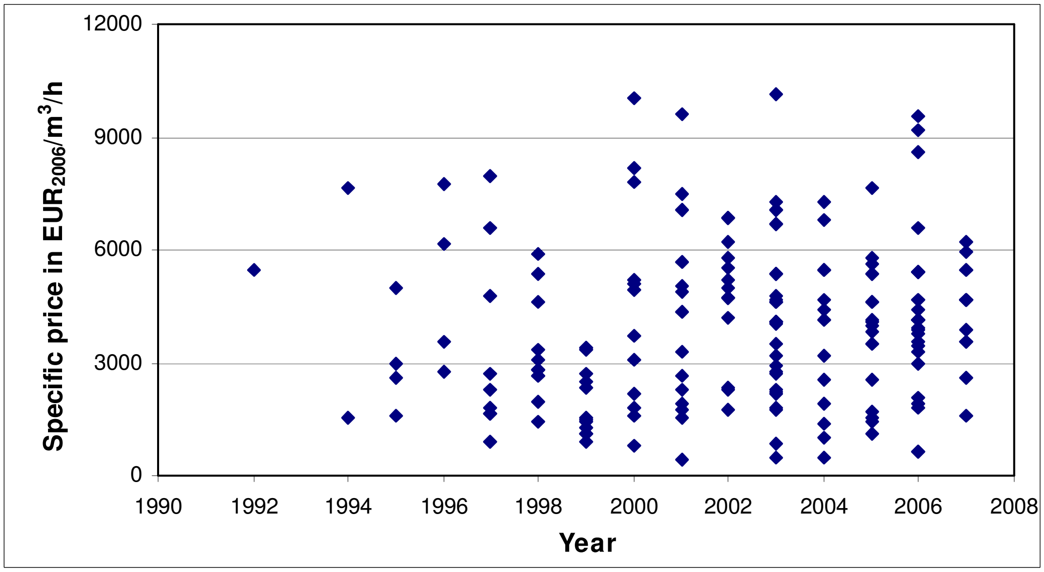

Figure 63: Overview of specific price [$EUR_{2006}/m^3/h$] for hot and cold storage systems in the Netherlands

In conclusion, both price and energy performance of hot and cold storage systems depend to a large extent on exogenous, non-technology-related factors. We therefore expect that while *technology-related* costs of hot and cold storage systems are likely to decline due to technological learning, *non-technology-related* factors might affect absolute costs (an prices) to such an extent that the experience curve approach is probably unsuitable for analyzing the cost dynamics of this technology. This hypothesis is supported by the results of our experience curve analyses presented in Figures 64-68.

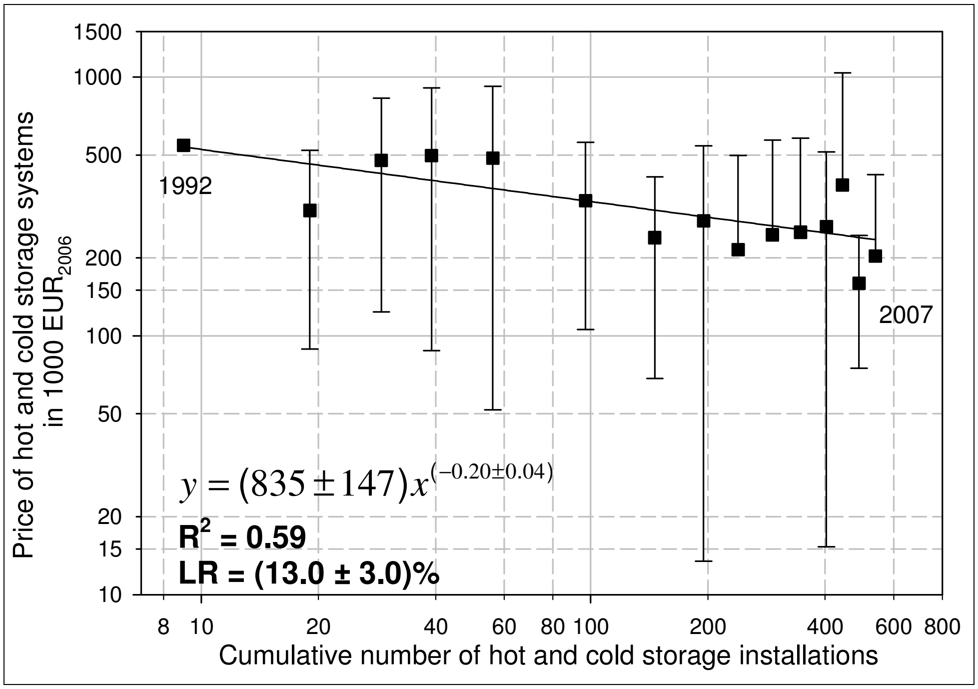

Figure 64: Experience curve for hot and cold storage systems in the Netherlands covering the period of 1992-2007; error bars indicate the standard deviation of average prices, standard deviations for prices in the years 2001, 2002, 2003, 2005, and 2007 reach negative values and can therefore not be shown in the diagram

Based on available price data, we find a learning a rate of (13 ± 3)% with each doubling in the number of cumulative hot and cold storage installations (Figure 64). This result is, however, subject to major uncertainties because error margins of price averages are large and because our analysis so far disregards changes in size (i.e., capacity, flux density, and number of wells) of hot and cold storage installations. Taking these parameters into account, we find learning rates of:

- (-4.6 ± 4.2)% ($R^2 = 0.08$) for prices per kW capacity (Figure 65)
- (2.0 ± 3.1)% ($R^2 = 0.03$) for prices per flux density (Figure 66)
- (11.9 ± 6.0)% ($R^2 = 0.26$) for prices per well (Figure 67)
- (-21.5 ± 7.4)% ($R^2 = 0.47$) for prices per flux density and well (Figure 68)

Depending on the functional unit chosen, we find weak trends to either decreasing or increasing costs in the entire period of 1992-2007 at extremely low coefficients of variation. Figure 64, Figure 66, Figure 67 might indicate a trend towards declining costs in the period 1996-1999. It remains, however, doubtful whether this trend is statistically significant.

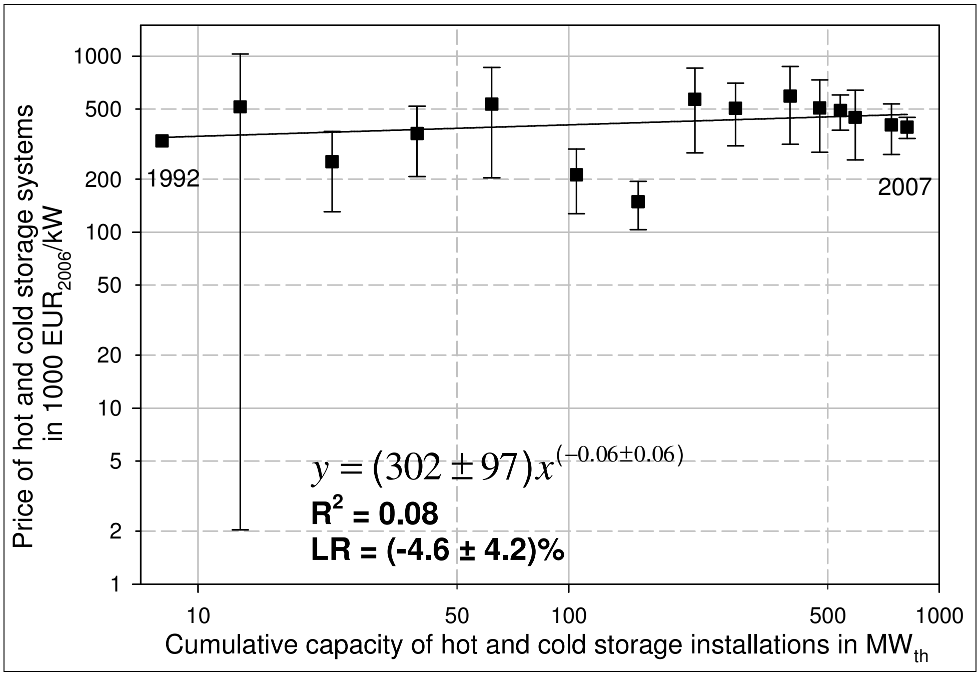

Figure 65: Experience curve - price [1000 EUR$_{2006}$/kW] of hot and cold storage systems in the Netherlands covering the period of 1992-2007; error bars indicate the standard deviation of average prices

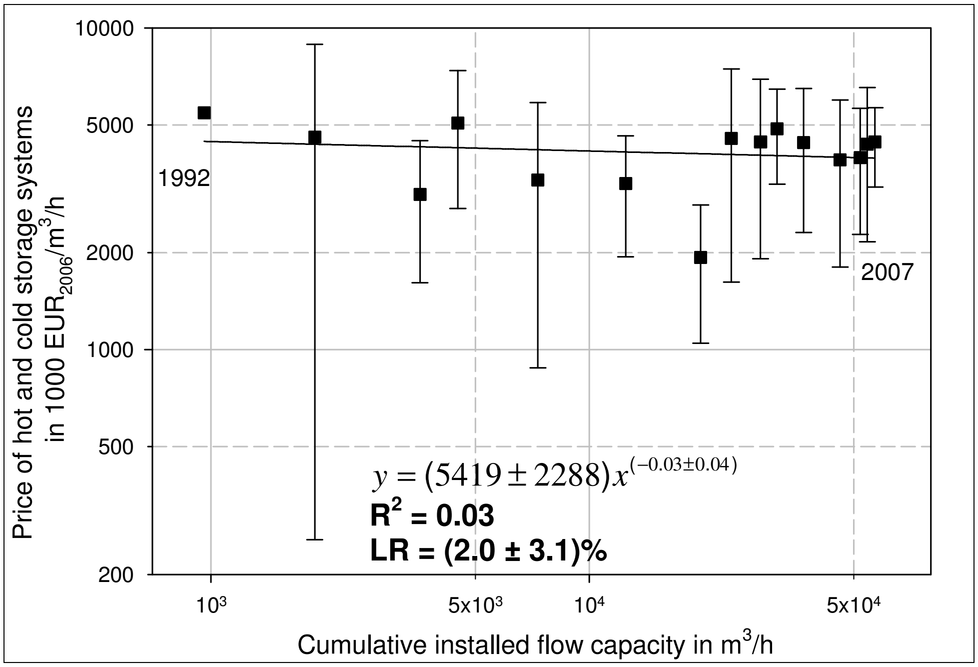

Figure 66: Experience curve - price [1000 EUR$_{2006}$/m^3/h] of hot and cold storage systems in the Netherlands covering the period of 1992-2007; error bars indicate the standard deviation of average prices

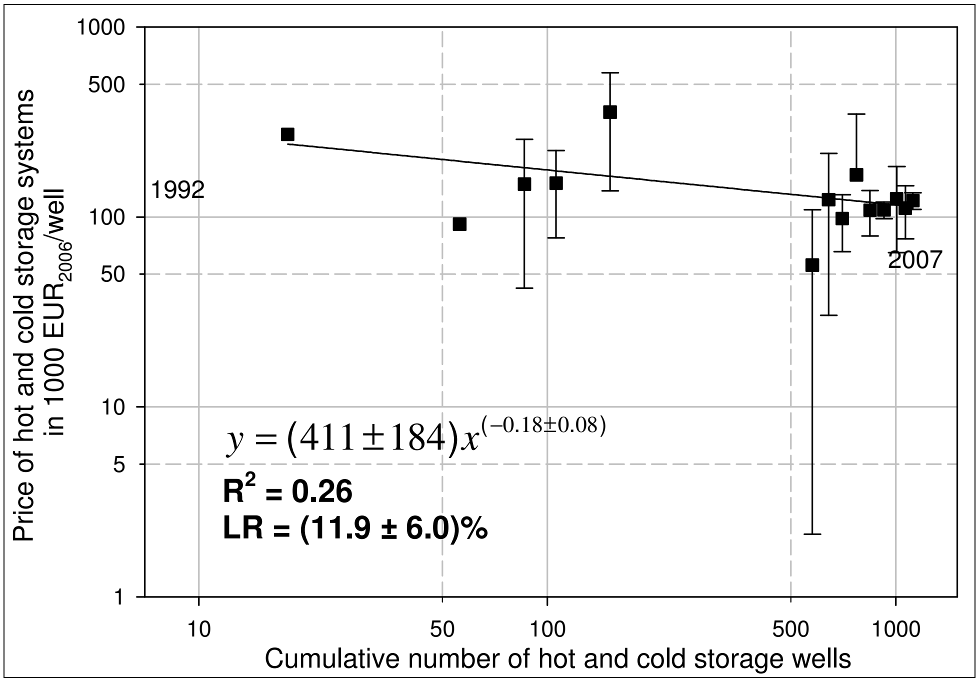

Figure 67: Experience curve - price [1000 EUR$_{2006}$/well] of hot and cold storage systems in the Netherlands covering the period of 1992-2007; error bars indicate the standard deviation of average prices

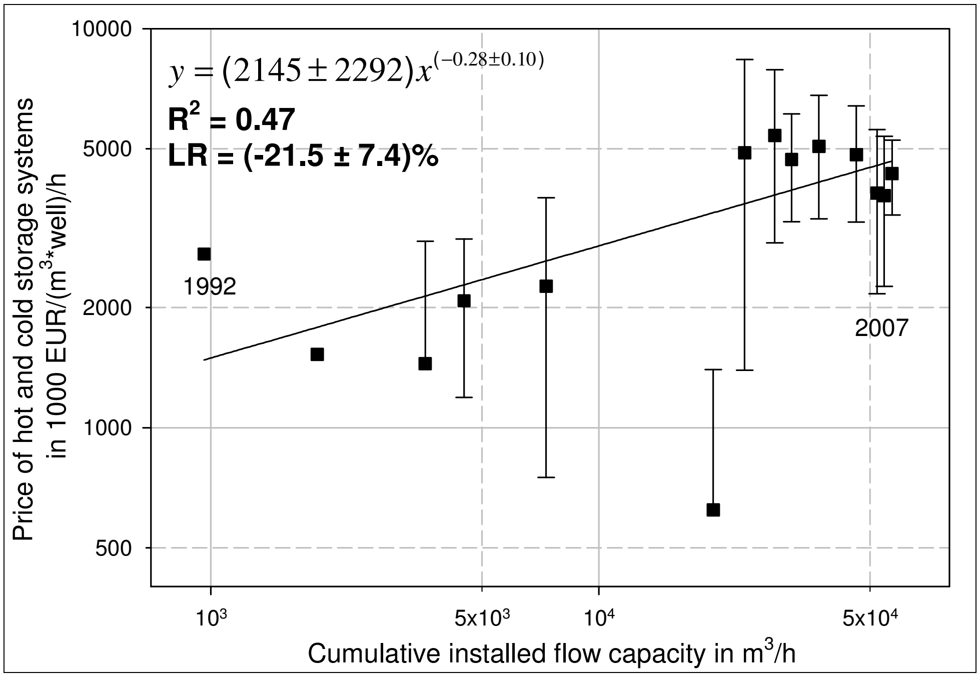

Figure 68: Experience curve - price [1000 EUR$_{2006}$/(m$_3$*well)/h] of hot and cold storage systems in the Netherlands covering the period of 1992-2007; error bars indicate the standard deviation of average prices; standard deviation for prices in the year 1998 reach negative values and can therefore not be shown in the diagram

Prices (as indicator for costs) for hot and cold storage systems do apparently not follow an experience curve. This is likely due to the following reasons:

- Profit margins of installers (e.g., drilling companies) did not remain constant in the period analyzed but showed considerable variability (low margins until the end of the 1990s; high profit margins due to shortage in installation capacity in the period of 2000-2002, economic recession and declining profit margins in 2003 and 2004, economic boom, again shortage of installation capacity, and rising profit margins since 2005) (IF Technology, 2007).
- Raw material prices (e.g., for stainless steel) increased considerably in the years 2005-2007.
- Neither of the functional units chosen (e.g., capacity, flux density, number of wells, see Figures 64-68) is sufficient as indicator for costs. For example, hot and cold storage systems become in general more expensive with an increasing number of wells. However, depending on depth and diameter of wells as well as on the characteristics of aquifers, costs per well can vary considerably, e.g., leading to the situations where drilling two wells at favourable sites can be cheaper than drilling only one well at less favourable underground conditions (DWA, 2007).
- Clear economies of scale that indicate strong dependency of specific costs on the size of a hot and cold storage installation; for example, the decreasing plant size (due to increased attractiveness for smaller buildings) may be one explanation for the small and partly negative learning rates (see Figure 69 below).

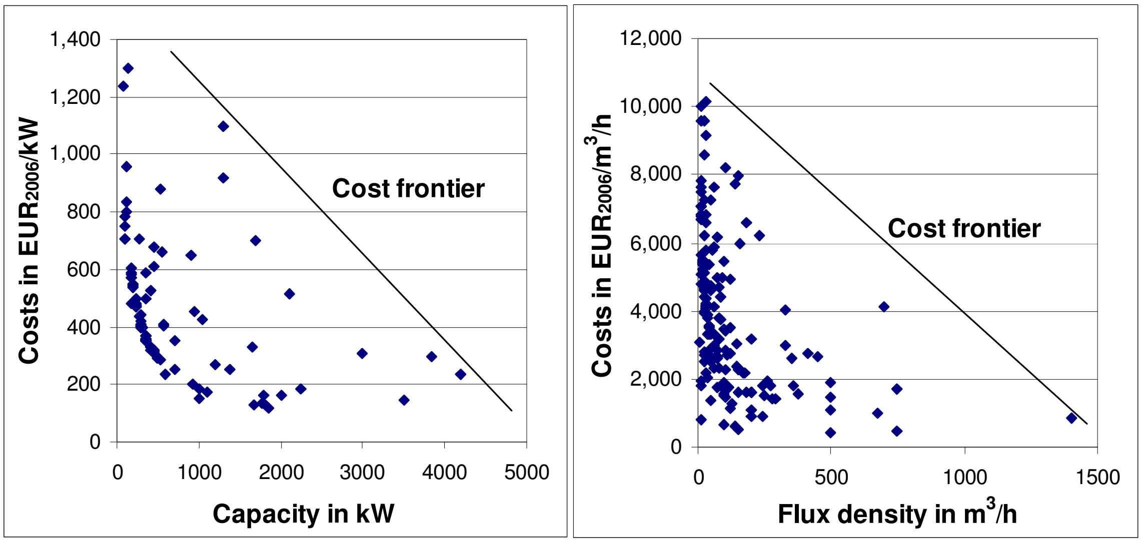

Figure 69: Costs of hot and cold storage systems as function of capacity and flux density[36]

We conclude that the experience curve concept can be applied only to a very limited extent to hot and cold storage systems because cost and performance of hot and cold systems are largely determined by exogenous, non-technology-related factors, i.e.,

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[36] We approximate costs in Figure 69 by the price data that are also used for our experience curve analysis.

geological underground characteristics. For this reason, IF Technology (2007) refrained already earlier from developing experience curves for hot and cold storage systems.

Based on expert interviews, we identified drivers for prices and costs of hot and cold storage systems in the Netherlands (IF Technology, 2007, DWA, 2007, Heinis, 2007, IA, 2007):

- Rising energy prices make the installation of hot and cold storage systems also profitable at less favourable sites. Therefore, an increase rather than a decrease of costs might be expected.
- Local subsidies are important for the realization of hot and cold storage projects.
- Local subsidies support the installation of hot and cold storage systems at less favourable sites.
- Market for doublet systems experienced fierce competition around the year 2000, leading to temporarily declining profit margins until 2003.
- Profit margins for installation and drilling companies have increased due to high demand in recent years.
- Hot and cold storage technology is relatively mature.
- Costs for investors are mainly driven by external factors (e.g., geological conditions of the underground).
- Costs seem to depend to some extent on the quality of work, e.g., whether or not the source well is cleaned after drilling can have a considerable impact on the costs documented in open literature.
- Technological learning in drilling, system integration, and component manufacturing took mainly place in the period between the mid 1980s and the mid 1990s.
- Between 1999 and 2002, especially economies of scale contributed to considerable cost reductions.
- After 2003, prices and costs increased due to demand-driven market for hot and cold storage installations and increasing material prices (e.g., prices for stainless steel as a major component of hot and cold storage systems has risen by 40% between 2005-2007.

Given the information from industry experts, one may conclude that flux density is the *best* among the *poor* indicators for tracing cost dynamics of hot and cold storage systems in the Netherlands (see Figure 66). Indeed, Figure 66 describes the main cost trends better than the other experience curves: (i) reducing costs in the 1990s, (ii) cost increase in the years 2000-2002, (iii) decreasing costs in 2002-2004, and finally (iv) cost increases since 2005 due to increased profit margins and material, e.g., stainless steel prices.

By plotting specific costs as a function of capacity and flux density, the scale effect for hot and cold storage systems can be identified (Figure 69). The stylized cost frontiers represent the dynamics of *maximum* marginal costs below which hot and cold storage systems are installed in the Netherlands. Based on the capacity data, we can also identify *minimum* marginal costs that represent the lower boundary of costs for a given capacity installed.

The minimum marginal costs follow a power function (coefficient of determination of $R^2 = 0.93$) and can be estimated as:

$$C_{kW} = 13{,}851 \times CAP^{-0.0172} \tag{16}$$

where C_{kW} stands for the costs per kW_{th} capacity and CAP for the capacity [kW_{th}] of hot and cold storage systems. Irrespective of this finding, Figure 69 confirms our earlier result according to which specific costs and prices can vary substantially, even if hot and cold storage systems are of similar size.

In the last part of our analysis, we correct the data shown in Figure 66 for the dynamics of the stainless steel price. The results indicate that average prices would have dropped since 2004 (Figure 70), if steel prices remained constant (see curve *Price in* $EUR_{2006\text{-}Steel}$ in Figure 70). However, the best fit for the entire period shows a price increase, if the changes in steel prices are taken into account. The analyses presented should not be over-interpreted because none of the two experience curves shown in Figure 70 have an acceptable fit (see R^2 values).

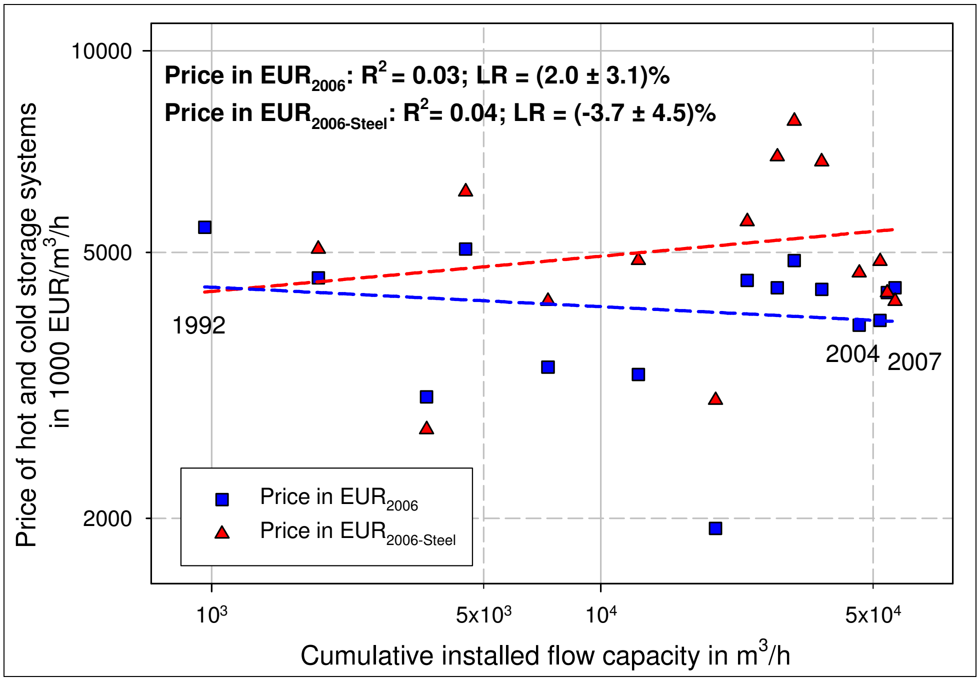

Figure 70: Experience curve – sensitivity analysis for specific price of hot and cold storage systems in the Netherlands covering the period of 1992-2007

Finally, we would like to emphasize that the price data used for the analyses presented above are subject to uncertainties that result from potentially inconsistent system boundaries (see Figure 56) of data provided by the various sources.

4.4.6 Hot and cold storage – conclusions and outlook

The Netherlands are international leader in the installation of hot and cold storage systems. Since 1985, more than 500 hot and cold storage systems with a combined capacity of roughly 800 MW_{th} have been installed. Hot and cold storage in aquifers has been most profitable for large office buildings, greenhouses, and industrial installations with considerable demand for space heating and cooling. Due to rising energy prises, future potentials for hot and cold storage systems are also expected in the residential sector (IF Technology, 2007).

Our experience curve analysis for the period 1992-2007 yields both trends towards increasing and decreasing average costs (i.e., learning rates between -22% and 12%) depending on the functional unit chosen. The identified trends are statistically weak, i.e., they are attached with a low coefficient of determination. The diverse results are caused by (i) varying profit margins of producers, (ii) relatively large fluctuations of material costs, i.e., stainless steel prices, (iii) different unit sizes, and (iv) the fact that installation costs are largely determined by exogenous, non-technology-related factors, i.e., geological underground conditions.

We therefore conclude that based on the data available, meaningful experience curves for hot and cold storage systems cannot be constructed. The complexity of the system and the factors affecting the magnitude of costs require an experience curve analysis based on far more disaggregated data, i.e., with the inclusion of more price-determining variables. Due to constraints with regard to data availability, it remains, however, highly questionable whether such analysis can be done.

With regard to the general dynamics of costs, we can identify various phases, in which costs decreased (mid 1990s, 2002-2004) and increased (1999-2003, 2005-2007). The observed dynamics can be attributed to increasing/decreasing market demand, rising material prices, and fluctuations of energy prices. Increasing energy prices make systems profitable (i) at sites with less favourable geological underground conditions and (ii) for buildings with a lower cooling/heating demand and might be ultimately the cause for increasing specific costs.

4.5 Compact fluorescent light bulbs (*Spaarlampen*)

4.5.1 Introduction and objective

Lighting accounts for 19% of global electricity consumption. In 2005, residential lighting consumed worldwide 811 TWh of electricity, being responsible for roughly 18% of the residential sector's total electricity use (IEA, 2006a). In 2003, Dutch households used 16% (roughly 550 kWh) of their total electricity consumption for lighting (ECN, 2008).

The Dutch company Philips is the international market leader in lighting technology with annual worldwide sales of EUR 4.5 billion in 2004 followed by Osram (EUR 4.2 billion) and General Electric (sales of USD 2.6 billion). The largest producer of lighting equipment in the world (in monetary terms) is the EU with annual revenues of EUR 12 billion. China is the largest producer in physical terms generating revenue of EUR 9 billion (IEA, 2006a).

The residential lighting market is dominated by incandescent light bulbs with estimated yearly sales of more than 13 billion units in 2003 (Figure 71). Incandescent light bulbs offer a warm-colored light, are available in an enormous range of styles and sizes, can be dimmed, and their unit prices are much lower than the ones for alternative (and more energy efficient) compact fluorescent light bulbs (CFLs).

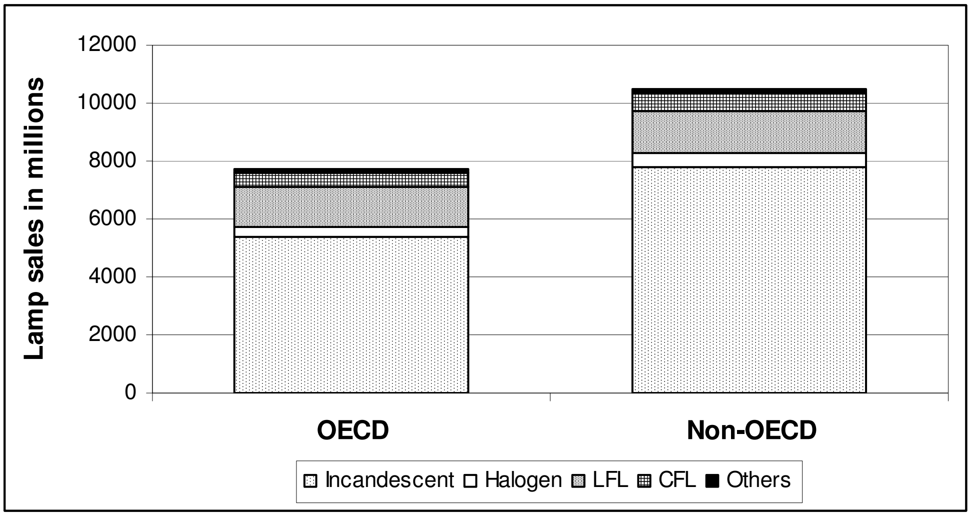

Figure 71: Global lamp sales in 2003 as estimated by IEA (2006b)

With increasing electricity prices and intensifying discussions about CO_2 emissions reduction and energy efficiency, CFLs received special attention in recent years. CFLs were first introduced to the market in 1980 by Philips in the Netherland and in the USA. They recently experienced considerable growth in yearly sales but still constitute only a niche in today's lighting market (Figure 71). The penetration of CFLs in Dutch households increased from 2 per dwelling in 1995 to 4 in recent years but at the same time also the amount of conventional light bulbs increased (i.e., the number of halogen light bulbs increased from 2 to 6 in the same time period). CFLs are generally regarded as *THE* technological solution to improve the energy efficiency of household lighting. Whether or not these efficiency potentials can be realized will depend (i) on the development of CFLs for a broader range of applications (e.g., dimmable light bulbs and a broader spectrum of bulb sizes and light chromaticity) and (ii) on the further reduction of CFL production costs and sales prices.

The primary objective of this chapter is to apply the experience curve approach to CFLs. In the second part of our analysis, we extend the conventional experience curve approach by modeling the dynamics of luminous efficacy[37] *[lm/kW$_e$] as a function of cumulative CFL production. We base our analysis on price and efficacy data for CFLs sold in the Netherlands and in Germany (years 2002 and 2006) and on cumulative global CFL sales data. We, furthermore, analyze consumer cost savings generated by CFLs relative to conventional incandescent light bulbs in the Netherlands.*

In the following sections, we will briefly explain the technology and market development of CLFs. We analyze in detail historic cost reductions of CFLs (Section 4.5.5 and Section 4.5.6). In Section 4.5.7, we discuss and summarize our findings and we give a short outlook on possible future developments.

4.5.2 Technology description

CFLs consist of three main components, (i) a miniaturized gas-filled glass tube, (ii) a magnetic or electronic ballast, and (iii) a lamp foot (Figure 72). Unlike conventional tube-shaped fluorescent lamps, CFLs typically have the same screw-in lamp foot as conventional incandescent light bulbs. CFLs can therefore directly replace conventional and less efficient incandescent light bulbs in households.

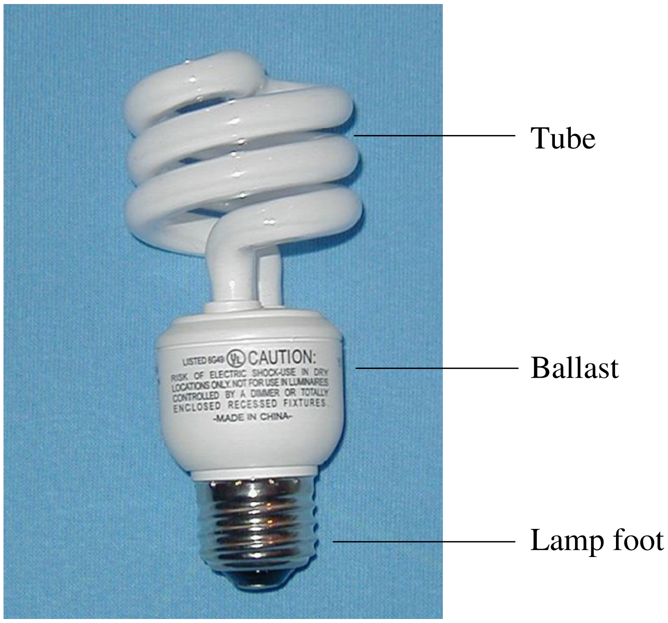

Figure 72: Principal components of a CFL (Source: Wikipedia (2008b))

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[37] We refer in this report to the *efficacy* of a light bulb as the ratio of light output [lm] to capacity [W$_e$].

The inner side of the glass tube is coated with phosphorus and filled with one or more inert gases (e.g., argon) and typically trace amounts of mercury. Ultra violet light is emitted by creating a low-intensity arc that excites the mercury vapour. The ultraviolet radiation excites the phosphorus at the glass tube and leads to the emission of radiation in the visible spectral range. CFLs need a ballast to regulate input current and voltage for initiating and maintaining lamp discharge it at the required level. In the early phase of market commercialisation, CFLs with magnetic ballasts were offered, which became successively replaced by electronic ones at the end 1980s/mid 1990s. In recent years, a large variety of CFLs in different shapes and sizes are offered at the market. Most CFLs sold today have capacities of 5 W_e to roughly 20 W_e. CFLs reach much higher efficacy levels (35-80 lm/W) than conventional incandescent light bulbs (6-18 lm/W_e) (IEA, 2006b) because they emit a larger percentage of radiation in the visible spectrum. While conventional incandescent light bulbs convert only 5% of the consumed energy to (visible) light, CFLs reach 25% and light emitting diodes (LEDs) even above 30% (Table 13).

Table 13: Typical characteristics of CFLs (adapted from IEA, 2006b)

	Incandescent light bulb	**CFL**
Initial cost of bulb [$]	0.5	4.0-10.0
Light output [lm]	900	900
Capacity [W]	75	15
Efficacy [lm/W]	12	60
Life time [h]	1,000	10,000

Another advantage of CFLs is their long life times, i.e., 5,000-25,000 h compared to on average 1,500 h for incandescent light bulbs. However, there were and still are several disadvantages of CFLs that limit their market success (see next section).

4.5.3 History and global market development

CFLs were patented as early as in 1972 (Oosterhuis, 2007). Triggered by the first oil crisis in 1973, Philips started large-scale R&D in the period of 1975-1980 with the actual product development starting in 1978. First CFLs were introduced to the market in the Netherlands and in the USA by Philips in 1980. Other major players in the lighting market, i.e., Osram, GE, and Sylvania followed 1-2 years later by introducing their own products. The first CFL model from Philips had a tube design, a capacity of 18 W_e and reached a light output of 900 lm. The first CFL model had an electro-magnetic ballast and the light tubes where covered by an additional glass envelop. This model was intended to replace 75 W conventional bulbs and had a weight of roughly 1 kg.

Until the mid 1980s, additional CFL models where offered at the market to replace incandescent light bulb of the whole capacity range of 40-100 W_e. During market commercialization in the early 1980s, CFLs have been also offered as modular constructions with a circular gas tube being connected to magnetic ballasts. The technological development in later years resulted, however, in integral light bulbs with magnetic ballasts being replaced by more efficient electronic ones. The early CFLs already had the advantage of high efficacies and comparatively long life times but were at the same time also subject to severe disadvantages compared to conventional light bulbs:

- The initial costs were high, i.e., market prices were 10-30 times higher than the ones for conventional incandescent light bulbs.
- The light quality was poor and limited to cooler light values at higher correlated colour temperature (CCT) ranges.
- The magnetic ballasts used to delay the starting of the light bulb, caused flickering, and required long warm-up times until CFLs reached their full efficacy.
- The size of CFLs was too large.
- CFLs were not dimmable and only available for a few lighting applications.

Due to these disadvantages, CFLs could only obtain a very small niche market with global yearly sales reaching less than 1 ‰ of total incandescent light bulb sales in the first 5 years after market introduction. According to Philips (2007), the size of CFLs is a very important criterion for the market success. Consumers tend to accept a deviation of up to 20% compared to the size of incandescent light bulbs. If CFLs become only 30% larger than standard light bulbs, the penetration of CFLs will drop by 70% (Philips, 2007).

By 1984, Philips started to replace magnetic lamp ballasts by electronic ones. Electronic lamp ballasts are smaller, lighter, and offer higher efficacies. This innovation allowed the development of CFLs with lower capacities, e.g., reducing 18 W_e bulbs to 15 W_e while maintaining the same initial light output of 900 lm. Furthermore, producers tried to adapt the light colour to comply with the European and North American consumer preferences for a warm coloured light. Although the quality of CFLs has been improved considerably in the 1980s/1990s, CFLs size remained too large and light quality still differed considerably from conventional incandescent light bulbs. Despite growing CFL sales of more than 20% per year in the mid and late 1990s (Borg, 1997), high prices and poor product characteristics remained major obstacles for the market breakthrough.

Prices declined considerably in the 1990s, when producers shifted CFL production to low-income regions, e.g., Eastern Europe and China. In the following years, price competition increased because Chinese companies increasingly entered the European CFL market. In 2001, the EU commission imposed anti-dumping duties on CFL imports from China (Oosterhuis, 2007, Philips, 2007). Despite substantial decreasing CFL prices, sales remained lower than expected because consumer confidence in CFL technology declined in the mid to late 1990s due the often poor light quality and high failure rates of cheap CFL imports[38].

CFLs have been and still are supported by numerous demand-side management programs, e.g., energy labels in the EU or the energy star program in the USA. The number of CFLs in OECD households is continuously growing but at a very moderate rate (IEA, 2006b). CFL sales were triggered in recent years by (i) increasing electricity prices, (ii) the intensifying discussions about anthropogenic CO_2 emissions, (iii)

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[38] Conventional CFLs maintain more than 80% of their initial efficacy over the entire life time, low quality CFLs do, however, often not even reach 60%.

improved product quality, and foremost (iv) reduced product prices. Producers aimed at miniaturizing CFL design and offering CFL for a broader range of lighting applications. Due to considerable price reductions (see also Section 4.5.5) and quality improvements, CFL sales increased in the past 20 years in absolute terms (Figure 73).

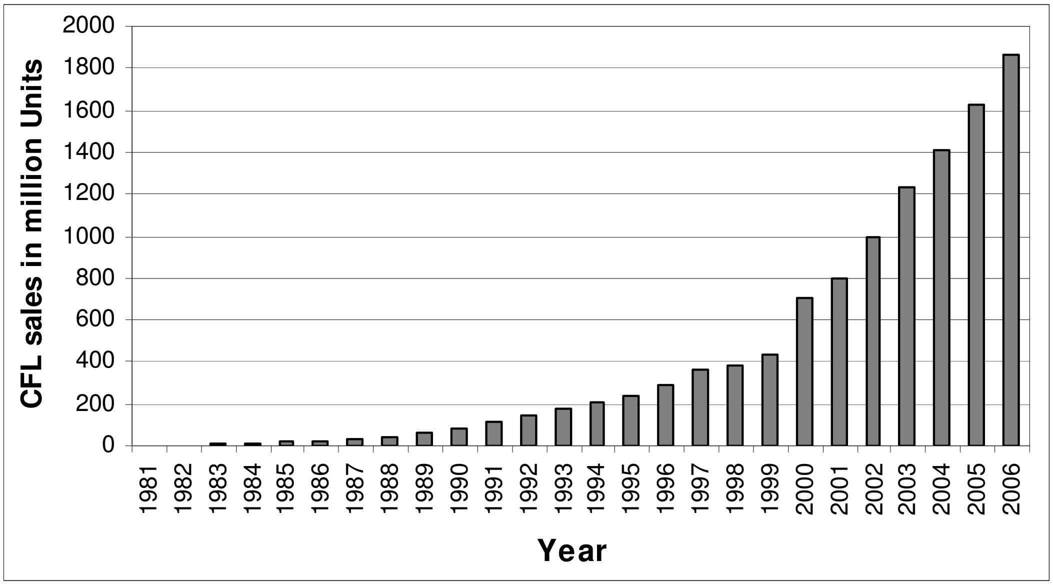

Figure 73: Worldwide CFL sales (Data sources: Borg et al. (1996), Ellis (2007), IEA (2006b))

In 2003, CFLs have reached yearly global sales of 1.1 billion, which accounts, however, for only 7% of the total global light bulb sales (IEA, 2006b). Today, China supplies almost 2 billion CFLs per year, thereby accounting for 80-90% of global CFL production (Philips, 2007). While China is also the largest market for CFLs, roughly 25 million CFLs are sold per year in the EU-27, of which 1 million CFLs are sold in the Netherlands. Current focus centers on the improvement of light quality and the market introduction of dimmable CFLs (which is expected for 2008). In Dutch households, 10% of installed light bulbs are CFLs. IEA (2006b) find similar numbers for other OECD countries (Figure 74).

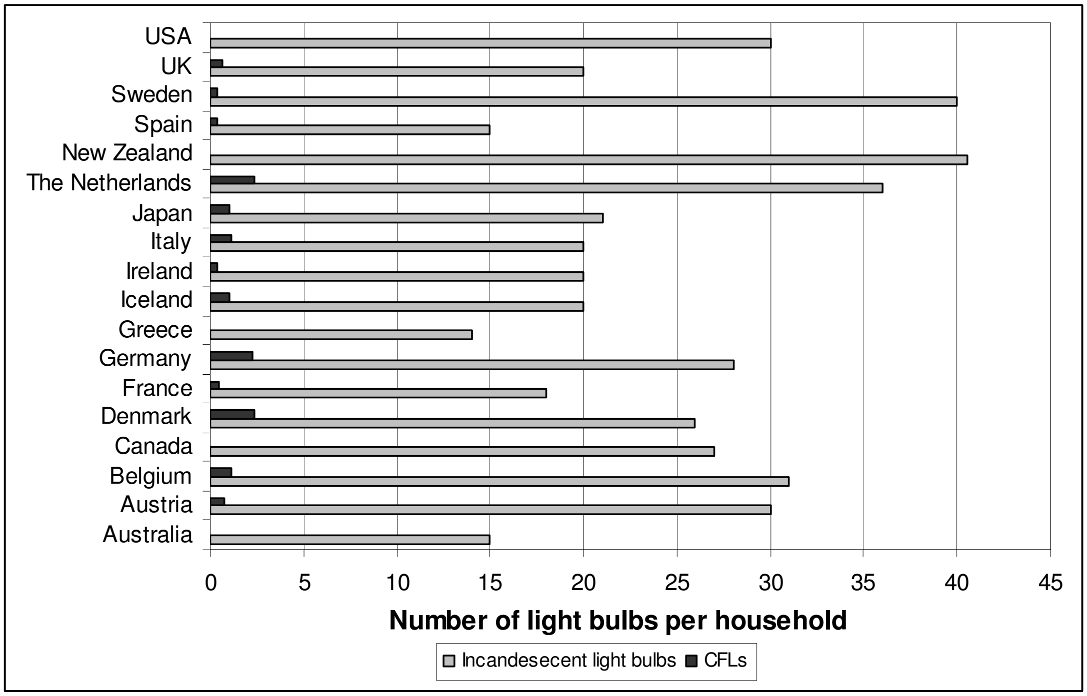

Figure 74: Penetration of CFLs in selected OECD countries (Data source: IEA (2006b))

4.5.4 Approach and data sources

In the first part of our analysis, we construct experience curves for CFLs. We uniformly approximate actual production costs by markets prices. We collect data on market prices, capacities, and light output of CFLs for the Netherlands and Germany based on Consumentenbond (various years) and Stiftung Warentest (2002, 2006, 2007). Similar to condensing gas boilers, CFLs have been invented and subsequently introduced to the market in the Netherlands (i.e., in the year 1980). CFL technology, however, spread quickly around the globe and was soon offered by several producers worldwide. We, therefore, estimate learning rates for CFLs based on global CFL sales as given by IEA (2006b), Borg et al. (1994, 1997), and Ellis et al. (2007). Based on this information, we construct experience curves for:

- CFL prices per bulb capacity [EUR_{2006}/W];
- CFL prices per bulb light output [EUR_{2006}/klm].

In our analysis, we include CFLs in the range of 5-32 W_e with a light output of roughly 200-1700 lm. This is equivalent to incandescent light bulbs with a capacity of 25-150 W_e and represents the spectrum of light bulb capacities typically used for household applications. Based on data given by Consumentenbond (various years) and Stiftung Warentest (2002, 2006, 2007), we calculate average specific prices (i.e., in EUR_{2006}/W_e and EUR_{2006}/klm) and the corresponding standard deviations for all CFL models for which data is available for respective years.

Based on price data provided for several countries by Oosterhuis (2007) and Philips (2007), we construct a *global* CFL experience curve for the period of 1985-2007. For this experience curve, we plot average absolute prices [EUR_{2006}] versus cumulative global CFL production. This approach is less reliable, as changes in average capacity and light output of CFLs are not distinguished in this global experience curve. We regard the *global* CFL experience curve therefore as a rough cross check for the experience curves constructed based on more detailed data from Consumentenbond (various years) and Stiftung Warentest (2002, 2006, 2007).

In the second part of our experience curve analysis, we extend the conventional experience curve approach and model CFL efficacy as function of cumulative global CFL production. Based on our *cost* experience curve analysis, we furthermore estimate life time costs for CFLs and conventional incandescent light bulbs as well as costs for energy and CO_2 emission savings achieved by CFLs. We perform these calculations as a showcase for light bulbs with a light output of 900 lm, i.e., we compare CFLs with a capacity of around 13-21 W_e with 75 W_e incandescent light bulbs. The assumptions and data sources used for these calculations are presented in Table 14 and Table 15.

Table 14: Assumption and data sources used to calculate life time costs for CFLs and incandescent light bulbs (75W_e equivalent)

Parameter	**Source**	**Assumption**
Prices of CFLs and incandescent light bulbs	Consumentenbond (various years), Stiftung Warentest (2002, 2006, 2007)	see Table 15
Capacity of CFLs	Consumentenbond (various years), Stiftung Warentest (2002, 2006, 2007)	see Table 15
Price of Electricity	Consumentenbond (various years), EnergieNed (2007), CBS (2007a)	see Table 15
Life time of CFLs and incandescent light bulbs	Consumentenbond (various years), Philips (2007)	see Table 15
Yearly bulb use	Consumentenbond (various years), Philips (2007)	1000 h
Emission factor of electricity	de Jong et al. (2006)	0.59 kg CO_2/kWh
Yearly discount rate	-	7%

Table 15: Assumptions used to calculate life time costs for CFLs and incandescent light bulbs (75W_e equivalent)

Year	Price in EUR_{2006}[1]			Average life time in h		Average power in W	
	CFL	Incandescent light bulb	Electricity [kWh]	CFL	Incandescent light bulb	CFL[2]	Incandescent light bulb
1983	18.85	1.01	0.15	7000	1200	18.0	75
1984	17.05	0.98	0.14	7000	1200	18.0	75
1985	20.16	0.96	0.14	7000	1200	18.5	75
1986	23.57	0.95	0.14	7000	1200	19.0	75
1987	27.09	0.96	0.14	7000	1200	19.4	75
1988	30.30	0.94	0.14	7000	1200	19.9	75
1989	27.24	0.91	0.13	7000	1200	18.8	75
1990	24.61	0.94	0.13	7000	1200	18.8	75
1991	24.21	0.90	0.14	7000	1200	17.8	75
1992	24.00	0.88	0.12	8000	1200	16.8	75
1993	24.02	0.86	0.13	8000	1200	15.8	75
1994	20.81	0.84	0.13	8000	1200	16.3	75
1995	17.85	0.82	0.13	8000	1200	16.8	75
1996	16.75	0.80	0.14	8000	1200	17.1	75
1997	14.01	0.79	0.15	9000	1200	16.8	75
1998	11.43	0.77	0.15	9000	1200	16.5	75
1999	8.92	0.75	0.16	9000	1200	16.2	75
2000	8.37	0.73	0.14	9000	1200	15.8	75
2001	7.59	0.69	0.18	9000	1200	15.3	75
2002	7.03	0.67	0.18	10000	1200	14.9	75
2003	7.75	0.66	0.18	10000	1200	15.7	75
2004	8.53	0.65	0.19	10000	1200	16.4	75
2005	9.24	0.64	0.20	10000	1200	17.2	75
2006	9.98	0.63	0.21	10000	1200	18.0	75

[1] Excluding Dutch sales taxes

[2] We state here the average capacity of CFLs that is necessary to replace a conventional 75 W_e incandescent light bulb.

4.5.5 Experience curves for compact fluorescent light bulbs

We estimate a learning rate of (18.8 ± 2.4)% for CFLs (Figure 75). This result indicates a considerable decline of production costs in the period 1988-2006. Our finding is in line with the results of Iwafune (2000), who found learning rates of 16% for integral CFLs with electronic ballasts but it is somewhat higher than the learning rate of 10% as identified by Ellis et al. (2007), who analyzed the price development of CFLs in the US in the period of 1990-2004.

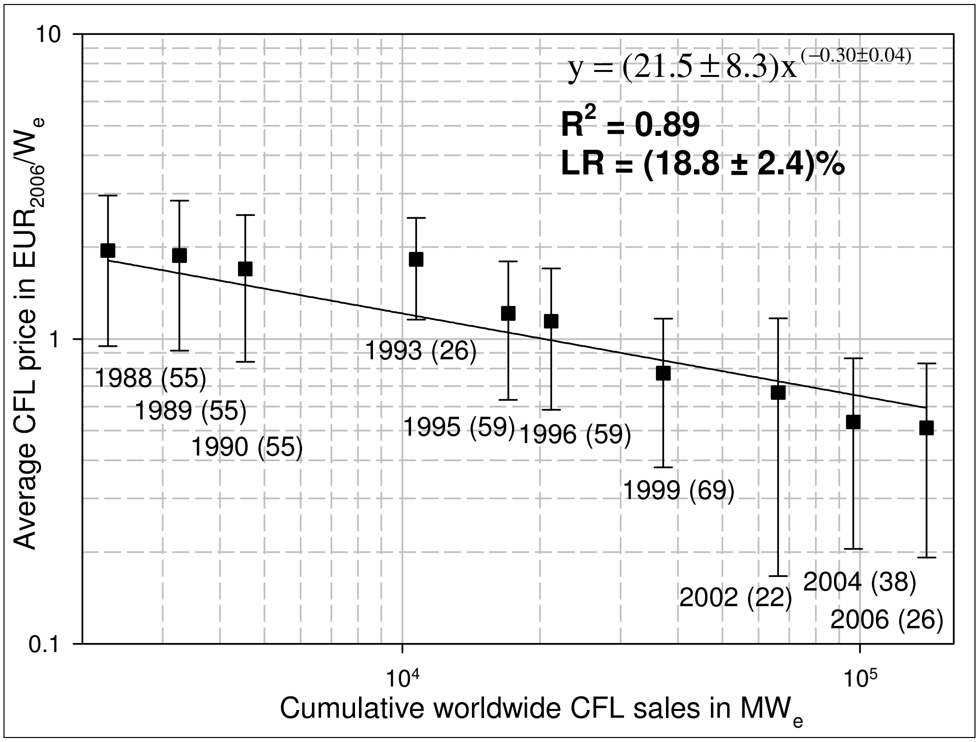

Figure 75: Experience curve for CFLs [EUR_{2006}/W_e] for the time period of 1988-2006; the error bars indicate the standard deviation of average prices; in brackets number of data points included in our analysis

The experience curve presented above can be disaggregated into experience curves for CFLs in various capacity categories (i.e., categories being equivalent to 40, 60, 75, and 100 W_e of incandescent light bulbs (Figure 76). The result indicates that CFLs with low and high capacities (being equivalent to 40 W_e and 100 W_e incandescent light bulbs) show higher learning rates than CFLs in the categories of capacity-equivalents of 60 W_e and 75 W_e). This finding is confirmed by significance testing with the *F-test*. At a 95% level of significance, we find that:

- CFLs with a capacity-equivalent of 60 W_e and 75 W_e learn slower than CFLs in the other two capacity categories.
- The price level of the four CFL categories is significantly different from each other, i.e., per W_e capacity, CFLs with a capacity-equivalent of 100 W_e are significantly cheaper than CFLs with a capacity-equivalent of 40 W_e.

Experience curves for CFLs can also be constructed based on CFL prices per unit of light output [lm]. Data for light output, i.e., luminous flux of CFLs in the various years are based to some extent on estimates, as reliable data were not always available. In principle, the CFL prices per unit of luminous flux show the same trend as the prices per bulb capacity (Figure 77).

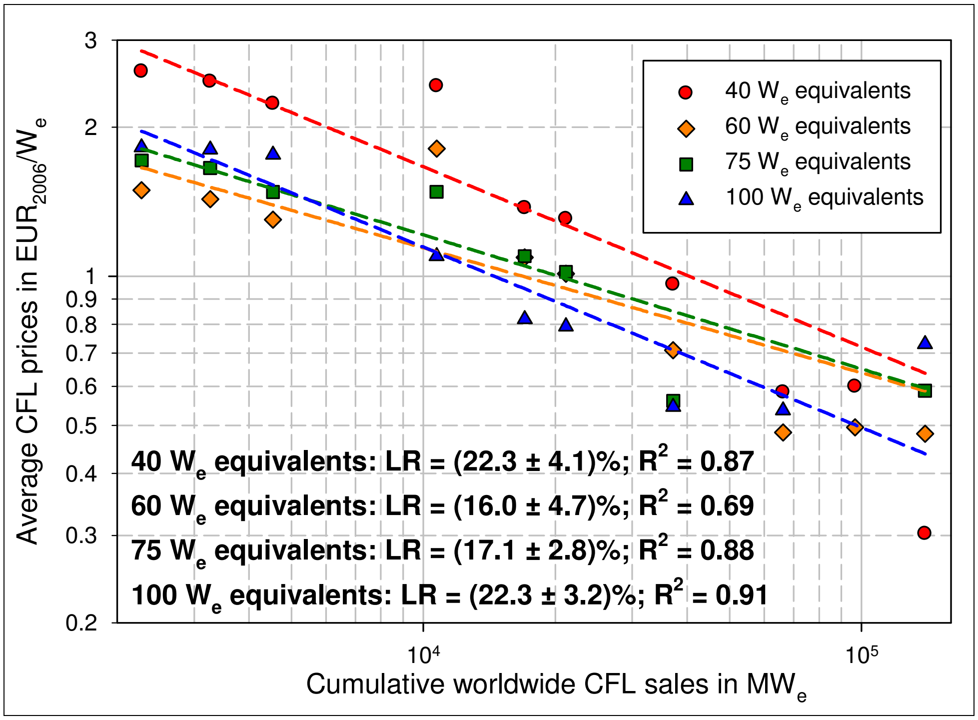

Figure 76: Disaggregated experience curves [EUR_{2006}/W_e] for four capacity categories of CFLs

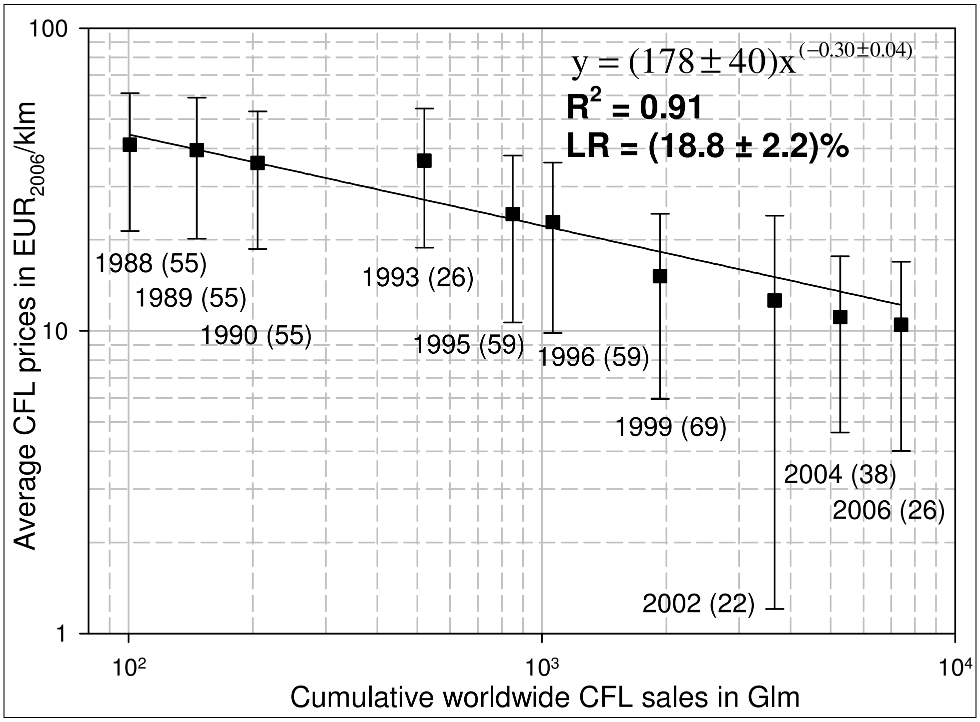

Figure 77: Experience curve for CFLs [EUR_{2006}/lm] for the time period of 1988-2006; the error bars indicate the standard deviation of average prices; in brackets number of data points included in our analysis

Based on prices per luminous flux, we calculate a learning rate of (18.8 ± 2.2)% for average CFLs (Figure 77). The experience curve analysis shown in Figure 77 can be further disaggregated according to the four principal luminous flux categories, i.e., 500 lm, 700 lm, 900 lm, and 1250 lm. These categories are equivalent to the light output of conventional incandescent light bulbs of 40 W_e, 60 W_e, 75 W_e, and 100 W_e, respectively. For CFLs of all of these luminous flux categories, we find a trend towards decreasing prices (Figure 78). In contrast to the experience curve analysis based CFL capacities, we find no significant differences in the learning rates for CFLs in the various luminous flux categories (*F-Test*, 95% level of significance). However, we find significant differences in the price levels of the four CFL categories.

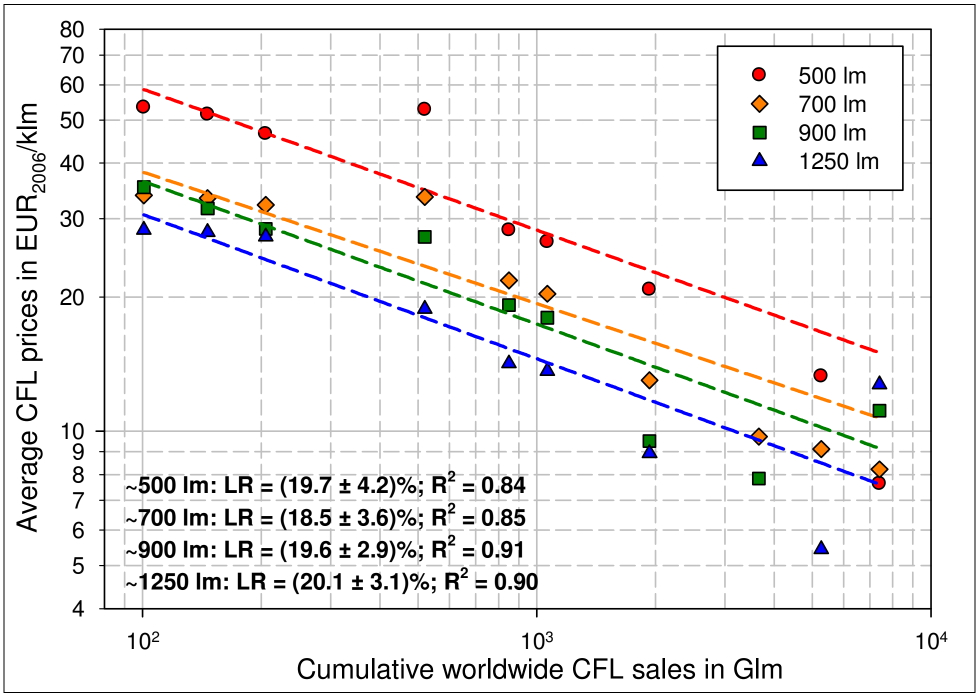

Figure 78: Disaggregated experience curves [EUR$_{2006}$/lm] for CFLs of four luminous flux categories

The experience curves presented so far indicate a decline in production costs by roughly 20% with each doubling of cumulative CFL capacity or luminous flux produced. The observed rates of cost reductions are confirmed by data from Oosterhuis (2007), whose data we used to construct a multi-national experience curve that indicates learning rates for CFLs of (20.7 ± 2.6)% (Figure 79).

The estimated learning rates for CFLs are somewhat higher than the ones found for, e.g., condensing gas boilers. We argue that the speed of learning, i.e., the gaining of experience depends to some extent on the novelty of a product and its components. Literature confirms that novel and truly innovative products (e.g., semi conductors, CFLs, photovoltaics) that require completely new material processing and production processes generally learn faster than novel technologies that consist of standard components, which are used already for a longer time and that are "just" assembled and combined in a new and innovative way (e.g., gas boilers) (see, e.g., Cunningham (1980), Junginger et al. (2008)).

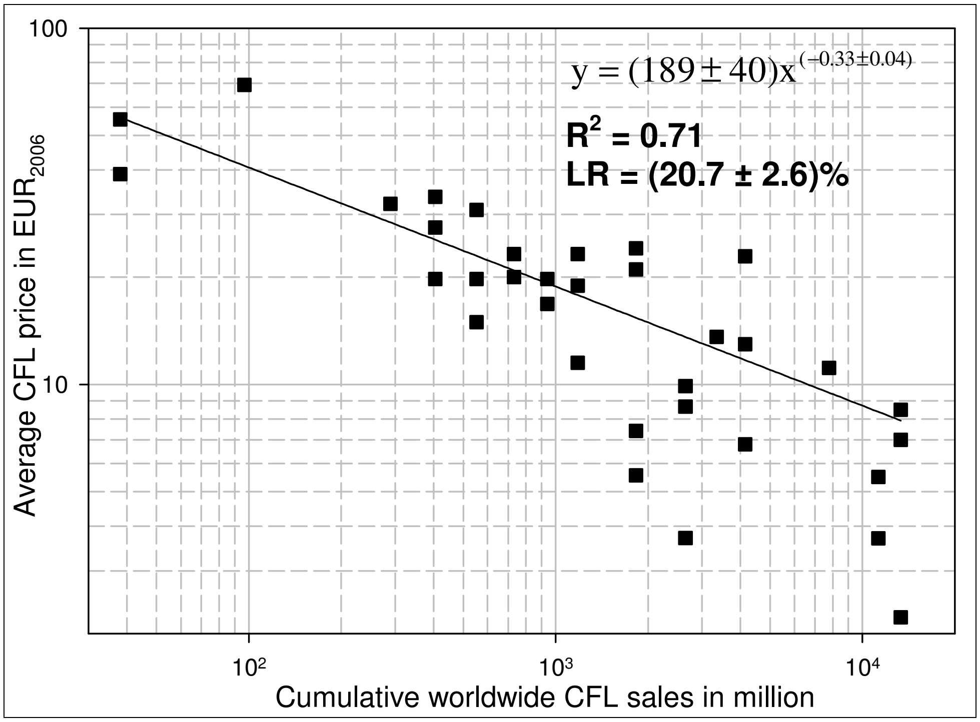

Figure 79: Multi-national experience curve for CFLs (Data source: Oosterhuis (2007))

The cost reductions identified for CFLs can be explained by technological learning and the gaining of experience in the course of CFL manufacturing. Cost reductions were achieved in the early years mainly by upscaling, streamlining, and increasing the automation of production processes, i.e., by reducing the share of human labour on CFL manufacturing costs. In the early 1980s, the CFL tube accounted for 70% and the ballast for 30% of CFL production costs. This, however, changed with the replacement of magnetic lamp ballasts by electronic ones in the mid 1980s (e.g., Philips started replacements in 1984, Osram in 1985). Electronic ballast were, however, relatively expensive at the end of the 1980s and led to the situation that ballasts accounted at that time for 90% of CFL manufacturing costs and tubes (i.e., burners) only for 10%. Automation and increased process speed was the major driver for cost reduction in burner manufacturing. For electronic ballasts, Iwafune (2000) and Duke and Kammen (1994) identify learning rates of only 11-13% covering the time period until the end of the 1990s. To lower production costs of CFL and especially ballast production, producers started to shift production to low-wage regions. Philips, for example, produces its CFLs in China and Poland since the early-mid 1990s (Philips, 2007). Production shifts referred to the assembly of components but also to burner (i.e., tube) and ballast production. Outsourcing of light bulb and component production to contracted producers furthermore contributed to substantial cost reductions of CFLs manufacturing in the 1990s. The cost reductions achieved by the shift of production to low-wage regions in the 1990s have lowered CFL prices substantially. At the same time, cheap 'no-name' products with relatively poor performance regarding lifetime, reliability, colour point, and maintenance of light output over the entire life time entered the CFL market in Europe. This development exerted additional pressure on the market price of CFLs produced by the market leaders, i.e., Philips and Osram. As the result of increased market competition, profit margins of producers decreased drastically until the end of 1990s (Philips, 2007).

The cost reductions achieved by production shifts to low-income countries might be regarded as *technological learning* because geographical production shifts are a process in which producers gain and use experience in finding and effectively using alternative ways of production. However, referring to our discussion in Section 3.2.6, cost reductions achieved by production shifts to low-income regions are in first instance not achieved by reducing the quantity of labour (Q_{LAi}) but rather by reducing the price of labour (P_{LAi}). The dynamics of prices for production factors are exogenous and not directly related to learning and the gaining of experience in the manufacturing of a specific product.

This argumentation applies also to CFL manufacturing, where we find another interesting phenomenon: Production shifts to low-wage regions resulted in an adaptation of CFL manufacturing processes from CFL production that is relatively less labour intensive (but capital intensive) in Western Europe to more labour (and less capital) intensive production routes in China (Philips, 2007). In other words: Because labour costs in China are low, i.e., 10% of that in Western Europe, Philips started to manufacture CFL ballasts in an alternative way, thereby reducing production costs for ballasts by 50% but requiring more *labour* and using at the same time a lower degree of automation than in Western Europe. However, in most recent years improved automation is seen as one possible way to further reduce production costs of CFL ballasts also in low-wage regions like China.

Industry experts expect that cost reductions as they have been realized in the past (i.e., >50% in 10 years) are unlikely to be repeated in the future. By contrast, rising energy and resource prices, e.g., prices for phosphorus and copper might result in increasing production costs and market prices. Philips (2007) would regard it as success, if CFL production costs and market prices could remain constant in future years. Future developments in CFL technology comprise:

- the shift of CFL light spectrum towards a higher share of red light, i.e., the generation of a warm coloured light;
- the miniaturization of CFLs to match as closely as possible incandescent light bulb design;
- the market introduction of dimmable CFLs.

Due to their more complex structure, CFLs will remain more expensive than conventional incandescent light bulbs. Philips (2007) expects CFLs to be also in the future roughly 5 times more expensive than conventional light bulbs, i.e., thereby anticipating market prices of 2-3 EUR. Despite drastically declining production costs, CFL manufacturing still generates higher producer profits per bulb than conventional incandescent light bulbs.

In the second part of our experience curve analysis, we extend the conventional experience curve approach and model CFL efficacy as function of cumulative global CFL capacity. To account for the fact that efficacy improvements are restricted by laws of physics, we introduce as additional term the thermodynamic maximum efficacy of 0.683 klm/W (1/efficacy = 1.46 W/klm) into our experience curve model[39] (Figure 80).

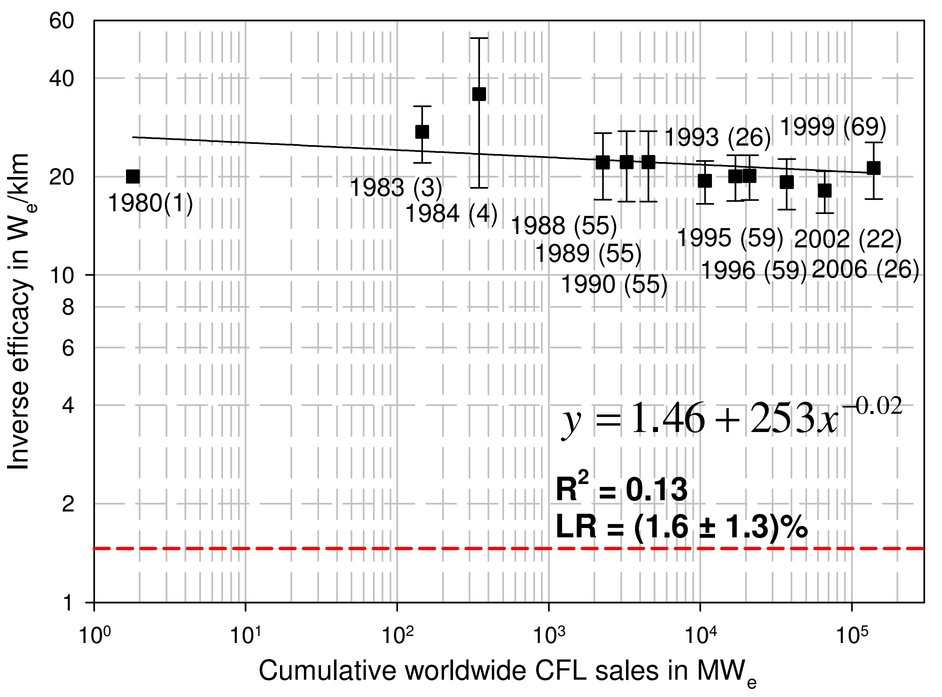

Figure 80: Experience curve for the efficacy of CFLs; period of 1980-2006, the dotted red line indicates the theoretical maximum efficacy (Data sources: Consumentenbond (various years), Stiftung Warentest (2002, 2006, 2007))

We find a learning rate of 1.6% at a very low coefficient of determination ($R^2 = 0.13$). Excluding the first data point for the year 1980 from our analysis yields more reliable estimates, i.e., a learning rate of 5.9% at a $R^2 = 0.64$[40]. These findings indicate a trend towards slightly increasing efficacies. The observed trend is, however, statistically weak. In the past, efficacy improvements were mainly achieved by replacing electro-magnetic ballasts by electronic ones. It remains however questionable, whether CFL efficacies do necessarily follow an experience curve trend. Industry experts argue that

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[39] As reference, we use here the luminous efficacy of monochromatic light at a wavelength of 555 nm (green), which has a maximum possible value of 683 lm/W.

[40] In 1980, CFLs were introduced to the market. Relatively low efficacies were (among others) caused by, e.g., low efficiencies of electro-magnetic ballasts and less sophisticated construction of light tubes.

this is *not* the case because (rather than improving CFL efficacies) producers aim at adapting light chromaticity to match the light emitted by CFLs as closely as possible to the warm-coloured light of incandescent light bulbs (Philips, 2007). Improving the light quality of CFLs is generally regarded as important strategy to obtain higher market shares *despite* the fact that it reduces bulb efficacies. We find hence a clear case in which further improvements in energy efficiency (i.e., bulb efficacy) are not regarded as crucial for the market success of a product. For CFLs, rather the opposite is true: Other product functions (i.e., light quality and design) are purposefully improved at the expense of energy efficiency. We therefore argue that the experience curve approach is *unsuitable* to analyze and project efficacy dynamics of CFLs (Philips, 2007).

4.5.6 Analysis of life cycle costs

The fact that CFLs have been and still are considerably more expensive than conventional incandescent light bulbs conceals their potentials in respect to life cycle costs. Our analysis for the Netherlands (for assumptions see Table 14 and Table 15) shows that CFLs offer considerable cost savings compared to conventional incandescent light bulbs along the entire period of 1988-2006 (Figure 81).

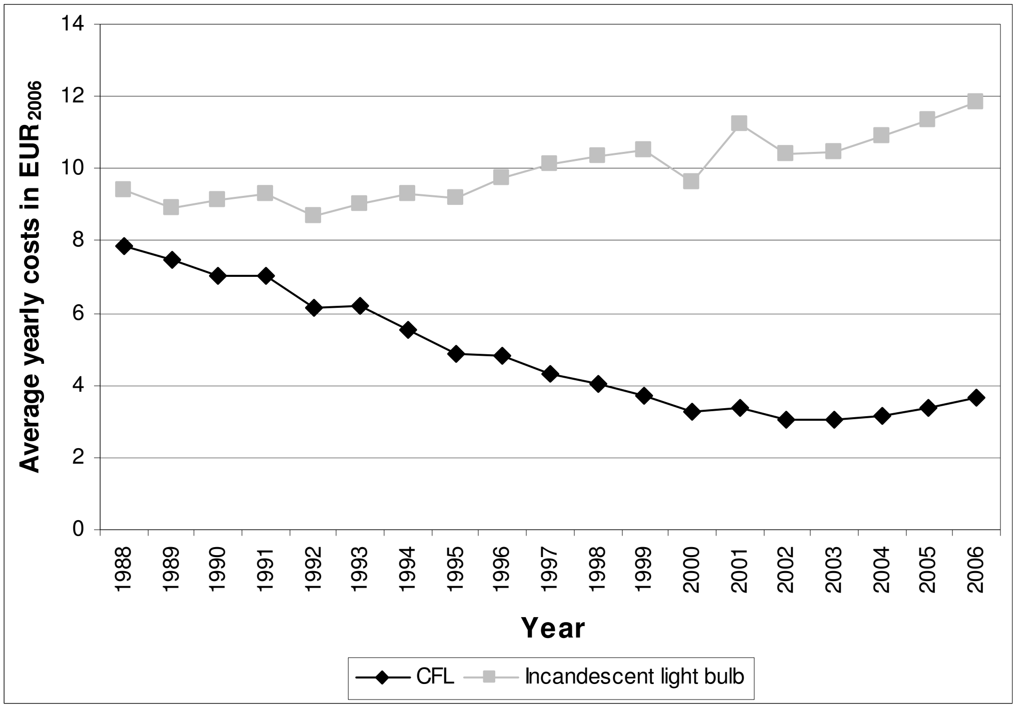

Figure 81: Average yearly costs of CFLs and conventional incandescent light bulbs; 75 W_e incandescent light bulb equivalent

The yearly savings per CFL bulb increase from roughly 1.60 EUR in the late 1980s to more than 8.20 EUR in 2006. Figure 82 shows that the growth of yearly savings can be attributed to:

- price reductions and increased life time of CFLs (relative cost reductions of 92%)
- savings of electricity and increasing electricity prices (relative cost reductions of 36%).

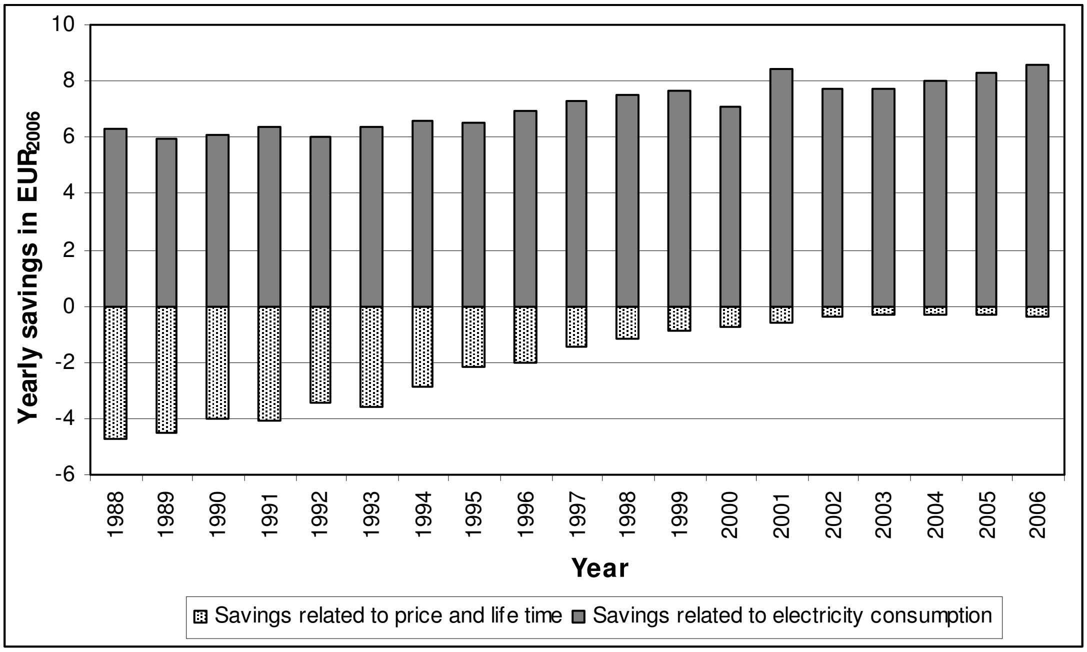

Figure 82: Contribution of principal cost components to the yearly savings of CFLs compared to conventional incandescent light bulbs in the Netherlands; 75 W_e incandescent light bulb equivalent

The results shown in Figure 81 and Figure 82 indicate that buying CFLs was profitable for consumers in the last 20 years. We hence find that CFLs contribute to savings of electricity and CO_2 emissions at negative additional costs. In the year 2006, CFLs offered savings of roughly 0.19 EUR/kWh_e and roughly 330 EUR/ t CO_2 avoided, respectively (Figure 83). These savings can be even expected to rise in the future, if electricity prices continue to increase. Even if CFL prices might increase in the future as it is predicted by industry experts (Philips, 2007), high electricity prices can be expected to compensate and even overcompensate this development, leading to a least constant overall savings of life cycle costs relative to conventional incandescent light bulbs.

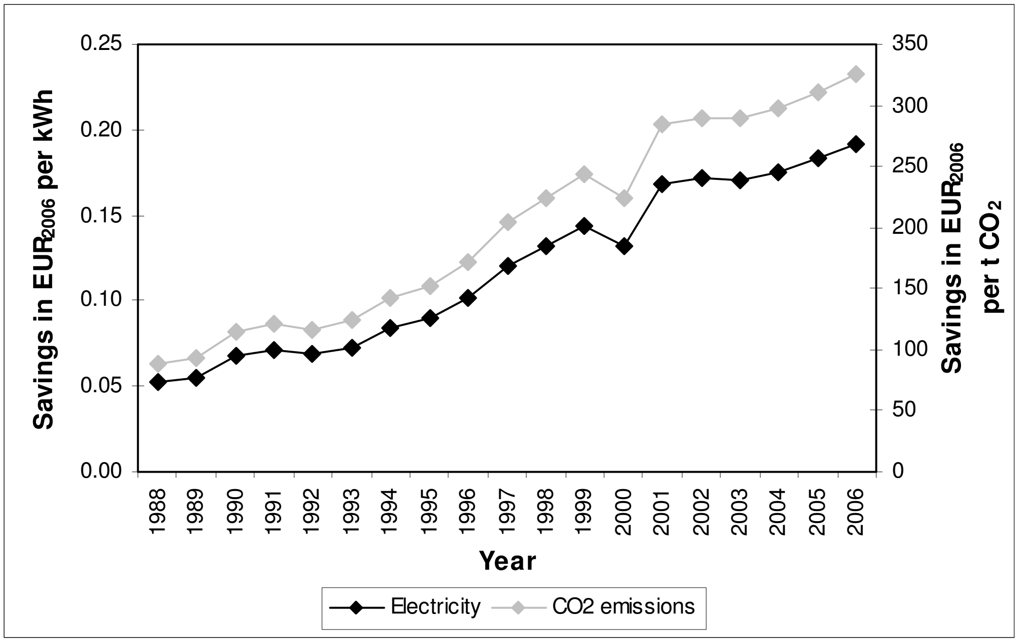

Figure 83: Cost savings of CFLs per kWh electricity saved and per t CO_2 not emitted in comparison to conventional incandescent light bulbs

4.5.7 Compact fluorescent light bulbs – conclusions and outlook

CFLs were introduced to the Dutch market by Philips in 1980. Worldwide sales experienced steady growth in the last 27 years. However, CFLs still account for only a small share on the total lighting market. This situation might be attributed to product quality (e.g., bulb size, limited variety of shapes and applications, colour point of light, product reliability) but also to the relatively high price that is still 5-10 times higher that that of conventional incandescent light bulbs.

In this research, we find the experience curve approach applicable to CFLs. We identify learning rates based on price data for the Netherlands and Germany of (18.8 ± 2.4)% [EUR_{2006}/W] and (18.8 ± 2.2)% [EUR_{2006}/klm], respectively. Constructing an experience curve based on international price data as given by Oosterhuis (2007) yields a learning rate of (20.7 ± 2.6)%.

The observed cost reductions can be attributed to the upscaling and streamlining of production processes and since the early 1990s to shifts of production to low-income regions like China. The analysis of production cost dynamics for CFLs based on price data is complicated by mainly two factors: (i) increasing market competition, starting in the mid 1990, led to a substantial decrease in profit margins for CFL producers and (ii) the subsequent replacement of magnetic by electronic ballasts in the mid to end 1980s resulted in changes regarding technology characteristics and production costs of CFLs.

The extension of the conventional experience curve approach to CFL efficacy [lm/kW_e] yields a learning rate of 1.6% at a very low coefficient of determination ($R^2 = 0.13$). Excluding the first data point for the year 1980 from our analysis yields more reliable estimates, i.e., a learning rate of 5.9% at a $R^2 = 0.64$. This finding indicates a trend towards increasing efficacies, which is however statistically weak. Industry experts argue that CFL efficacies do not follow an experience curve pattern because rather than improving CFL efficacies, producers aim at adapting light chromaticity to match the light emitted by incandescent light bulbs. Improving the light quality of CFLs is generally regarded as important strategy to obtain higher market shares *despite* the fact that it reduces bulb efficacies. We find hence a clear case in which further improvements in energy efficiency (i.e., bulb efficacy) are not regarded as crucial for the market success of a product. We therefore argue that the experience curve approach is *unsuitable* to analyze and project efficacy dynamics of CFLs.

Despite their relatively high sales price, CFLs offer substantial cost savings to consumers on a life time basis. We found yearly savings per CFL (75 W_e incandescent light bulb equivalent) to increase from 1.60 EUR_{2006} in 1988 to 8.20 EUR_{2006} in 2006.

In 2006, CFLs offered savings of roughly 0.19 EUR/kWh_e and 330 EUR/t CO_2 not used or emitted, respectively in the Netherlands. These savings can be even expected to rise in the future, if electricity prices continue to increase. Our analyses show that CFLs can improve energy efficiency in the building sector in a very cost effective manner. To utilize these efficiency potentials, consumer information and policy support is important. In this respect, the EU import tax on CFLs from China is a trade barrier that increases market prices of CFLs in Europe. We argue that removing the trade barrier might potentially increase market competition, leading to lower profit margins for producers and thus lower CFL market prices.

As a final comment, we point out that Light Emitting Diodes (LEDs) are a technology that quickly spreads for many lighting applications. LEDs are currently still too expensive for large scale application in the residential lighting sector. However, they are very efficient and have a great potential especially for lighting applications in the residential and commercial buildings sector. We recommend further research on this innovative technology.

4.6 Household appliances

4.6.1 Introduction and objective[41]

Household appliances are relatively mature products that have been on the market for around one century. The commercial production of electric washing machines dates back to 1908 while the first electric laundry dryers appeared on the US market around 1915. The history of refrigerators and freezers dates back more than two hundred years ago but it was not until 1922 when the absorption refrigerator was invented. Since their market introduction, household appliances spread around the world. They are global mass products that are produced by numerous manufacturers around the world. Worldwide sales of appliances increased steadily in the decades after the second world. In the year 2003, the worldwide market for washing machines reached roughly 65 million, yearly sales of laundry dryers were in the range of 11 million, and refrigerator sales amounted to 80 million. Producers of appliances have been typically located in Europe, North America, and Japan but falling trade barriers and increasing demand in developing countries have led to increased shares of production in China, Eastern Europe, and other low-wage regions.

In 2003, household appliances consumed roughly 30% of all electricity generated in OECD countries, thereby being responsible for 12 % of energy related CO_2 emissions (Ellis et al., 2007). Appliances are the main contributors to the increase in household electricity demand with an expected growth of 25% until the year 2020. At the same time, considerable and largely untapped energy saving potentials have been identified for household appliances (Ellis et al., 2007).

In this chapter, we apply the experience curve approach to four household appliances: (i) washing machines, (ii) laundry dryers, (iii) refrigerators, and (iv) freezers. In the second part of our analysis, we extend the conventional experience curve approach and model energy and water consumption as a function of cumulative production. We base our analysis on price data and on data for energy and water consumption of appliances sold in the Netherlands as well as on estimates for cumulative global appliance production.

In the following section, we will start out with a short description of household appliances' characteristics that are relevant for experience curve analyses (Section 4.6.2). We introduce the research approach and the data sources used for our analysis in Section 4.6.3. Afterwards, we present and discuss experience curve results for the analyzed household appliances. We focus especially on the extension of conventional *cost* experience curve analysis by modelling energy and water consumption as an exponential function of cumulative production (Section 4.6.4 and Section 4.6.5). We draw final conclusions and we provide a short outlook in Section 4.6.6.

4.6.2 Specific characteristics of household appliances

In contrast to most of the other energy demand technologies analyzed in this report, the primary function of household appliances is not energy related, i.e., the production or conversion of energy. Appliances provide services to consumers

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[41] Parts of the introduction base on Section 3.3.1.1 in Junginger et al. (2008).

(e.g., cleaning and drying laundry, keeping food fresh) for which (mainly) electricity is consumed. Energy consumption is hence a secondary product function; it is only a *means* to an *end*. Consumer decisions tend to be, therefore, often determined by non-energy related product criteria, i.e., brand name, product design, capacity to provide primary product functions, consumer convenience, or simply personal taste. Consumers can be characterized as a large and heterogeneous group of actors, who show a wide range of preferences, awareness, and levels of education. It can hence be expected that the awareness of consumers for all product functions that are offered by appliances is lower than the awareness of investors, who decide about the adoption of a particular energy *supply* technology.

This refers also to energy consumption and the associated life cycle costs of appliances. For many energy demand technologies, the price that has to be paid over the counter tends to be a far more important criterion for market success than overall life cycle costs.

Since their market introduction, both technology and functions of appliances have changed considerably. Washing machines do no longer only wash clothes, but they also centrifuge-dry them; specific washing programmes are available for different types of clothes (e.g., wool). Freezers and refrigerators are sold around the world 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. These changes in function and technology complicate the experience curve analysis of appliances because neither the *product* nor the *service* it provides remains entirely consistent throughout the time period of our analysis.

4.6.3 Approach and data sources

We develop experience curves to analyze the historic reductions of production costs. We differentiate high, medium, and low price as well as high, medium, and low efficiency products. In a second step, we attempt to extend the conventional experience curve concept by modelling the dynamics of energy consumption (energy and water consumption for washing machines) for the four selected household appliances as a function of cumulative production[42].

The construction of experience curves for household appliances involves extensive data collection and data standardization. The principal steps in data processing are depicted in Figure 84. We uniformly approximate product costs by Dutch market prices. Price data are solely based on information given by the Consumentenbond (various years). Table 16 gives an overview of the principal data sources used for constructing experience curves for household appliances. For early years, production data had to be estimated based on extrapolation, thereby making assumptions regarding growth rates of yearly production.

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[42] For a more detailed explanation on the theoretical framework of this analysis, we refer the reader to Section 3.2.7.

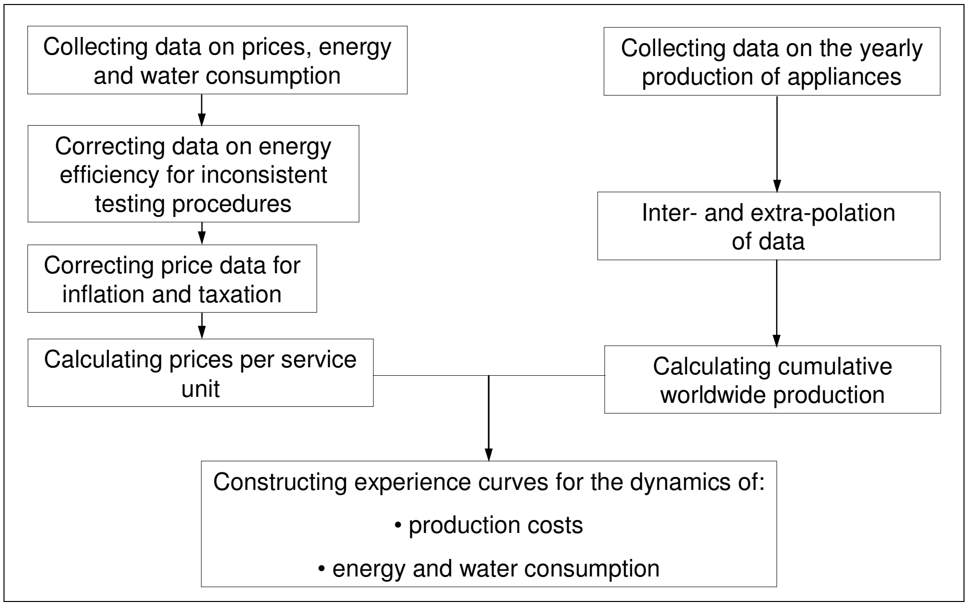

Figure 84: General scheme of data collection and data processing for analyzing household appliances

Table 16: Principal data sources used to construct experience curves for household appliances

Appliance	Washing machines	Laundry dryers	Refrigerators	Freezers
Time period covered by analysis	1965-2007	1969-2003	1964-2007	1970-2003
Price data	Consumentenbond (various years)			
Data on energy efficiency	Consumentenbond (various years)			
Production data	UN (2000), UN (2007), Eurostat (2007), AM (2007)			

In our experience curve analysis for refrigerators, we uniformly include refrigerator-freezer combinations. The production of freezers is partly estimated based on the fraction of freezer to refrigerator production in the EU between 1995 and 2005 and on miscellaneous data sources for individual years. We deflate nominal prices based on consumer price indices as given by CBS (2007a). Data on the energy consumption of appliances (Consumentenbond, various years) were not consistent throughout the entire time periods analyzed. We therefore had to make several data adaptations:

- Energy consumption of washing machines was given in the 1960s based on a 90 ^{o}C washing cycle, while energy consumption in more recent years was estimated based on washing cycles at 60 ^{o}C or even at 40 ^{o}C. Data on energy consumption were therefore harmonized by assuming a linear relationship between water temperature and the energy consumption of washing cycles.
- To correctly account for the energy consumption in refrigerator-freezer combinations, we consistently recalculated the energy consumption of the freezer unit. This recalculation bases on the finding of our analysis that freezers consume on average 1.6 times more electricity than refrigerators for a defined volume. We hence recalculate *refrigerator-equivalents* for the electricity consumption in

freezers by dividing the freezers' electricity consumption with a factor of 1.6[43]. We uniformly calculate energy consumption per 100 litres of storage volume in refrigerators and freezers.

- The ambient temperature at which energy consumption of refrigerators and freezers was measured by Consumentenbond (various years) is inconsistent throughout the time period analyzed. We standardized energy consumption, calculating values uniformly for 25 °C based on fractions of 1.40 and 1.25 obtained by analyzing energy consumption of refrigerator models at 18 °C and 25 °C and 20 °C and 25 °C, respectively.

Accounting for energy consumption of laundry dryers is complicated by limited data availability. Consumentenbond (various years) states only energy ratings until 1990 and energy classes for laundry dryers in the years afterwards. We therefore estimate actual energy consumption based on the rating of laundry dryers. This introduces uncertainties into our estimates. In the following section we present and discuss the results of our experience curve analysis for each of the four household appliances individually.

4.6.4 Experience curves for household appliances

4.6.4.1 Washing machines

We provide an overview of price data for all washing machines included in our analysis in Figure 85. Based on this overview, we can already identify two trends in the time period of 1965-2007, i.e., (i) washing machines became cheaper and (ii) the interval between high price and low price washing machines became smaller, thus indicating a convergence of sales prices.

Based on the data shown in Figure 85, we estimate for washing machines a learning rate of (31.7 ± 7.2)% (Figure 86). The average prices of washing machines dropped by roughly 80% between 1965 and 2007. We, however, find a relatively low coefficient of determination between price data and the fitted experience curve ($R^2 = 0.51$).

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[43] Despite the fact that we correct the efficiencies of refrigerator-freezer combinations for *efficiency differences* between refrigerators and freezers, we do not correct the prices of refrigerator-freezer combinations for *price differences* between refrigerators and freezers because the latter differences are relatively small (i.e., on average for all years and models included in our analysis around 14%).

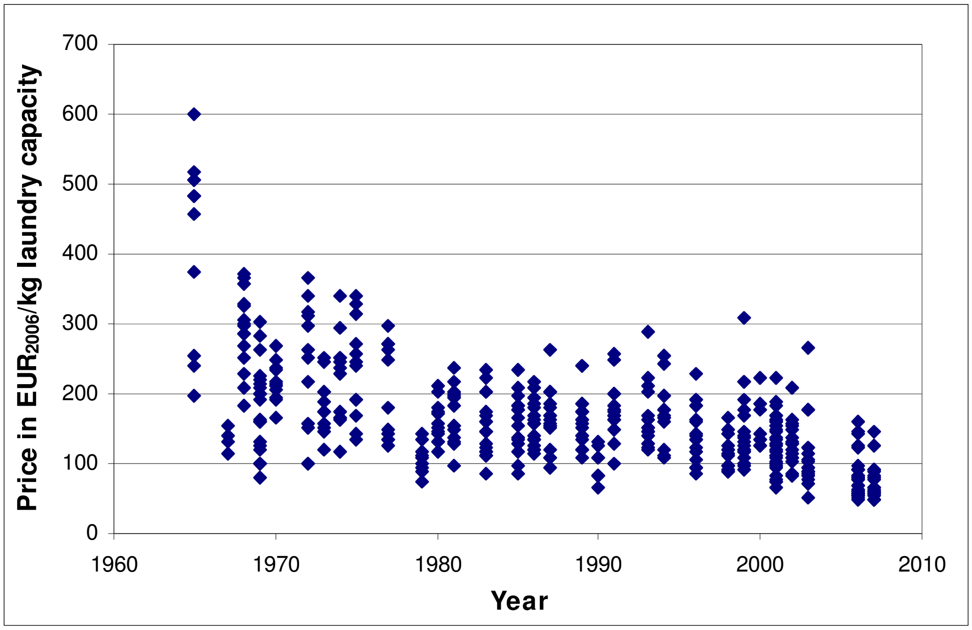

Figure 85: Overview of price data for washing machines included in our experience curve analysis (Data source: Consumentenbond (various years))

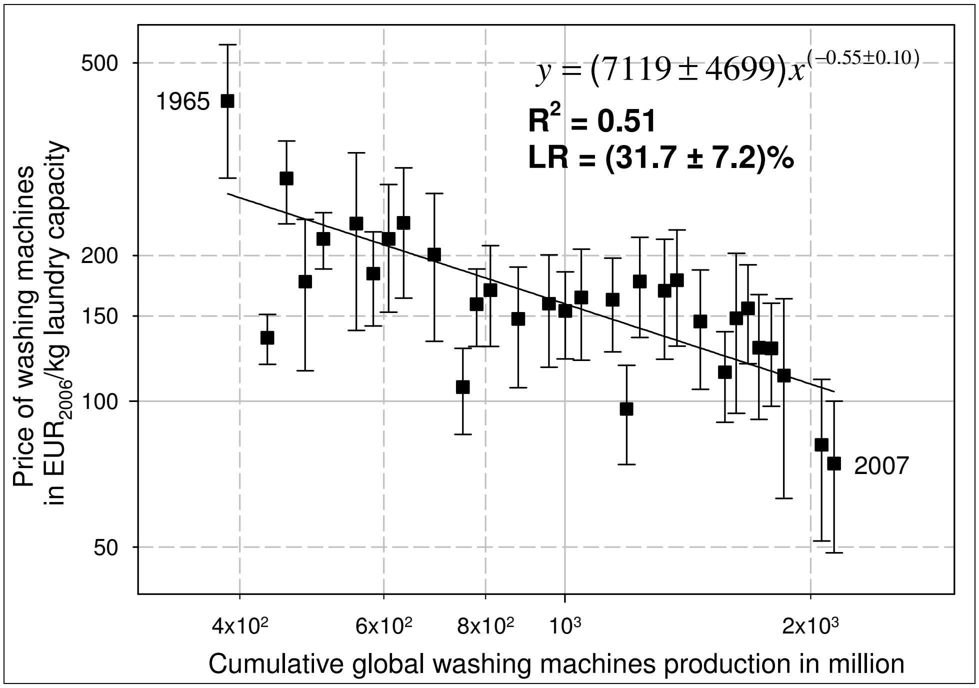

Figure 86: Experience curve for washing machines covering the period of 1965-2007; error bars indicate the standard deviation of average prices (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

Figure 86 indicates that production costs droped drastically in the years between 1965 and 1980, remained relatively constant or even show a slight increase in the 1980s and 1990s, and droped again after the end of the 1990. This observation might be explained by two factors:

- Washing machine technology and the services provided by washing machines improved in the period of 1980-1995. Technological changes include, e.g., the introduction of centrifuge drying and more sophisticated washing programs. Both innovations made modern washing machines more expensive than the relatively simple ones produced in earlier years.
- Automation, other means to boost productivity, and the shift of manufacturing to low wage regions caused a considerable decrease of labour costs in the manufacturing of washing machines and offers an explanation for the observed price reductions in the period after the end of the 1990s.

We now analyze the dynamics of production costs for washing machines on a more disaggregated level. We differentiate low, medium, and high price washing machines (Figure 87) as well as low, medium, and high energy and water consuming washing machines (Figure 88 and Figure 89). The Figures 87-89 indicate considerable cost differences between the individual categories of washing machines, e.g., between the least and most energy and water efficient washing machines. Significance testing with the *F-Test* based on a 95% level of significance reveals the following results:

- Prices differ for high and low price products (Figure 87), while learning rates are similar.
- Prices and learning rates do not differ significantly for washing machines with low, medium, and high energy consumption (Figure 88).
- Prices and learning rates differ for washing machines with low, medium, and high water consumption (Figure 89). This result indicates that, washing machines with high water consumption (i.e., low water efficiency) are cheaper and learn significantly faster than washing machines with high water consumption. We explain this finding with the fact that the least *water-efficient* washing machines sell in recent years mainly because of their low price. While inefficient washing machines were even more expensive than water-efficient washing machines in the 1960s, the former experienced more price pressure than efficient washing machines in recent years because efficient washing machines do not purely sell based on price but because they offer a higher standard of product quality.

Water consumption and energy consumption in washing machines are closely linked with each other. We would hence argue that the same cost dynamics as identified for water-efficient washing machines should also apply for energy-efficient washing machines (due to the expected relationship between water use and the energy required for heating it). The relatively high variability of price data in the period analyzed (see text below), does however not allow drawing stronger conclusions regarding cost dynamics of energy-efficient and -inefficient washing machines.

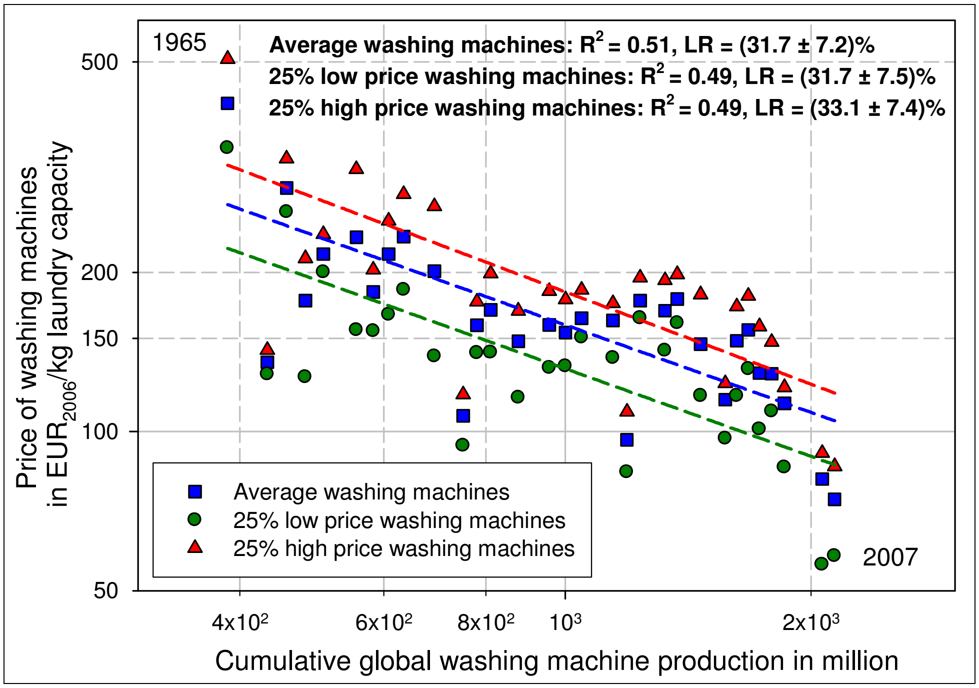

Figure 87: Disaggregated experience curves for low, medium, and high price washing machines covering the period of 1965-2007 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

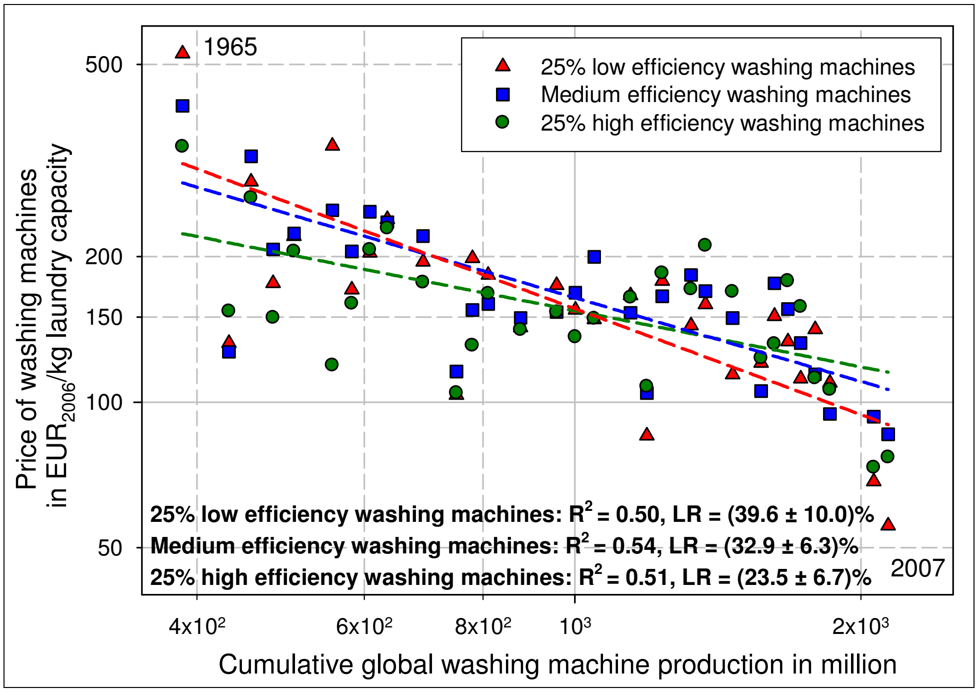

Figure 88: Disaggregated experience curves for low, medium, and high energy consuming washing machines covering the period of 1965-2007 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

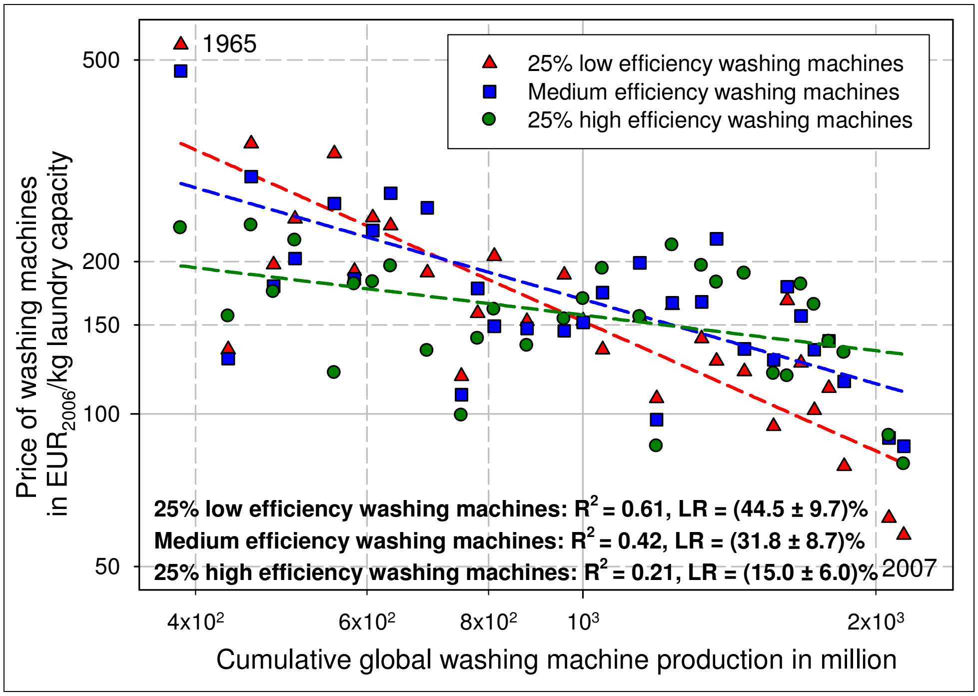

Figure 89: Disaggregated experience curves for low, medium, and high water consuming washing machines covering the period of 1965-2007 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

The average learning rate as identified for washing machines in this report is higher than the one determined by Laitner and Sanstad (2004), who found a learning rate of 20% for washing machines in the USA (covering a time period of 1980-1998). The observed difference might be attributed to the fact that Laitner and Sanstad (2004) estimate cumulative production of washing machines for the USA based on production estimates dating back to 1980 only. We argue that the exclusion of washing machines production in earlier years and in other parts of the world leads to estimates for cumulative washing machines production that are lower than our values and thus to an underestimation of actual learning rates.

We now extend the conventional experience curve approach by modelling the dynamics of electricity and water consumption as a function of cumulative production. We first introduce an overview of all data that are included in our experience curve analysis for electricity and water consumption of washing machines (Figure 90 and Figure 91).

The data for electricity and water consumption indicate similar dynamics as identified for the development of prices. We find a general trend towards declining electricity and water consumption and towards market homogenization, i.e., towards convergence with regard to efficiency.

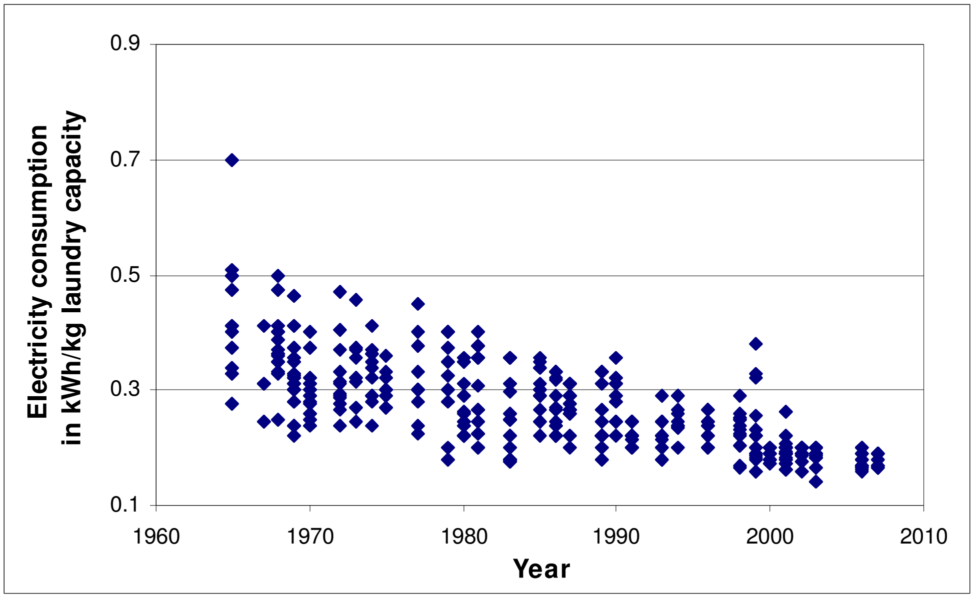

Figure 90: Overview of electricity consumption of washing machines (Data source: Consumentenbond (various years))

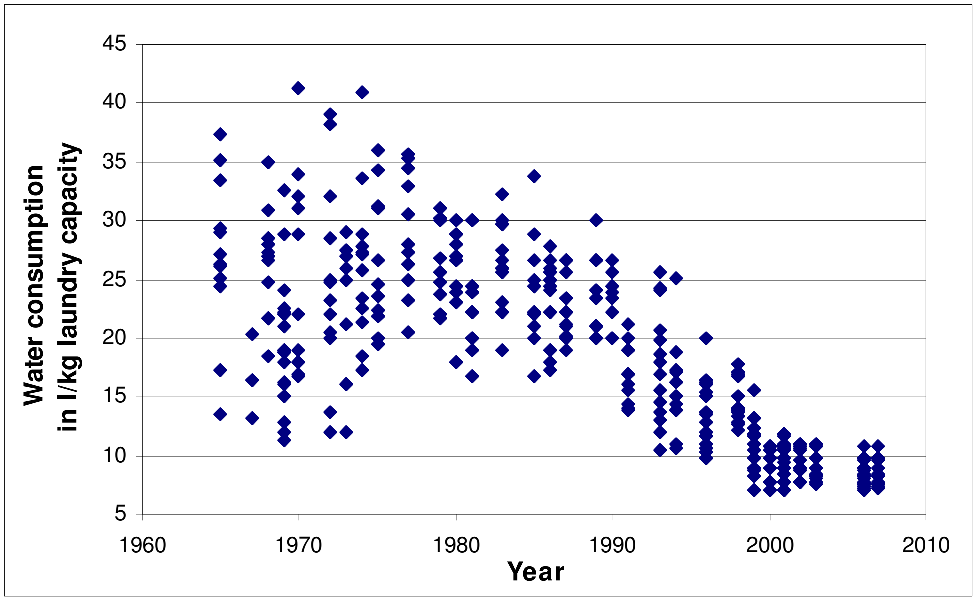

Figure 91: Overview of water consumption of washing machines (Data source: Consumentenbond (various years))

In our experience curve analysis, we identify average learning rates of (24.7 ± 2.2)% and (27.3 ± 6.1)% for the consumption of electricity and water, respectively (Figure 92). This result indicates that electricity and water consumption decreased in the washing machines that have been sold in the Netherlands by 25% and 27%, respectively with each doubling of cumulative global production. In the entire period of 1965-2007, electricity consumption decreased by roughly 60% and water consumption by almost 70%.

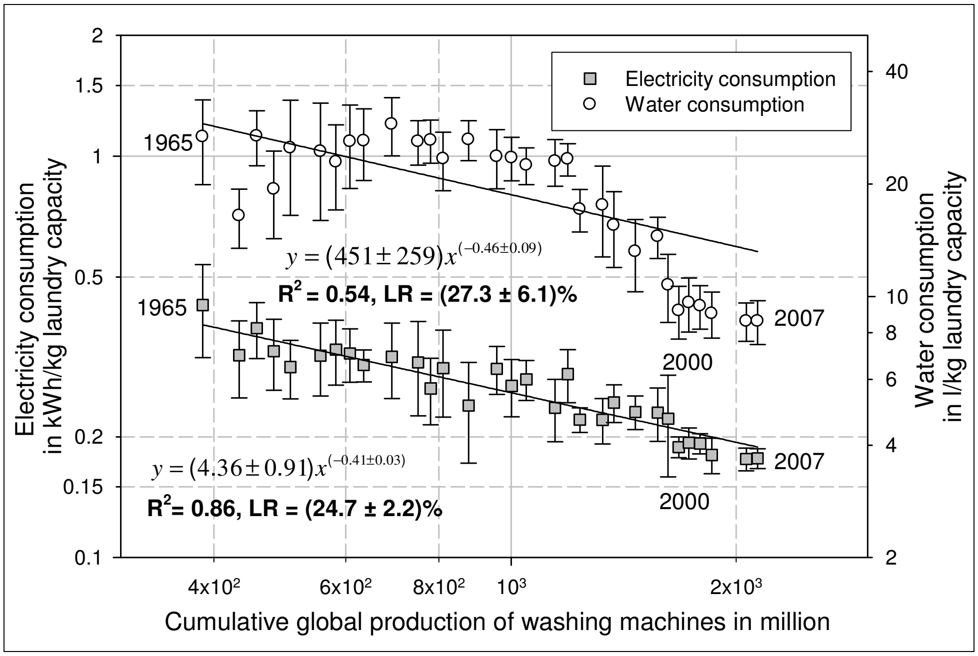

Figure 92: Experience curve for electricity and water consumption of washing machines covering the period of 1965-2007; error bars indicate the standard deviation of averages (Data sources: Consumentenbond (various years), UN (2000, 2007))

The experience curves for electricity and water consumption show two remarkable features:

- Water consumption seems to have been almost stable until the late 1980s but declines in the 1990s. This development might have been triggered by increasing environmental awareness and the public discussions about excessive water use in the late 1980.
- Electricity consumption shows a steady, autonomous decline until the end of the 1990s (despite the introduction of centrifuge drying in the 1980s). At the end of the 1990s, we identify a drop of electricity consumption. This drop might be attributed to the introduction of energy labels in the European Union (EU, 1995a). Although the energy label for washing machines was introduced in the Netherlands already in 1996, the percentage of label A washing machine sales, i.e., sales of energy efficient washing machines, remained below 20% until 1998 but increased to 95% between 1998 and 2002 (Luttmer, 2006).
- Electricity and water consumption are to some extent coupled. Reducing water consumption reduces, e.g., the electricity consumption for water heating. However, the decline in energy consumption shows a steadier trend than the decline in water consumption. This finding might be the result of technological innovation in component manufacturing (e.g., production of more efficient pumps and electric motors) as well as improvements in component integration by washing machine producers.

Disaggregating the experience curves presented in Figure 92 according to various time periods yields for water consumption considerably higher coefficients of determination and allows identifying different learning rates for distinct time periods (Figure 93).

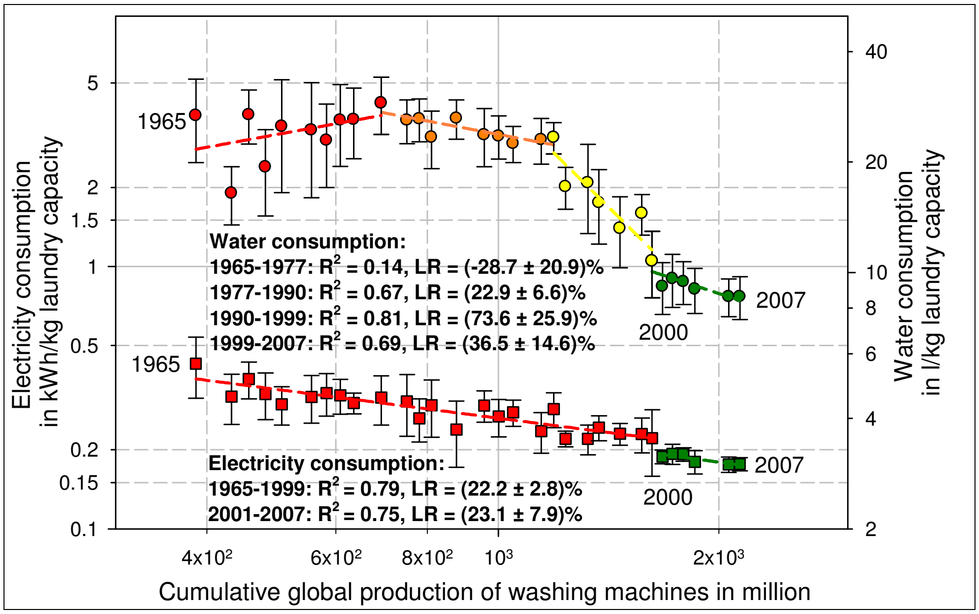

Figure 93: Disaggregated experience curve for electricity and water consumption of washing machines covering the period of 1965-2007; error bars indicate the standard deviation of averages (Data sources: Consumentenbond (various years), UN (2000, 2007))

This finding indicates that (i) the rate at which especially water consumption declines changes in distinct time periods and that (ii) the experience curve approach might hence only to a limited extent be suitable to model water (but also energy) consumption of washing machines. The result links to our discussion in Section 3.2.7, where we state that the extension of the conventional *cost* experience curve to energy and water consumption is only valid, if these parameters are critical for the market success of products. This seems to have not been the case for water consumption (and to some extent also electricity consumption) of washing machines in the 1960s and 1970s. We therefore argue that the experience curve approach might be used to model energy (electricity) and water consumption of washing machines for recent years (e.g., after the period 1980-1990) but not for earlier years.

In Figure 94 and Figure 95, we analyze the dynamics of electricity and water consumption as shown in Figure 92 on a more disaggregated level. We differentiate between low, average, and high efficiency washing machines. These analyses confirm the identified trend towards more efficient washing machines. We find slight differences in the learning rates for energy and water consumption of low, average, and high efficient washing machines (*F-Test*, 95% level of significance).

This result confirms a convergence regarding electricity and water consumption of washing machines. We therefore conclude that the efficiency of the 25% least efficient washing machines improves significantly faster than the efficiency of the 25% most efficient ones. In other words, the differences regarding water and energy efficiencies between least and most efficient washing machines decreased significantly in the period 1965-2007.

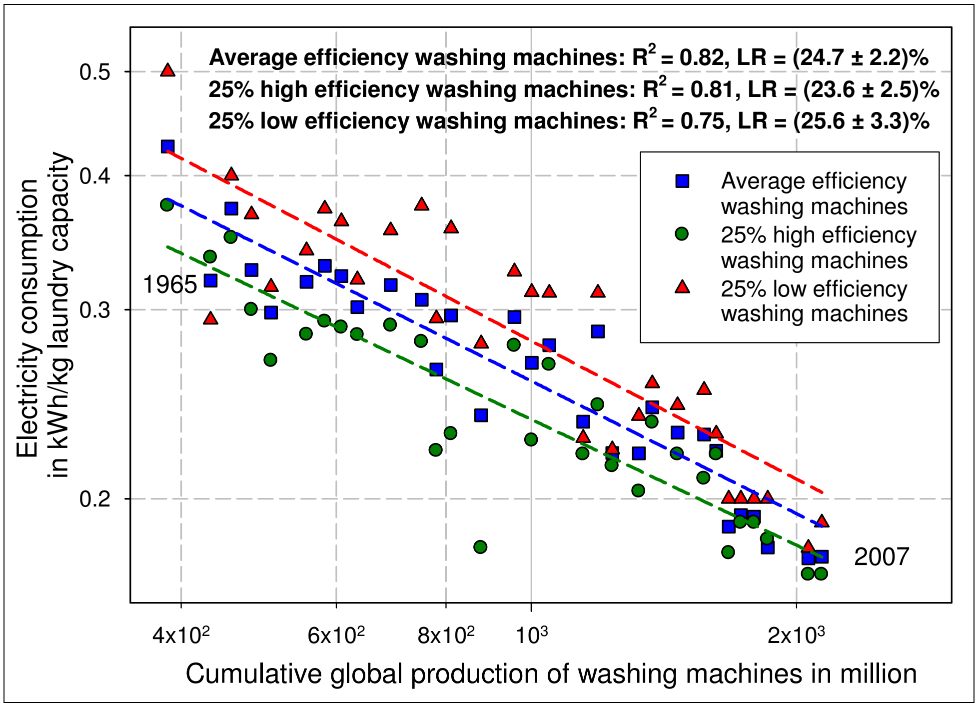

Figure 94: Experience curves for the electricity consumption of low, average, and high efficiency washing machines covering the period of 1965-2007 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

From our analysis, we conclude that washing machines became both cheaper and more efficient with respect to electricity and water consumption in the time period of 1965-2007. The main drivers for the observed cost reductions were increased automation and the streamlining of production processes as well as production shifts to low wage regions (see also Section 4.6.5). The prices of least water-efficient washing machines decrease considerably faster than the prices for most water-efficient ones. We furthermore find a significant trend towards convergence of water and electricity consumption in efficient and inefficient washing machines. Inefficient washing machines show thereby significantly higher learning rates than efficient ones.

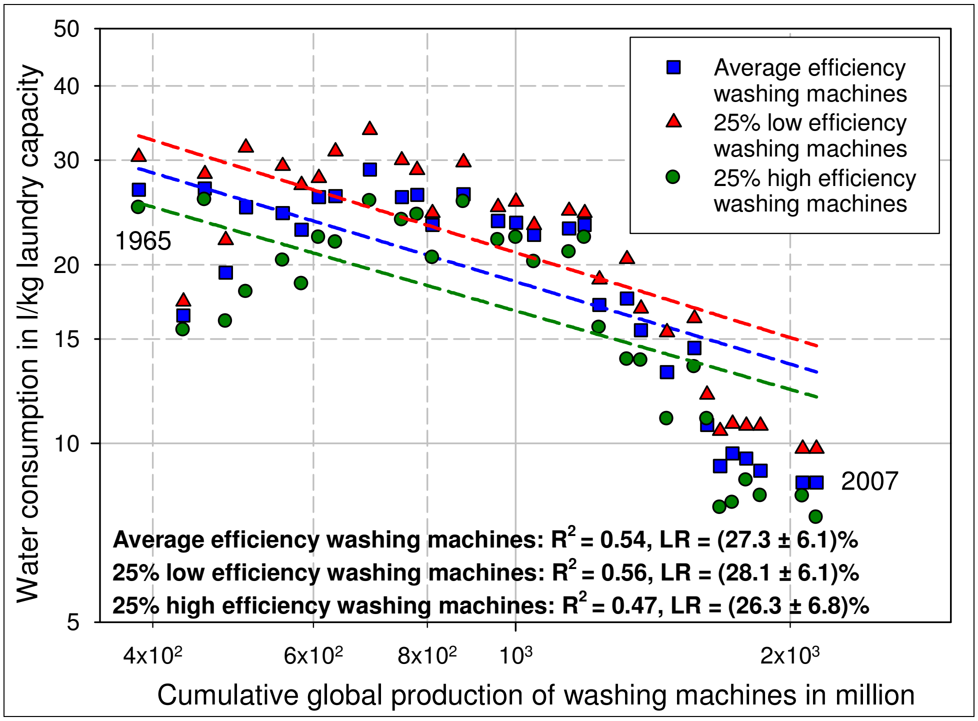

Figure 95: Experience curves for the water consumption of low, average, and high efficiency washing machines covering the period of 1965-2007 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

4.6.4.2 Laundry dryers

In the analysis of laundry dryers, we include data for the time period of 1969-2003. We exclude from our analysis relatively new and innovative heat-pump laundry dryers because time series data were not available to us. Heat pump laundry dryers are currently roughly by a factor of two more expensive van conventional laundry dryers but offer energy efficiency improvements up to 45%.

Figure 96 provides an overview of price data that are included in our analysis. The overview shows that laundry dryer prices decrease but unlike washing machines, the intervals between high price and low price laundry dryers do not appear to become smaller in the time period of 1969-2003. One explanation for this observation might be given by the fact that laundry dryers represent a more heterogeneous product group than washing machines.

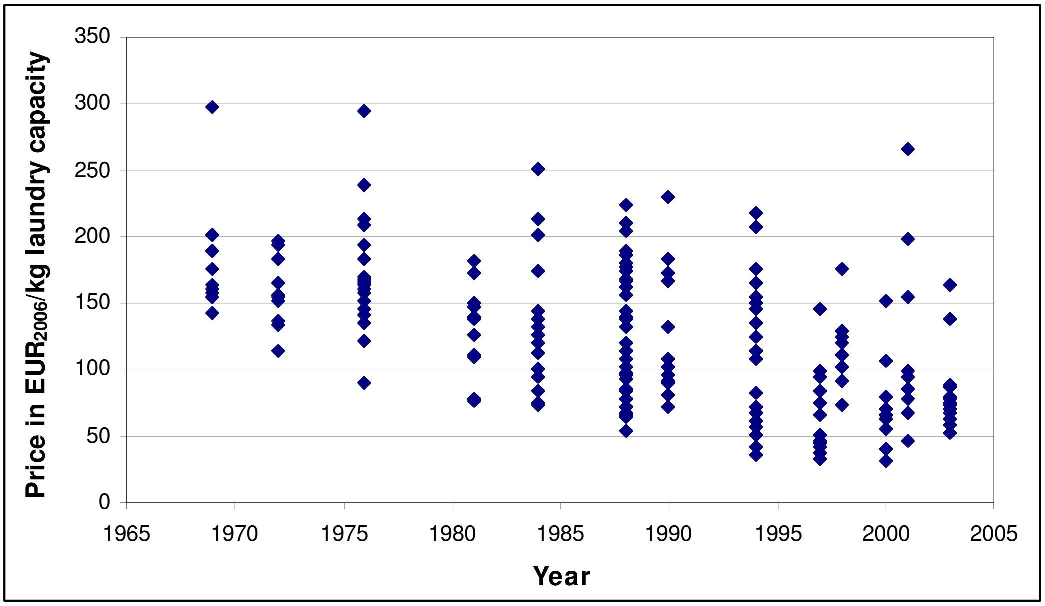

Figure 96: Overview of price data for laundry dryers (Data source: Consumentenbond (various years))

Assuming again that over the entire period prices are a reasonable proxy for production costs, we identify a learning rate of (27.2 ± 4.9)% (Figure 97). This result indicates that the costs for laundry dryers decline at a similar rate than the ones for washing machines.

In the period of 1969-2003, laundry dryers show price reductions of roughly 50% in the Netherlands. This result thereby exceeds the findings of Bass (1980), who identified learning rates of 6% and 12% for laundry dryers in the USA covering the time periods of 1950-1961 and 1950-1974, respectively. Laitner and Sanstad (2004) estimated learning rates of 18% and 15% for electric and gas laundry dryers in the USA, covering the period of 1980-1998. The difference between our estimate and the values found in literature are likely to be caused by deviations in the system boundary of the experience curve analyses (i.e., deviations in the analyzed time periods, countries, and deviations with regard to the assumed cumulative laundry dryer production).

Disaggregating the experience curve in Figure 97 for average, low, and high price laundry dryers (Figure 98) does not yield significant differences in the learning rates for low and high price laundry dryers at a 95% significance level. Due to the relatively large error intervals of average prices in (Figure 97) and based on the fact that the category of laundry dryers comprises a relatively heterogeneous group of products, we decided to differentiate three types of laundry dryers: (i) non-condensing laundry dryers, which do not condensate the moisture but release it to the ambient or outside air, (ii) non-programmable laundry dryers, and (iii) relatively simple laundry dryers without a time clock (Figure 99)[44].

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[44] The chosen classification is an attempt to differentiate various categories of laundry dryers. Individual models of laundry dryers can be contained in more than one category. The categories chosen are not exclusive, i.e., they do not comprise all laundry dryer models included in our analysis.

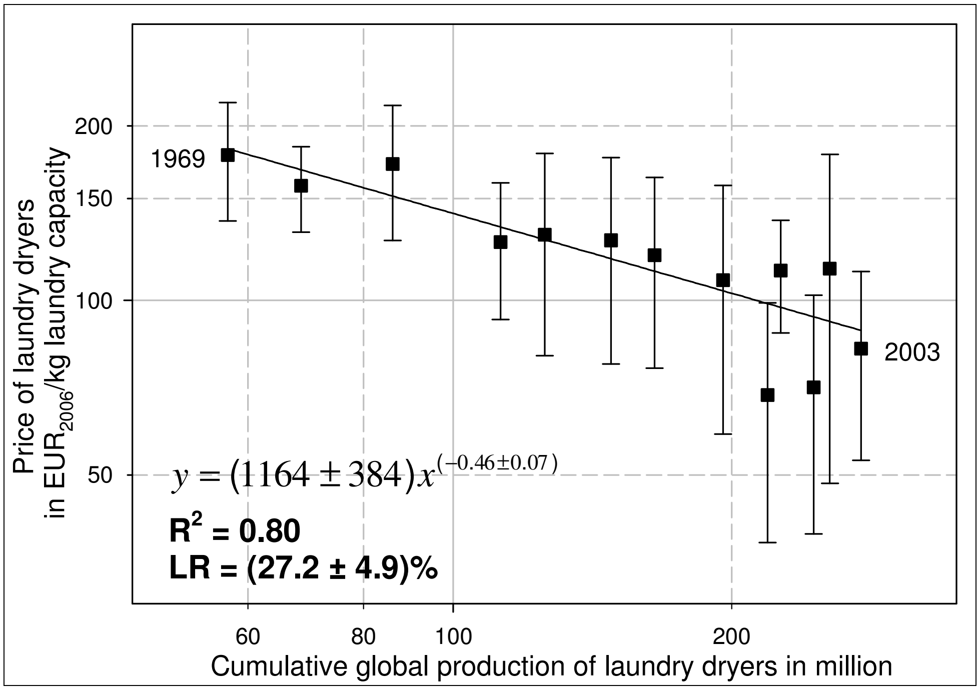

Figure 97: Experience curve for laundry dryers covering the period of 1969-2003; error bars indicate the standard deviation of average prices (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

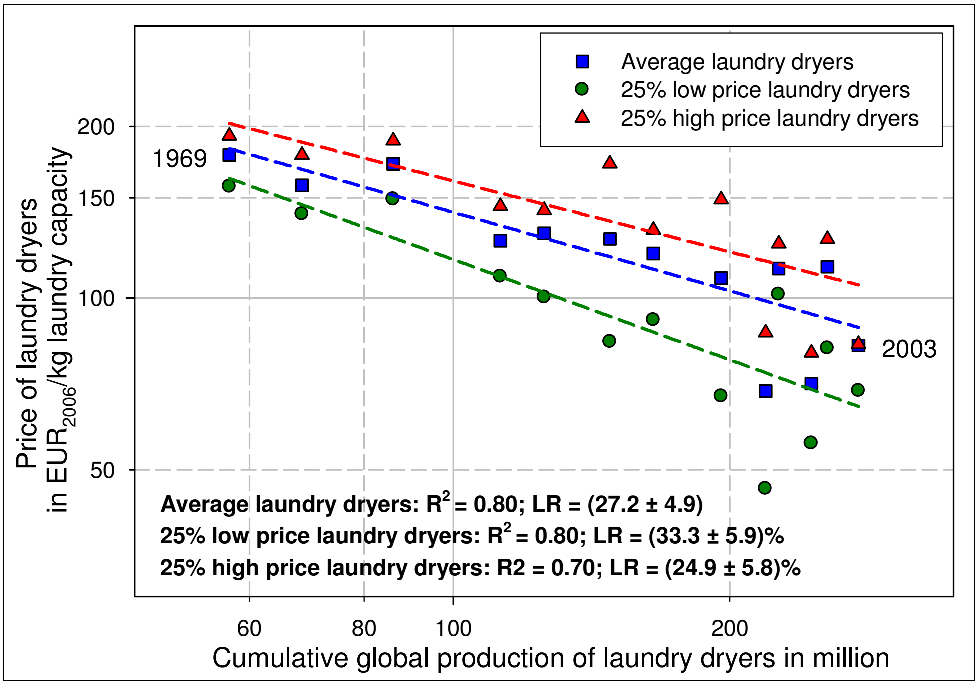

Figure 98: Disaggregated experience curves for average, low, and high price laundry dryers covering the period of 1969-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

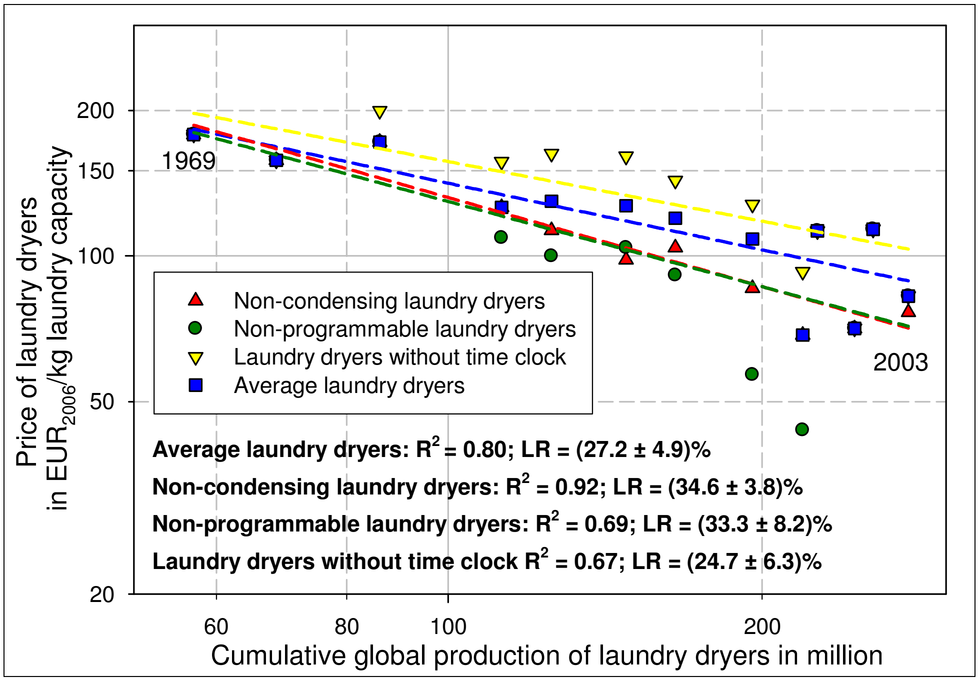

Figure 99: Disaggregated experience curves for three types of laundry dryers covering the period of 1969-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

For the three different types of laundry dryers, we find learning rates in the range of 25-35%. This result indicates considerable cost reductions in the period of 1969-2003 for all three types of laundry dryers. Given the variability of price data, the differences between the learning rates of the individual types of laundry dryers are, however, not significant (*F-Test*, 95% level of significance). Similar to our analysis for washing machines, we also disaggregate the cost experience curve for laundry dryers into high, medium, and low efficiency products (Figure 100).

We find considerable differences in both cost levels and learning rates for high and low efficiency dryers. The results in Figure 100 suggest that the rate of technological learning in the manufacturing of energy efficient dryers is roughly half of that for inefficient ones and even 3 times the one for medium efficient laundry dryers. The observed differences between low- and high-efficiency dryers are statistically significant at a 95% level of significance.

The dynamics of prices and production costs for laundry dryers are driven by increased automation and efficiency of production processes and production shifts to low wage regions. The technical characteristics of laundry dryers are diverse and changed in the time period of our analysis. Especially during the 1970s and 1980s, new functions were introduced such as the replacement of conventional and less expensive time-clock dryers by more expensive dryers with automatic drying programs. This complicates the construction of meaningful experience curves because the system boundary of our analysis (i.e., the technical characteristics of products and the services provided by them) are to some extent inconsistent throughout the time period of our analysis.

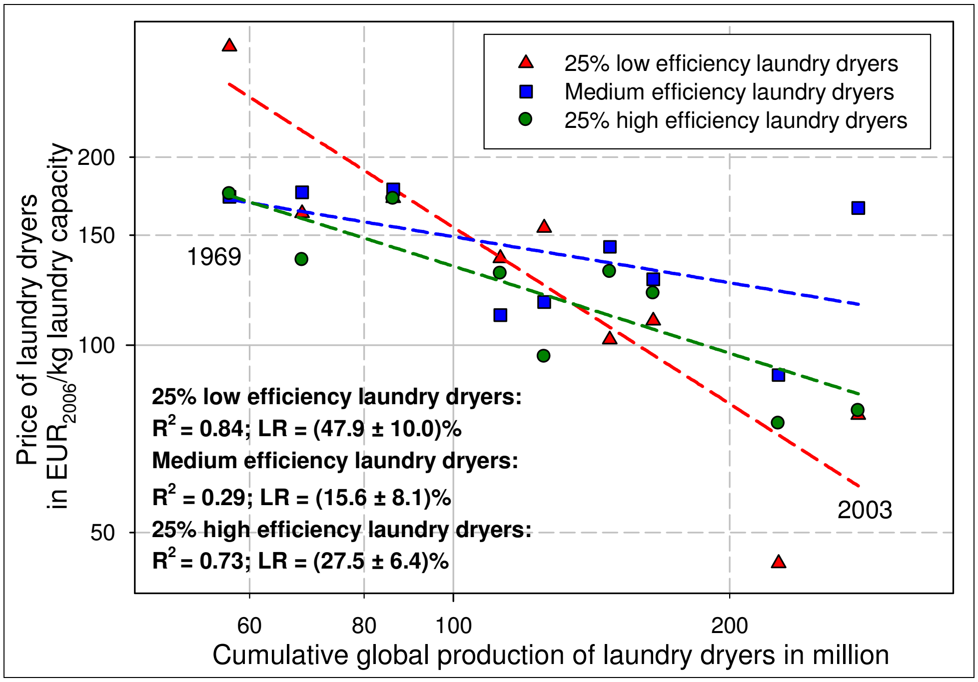

Figure 100: Disaggregated experience curves for low, medium, and high electricity consuming laundry dryers covering the period of 1969-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

We now extend the conventional experience curve approach by analyzing energy consumption of laundry dryers as a function of cumulative worldwide production. Prior to constructing experience curves, we provide an overview of all data included in our analysis (Figure 101).

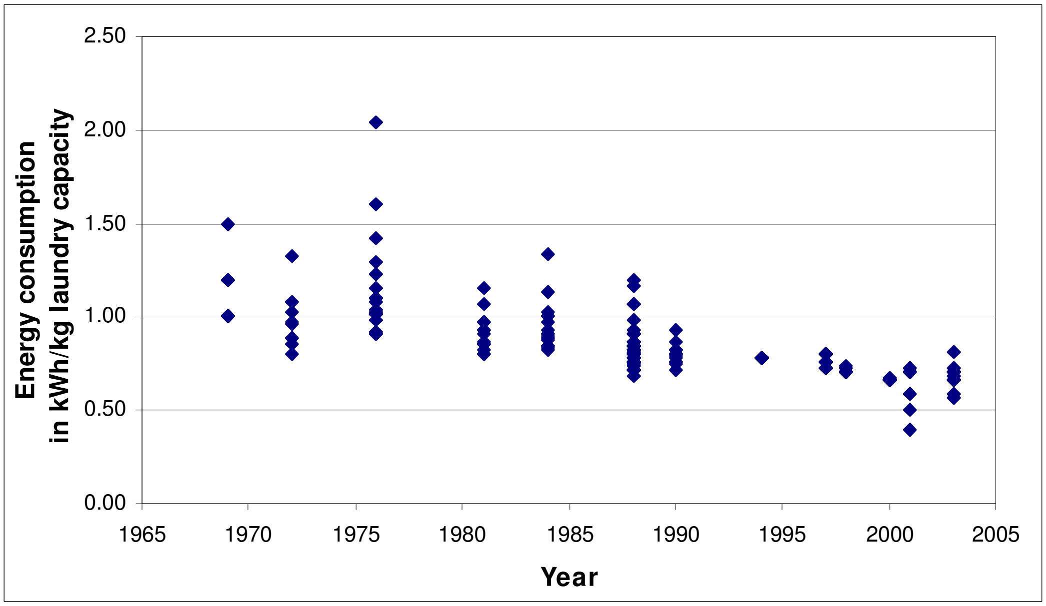

Figure 101: Overview of the energy consumption of laundry dryers that are included in our experience curve analysis (Data source: Consumentenbond (various years))

The data indicate a general trend towards increasing efficiency and homogeneity of laundry dryers with regard to energy consumption. The experience curve analysis shown in the Figure 102 confirms this finding. The energy efficiency of laundry dryers that have been sold in the Netherlands increased in the period of 1969-2003 by (19.9 ± 3.1)% with each doubling of cumulative global laundry dryer production. This is equivalent to an energy efficiency improvement of roughly 40%.

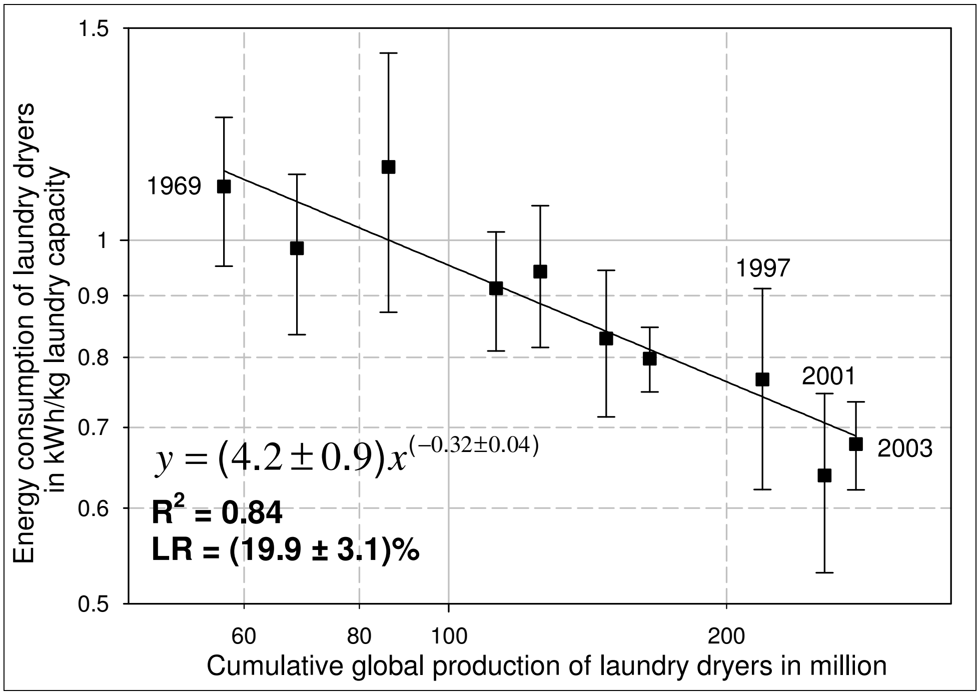

Figure 102: Experience curve for energy consumption in laundry dryers covering the period of 1969-2003; error bars indicate the standard deviation of averages (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

The data in Figure 102 indicate a drop in the average specific energy consumption between 1997 (0.77 kWh/kg) and 2001 (0.64 kWh/kg) and a slight increase until 2003 (0.68 kWh/kg). Although the energy label was introduced during this time period (EU, 1995b), the reduction of energy use in addition to the autonomous reductions observed in the period before 1997 is less pronounced than for washing machines. In other words: Our data do not reflect the effect of the energy label on the energy efficiency of laundry dryers.

Analyzing energy consumption on a more disaggregated level, we find no *significant* differences in the learning rates for the energy efficiency of (i) low and high efficiency laundry dryers (Figure 103) and (ii) the three different laundry dryer types (Figure 104).

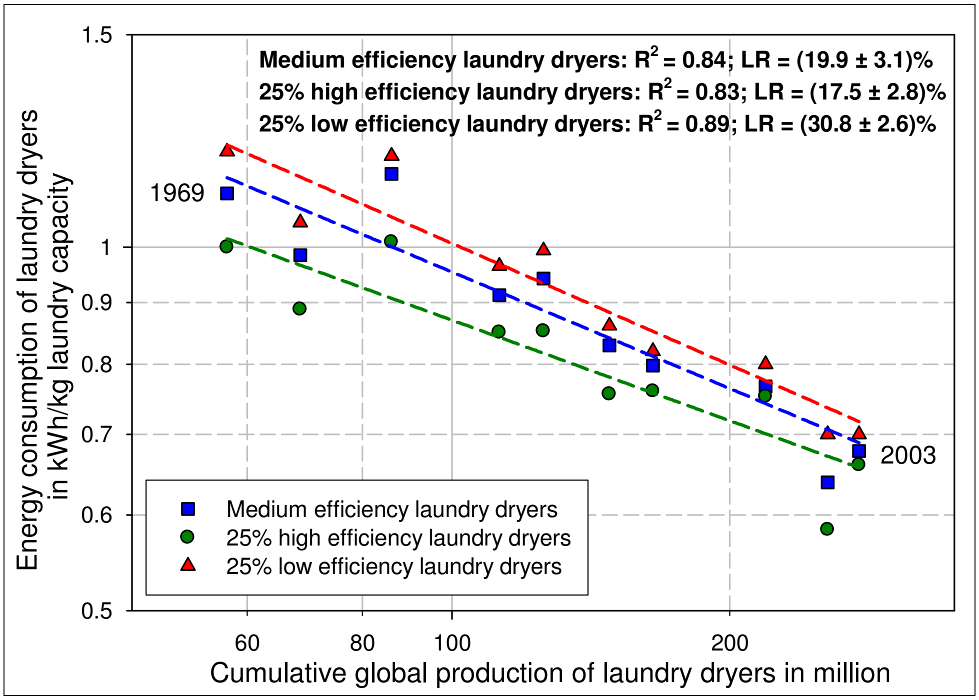

Figure 103: Experience curves for the energy consumption of medium, low, and high efficiency laundry dryers covering the period of 1969-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

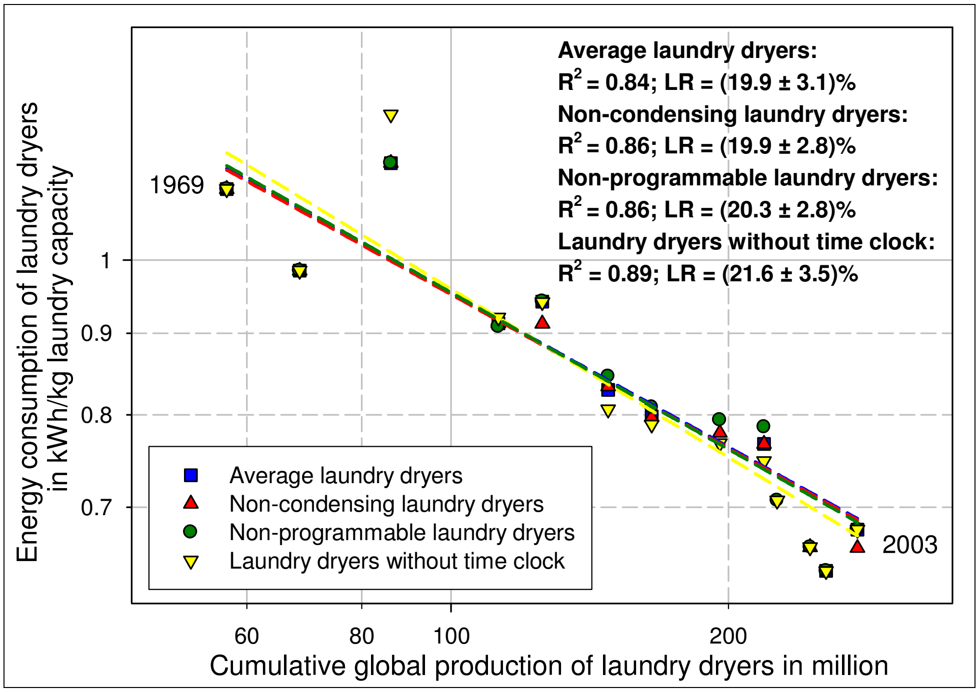

Figure 104: Experience curves for the energy consumption of different laundry dryer types covering the period of 1969-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

4.6.4.3 Refrigerators

In our analysis of refrigerators, we include data for the time period of 1964-2007 (Figure 105). We find a general trend towards decreasing prices, which is however less pronounced than for the other appliances analyzed so far.

The general trend observed in Figure 105 is confirmed by the results of our experience curve analysis (Figure 106). For refrigerators, we identify a learning rate of (9.1 ± 2.0)%, which indicates a much smaller reduction of production costs than it was found for washing machines and laundry dryers. The attached coefficient of determination is comparatively low, i.e., $R^2 = 0.39$. This relatively poor data fit can be explained by the fact that we include in our analysis both refrigerators and refrigerator/freezer combinations. This leads to inconsistencies in the system boundary of the analyzed product system.

In the period of 1964-2007, refrigerators show price reductions of roughly 60% in the Netherlands. Our results are in line with the findings of Bass (1980), who identified learning rates of 7% for refrigerators in the USA, analyzing the early time period of 1922-1940. Laitner and Sanstad (2004) identify, however, learning rates of roughly 18% for refrigerators in the USA in later years, i.e., covering the period of 1980-1998.

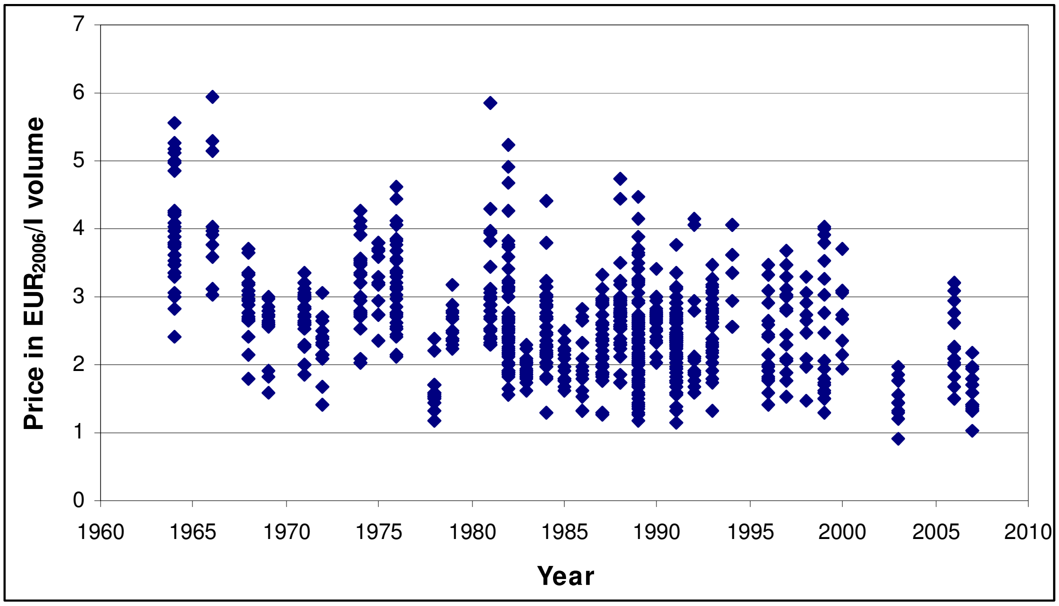

Figure 105: Overview of price data for refrigerators included in our experience curve analysis (Data source: Consumentenbond (various years))

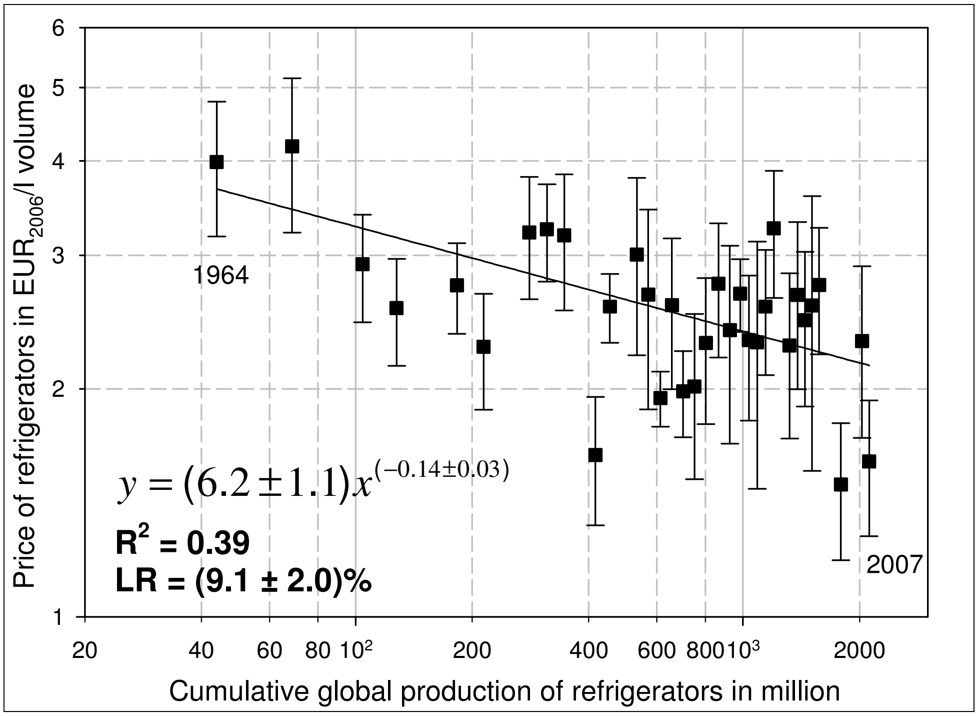

Figure 106: Experience curve for refrigerators covering the period of 1964-2007; error bars indicate the standard deviation of average prices (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

As in the case of laundry dryers, we explain the observed differences with deviations regarding analyzed product system, geographical system boundaries, and data on cumulative global production. As for washing machines and laundry dryers, we also disaggregate the cost experience curve for refrigerators into high, medium, and low price as well as high, medium, and low efficiency refrigerators (Figure 107 and Figure 108).

The differences observed in the learning rates for high, average, and low price refrigerators as well as for high, medium, and low efficiency refrigerators are, however, not significant (*F-Test*, 95% level of significance). Furthermore, we cannot identify significant differences in the price level for inefficient and efficient refrigerators based on the data presented in Figure 108.

As for other appliances, production costs of refrigerators declined due to increased automation and efficiency of production processes as well as shifts of production to low wage countries. The replacement of CFCs increased, however, (temporarily) the production costs of refrigerators.

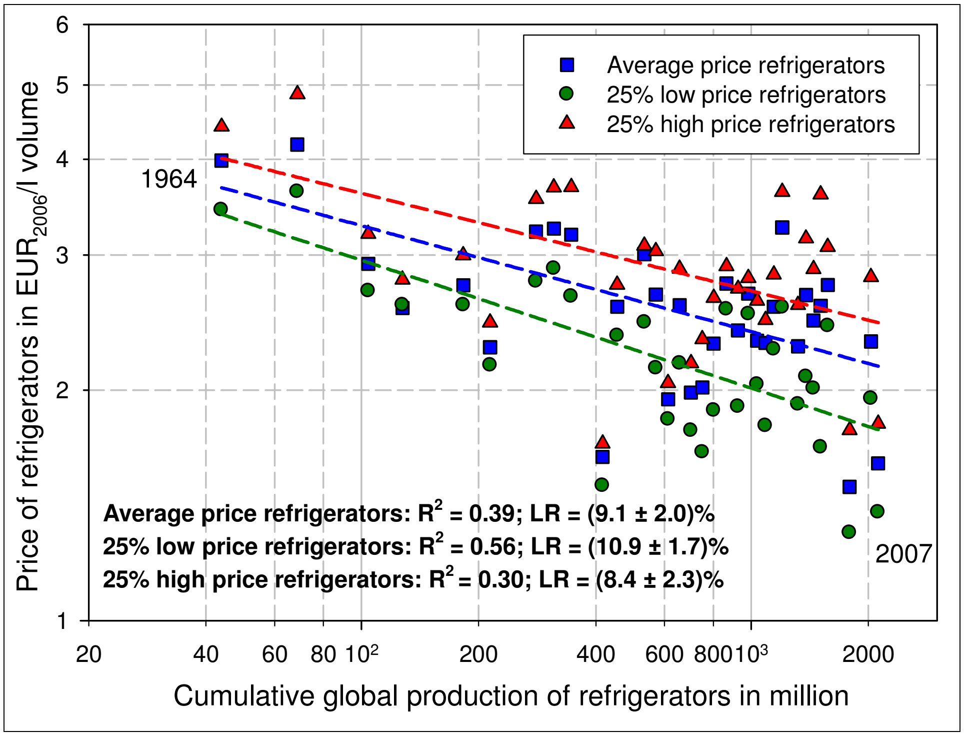

Figure 107: Disaggregated experience curves for average, low, and high price refrigerators covering the period of 1964-2007 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

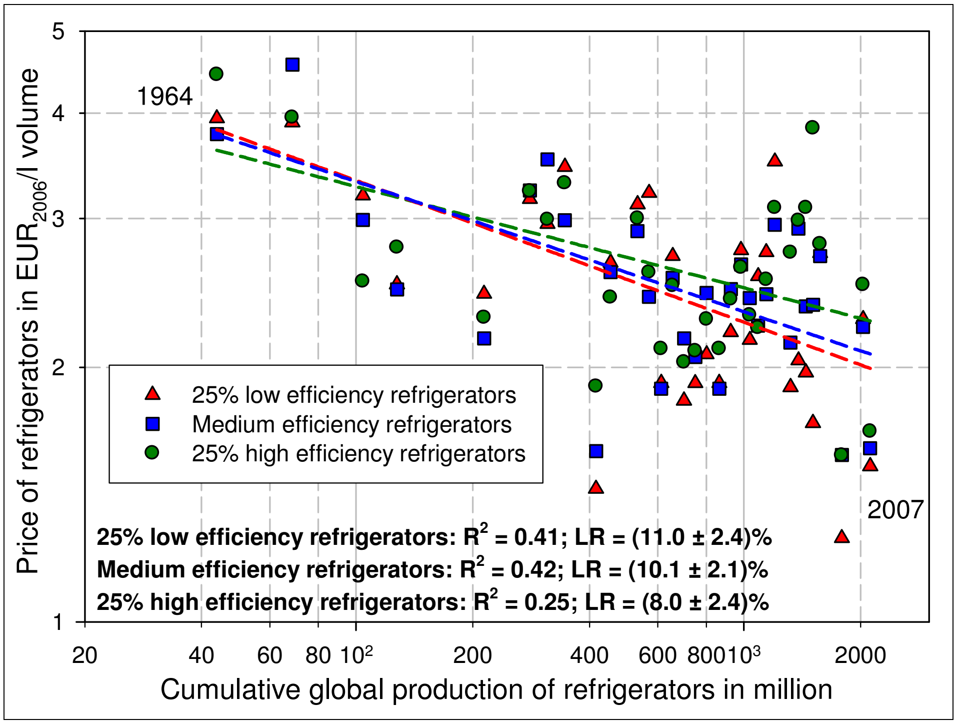

Figure 108: Disaggregated experience curves for low, medium, and high electricity consuming refrigerators covering the period of 1969-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

The energy consumption of refrigerators that have been sold in the Netherlands is depicted by Figure 109, in which we present all energy consumption data used for our experience curve analysis.

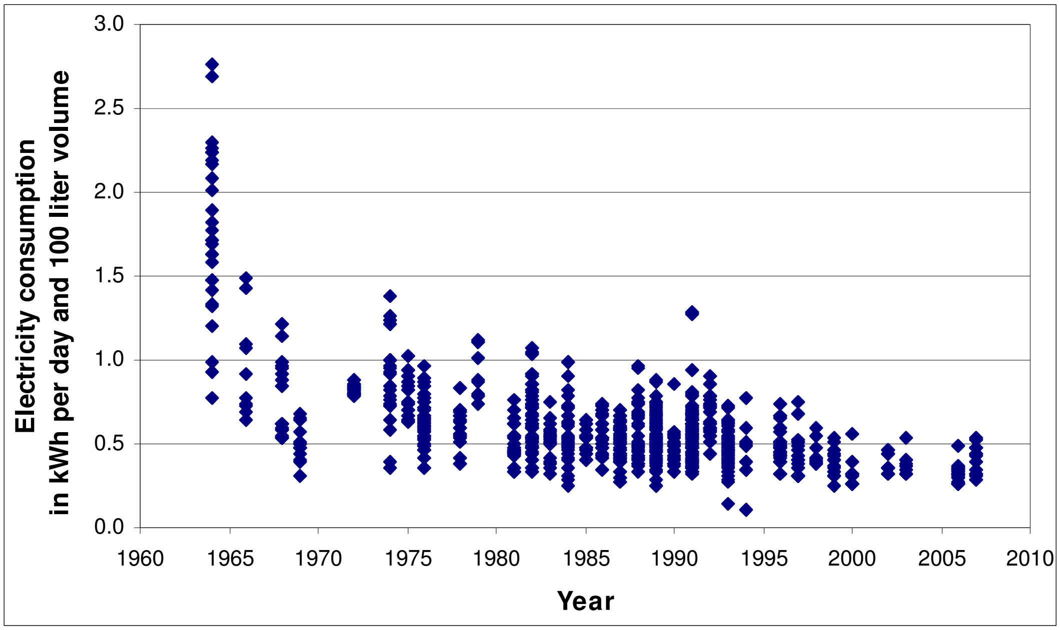

Figure 109: Energy consumption of refrigerators included in our experience curve analysis (Data source: Consumentenbond (various years))

Refrigerators show a general trend towards both reduced energy consumption and greater convergence with regard to efficiency in the period of 1964-2007. Visual inspection reveals improving efficiencies between 1996 and 1999, i.e., during the time period in which the European energy labels became effective at the market (Luttmer, 2006). Efficiencies remained more or less constant in the years afterwards.

Our experience curve analysis confirms the general trend towards improved efficiencies and yields a learning rate of (19.9 ± 2.4)% (Figure 110). This finding indicates that the energy efficiency of refrigerators improved by 77% in the period of 1964-2007. For refrigerators, we find a drop in average energy consumption from 0.48 kWh/(d*100 l) in 1996 to 0.39 kWh/(d*100 l) in the year 1999. As already mentioned, this drop might be attributed to the introduction of energy labels for refrigerators in 1994 (EU, 1994). However, data fluctuations in earlier and later years suggest that also inconsistencies in the product system (e.g., inclusion of both refrigerators and refrigerator/freezer combinations in our analysis) might be responsible for the observed energy efficiency dynamics.

Analyzing the energy consumption of refrigerators on a more disaggregated level (Figure 111), we find no significant differences in the learning rates for the energy consumption of low and high efficiency refrigerators (*F-Test*, 95% level of significance). The main drivers for improvements in the energy efficiency of refrigerators were improvements in wall insulation and compressor technology.

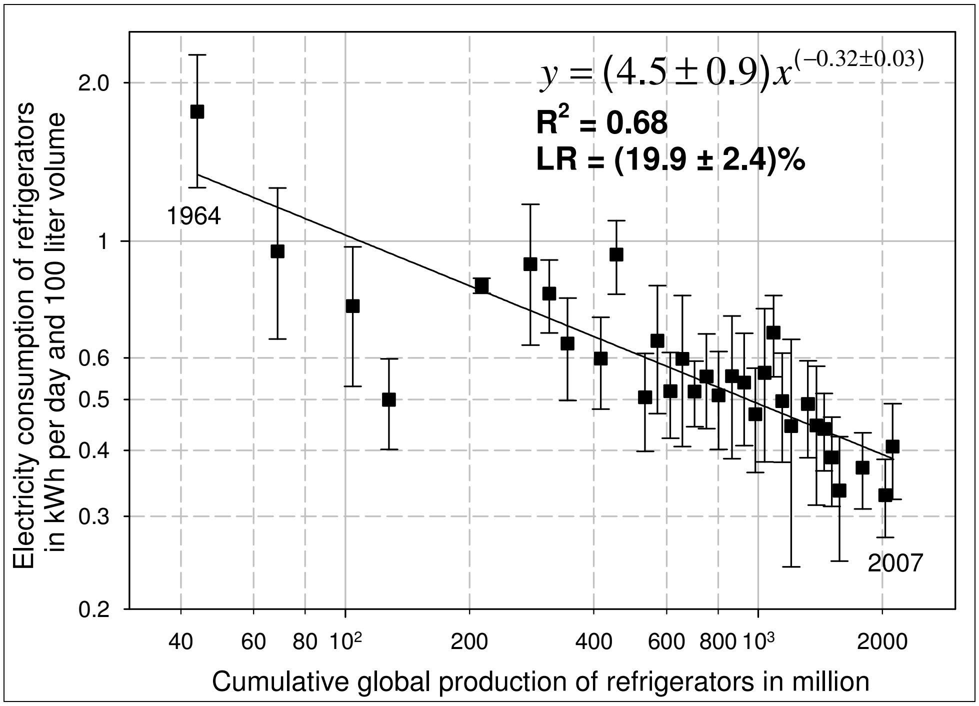

Figure 110: Experience curve for energy consumption in refrigerators covering the period of 1964-2007; error bars indicate the standard deviation of averages (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

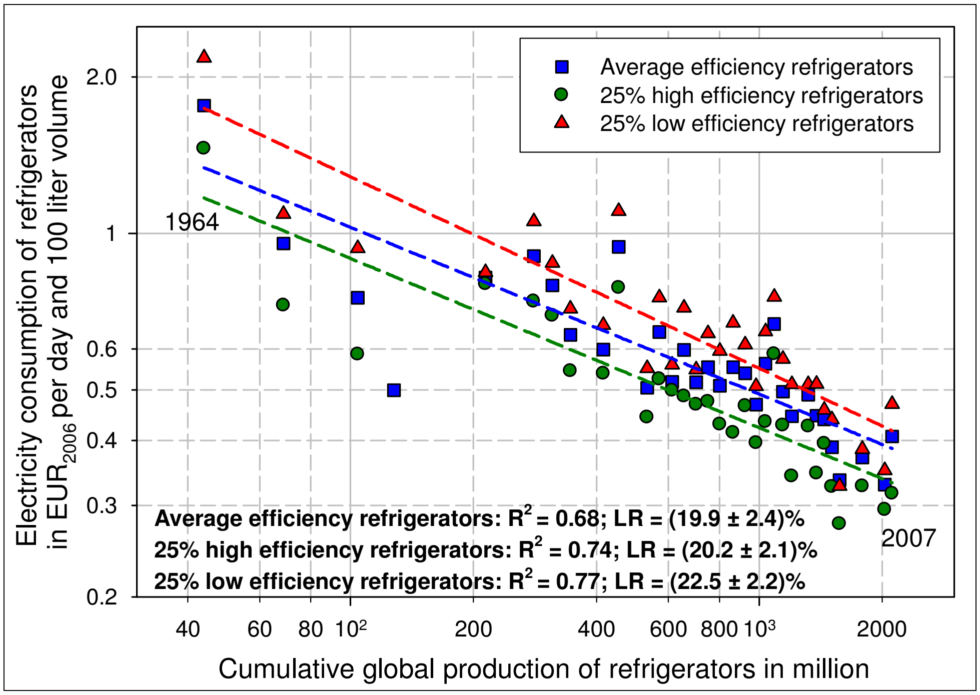

Figure 111: Experience curves for the energy consumption of medium, low, and high efficiency refrigerators covering the period of 1964-2007 (Data sources: Consumentenbond (various years), UN (2000, 2007))

As for washing machines and laundry dryers, our experience curve analysis reveals that also refrigerators became both cheaper and more energy efficient. The experience curve analysis for refrigerators is subject to uncertainties. Unlike for laundry dryers, these refer *not* to the heterogeneity in refrigerator technologies but to the wide spectrum of refrigerator models, ranging from small table refrigerators to comparatively large refrigerator/freezer combinations.

4.6.4.4 Freezers

Freezers represent a relatively heterogeneous group of products. Our experience curve analysis includes data for the period of 1970 to 2003 (Figure 112). The price data in Figure 112 might indicate a trend towards market homogenization, i.e., declining differences between high and low price products. Unlike for the other appliances analyzed so far, the data indicate, however, no general trend towards declining production costs in the period of 1970-2003. This finding can be explained by the fact that the product category of freezers comprises a relative large group of models in different styles, shapes, and sizes. Based on the available data, we therefore categorize freezers for our experience curve analysis into two groups, (i) chest freezers and (ii) upright freezers. Chest freezers are usually much larger than upright freezers (i.e., having an average volume of 290 l compared to 130 l in case for upright freezers).

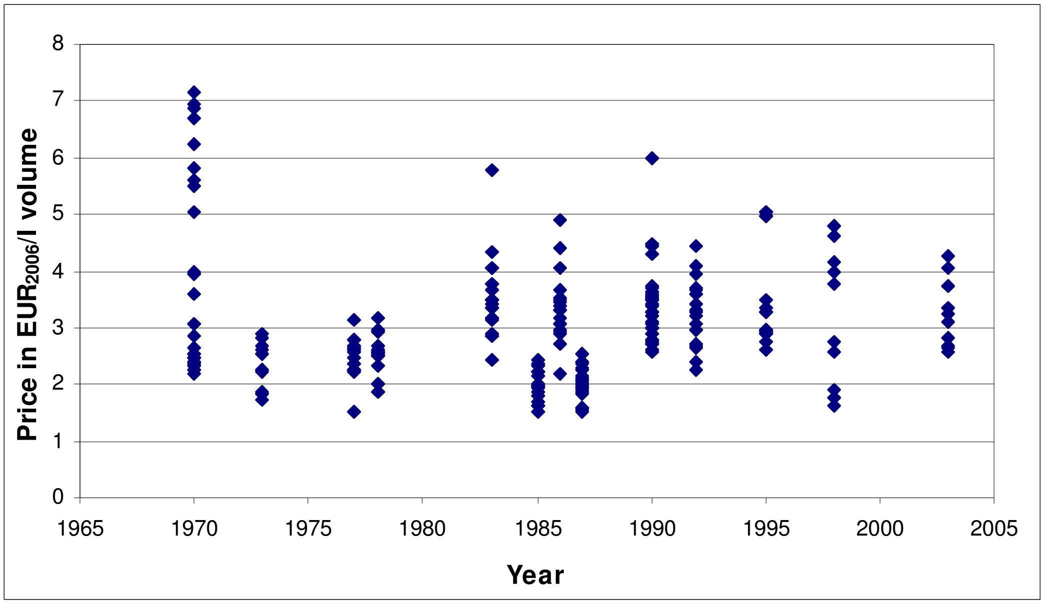

Figure 112: Overview of price data for freezers that are included in our experience curve analysis (Data source: Consumentenbond (various years))[45]

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[45] We exclude from this analysis camping-site freezers that have been tested by Consumentenbond (various years) in 1975 because these devices differ substantially in their specific price and energy consumption from the household freezers included in this analysis.

Chest freezers are not only larger than upright freezers, their specific price [EUR/l] is also lower (Figure 113). For both types of freezers, we find a general trend towards declining prices, i.e., production costs of (7.7 ± 1.2)% and (8.7 ± 3.8)%, respectively. These findings indicate that the price of chest freezers decreased by 30% in the period of 1970-1998 and the price of upright freezers declined by 40% in the period of 1970-2003, respectively. While data for chest freezers show a relatively good fit to the linear experience curve (R^2 = 0.88), data for upright freezers show considerable deviations from the fitted experience curve, resulting in a relatively low coefficient of determination (R^2 = 0.33). Significance testing with the *F-Test* reveals that the price difference between chest and upright freezers is indeed significant, the difference in the learning rate is, however, not.

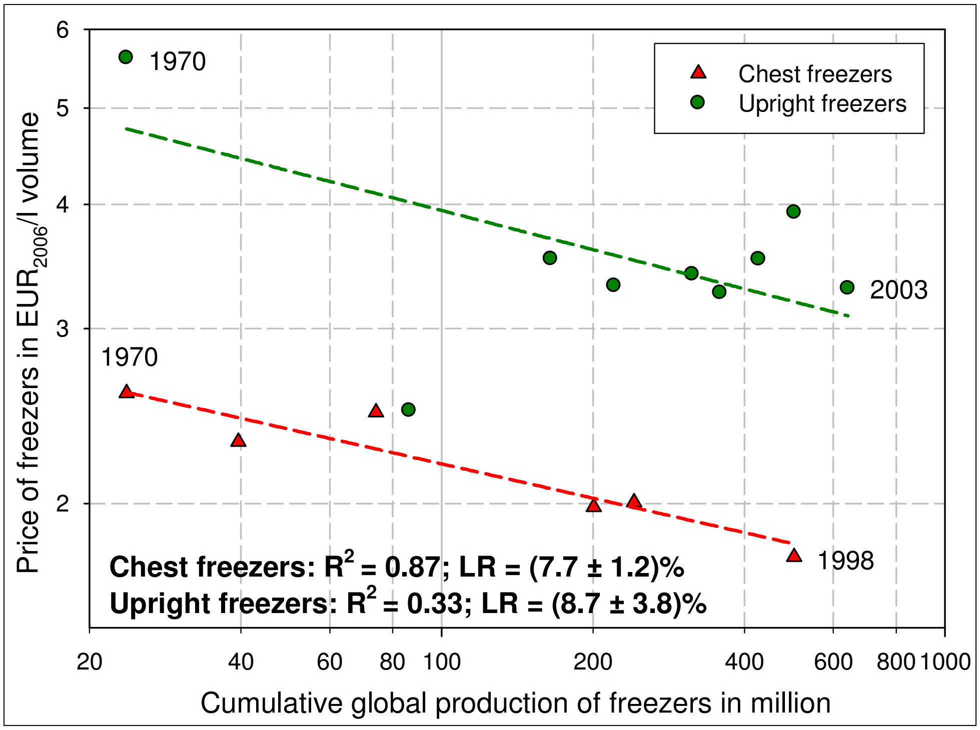

Figure 113: Disaggregated experience curves of chest and upright freezers covering the period of 1970-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

Based on the relatively small data sample, we conclude that the learning rates identified for chest and upright freezers are subject to considerable uncertainties. These uncertainties result from heterogeneity of the analyzed product systems. The uncertainties of our experience curve analysis are also reflected by the result of Laitner and Sanstad (2004), who found a considerably higher learning rate of 36% for freezers in the USA, covering the time period of 1980-1998.

We now extend the conventional experience curve analysis and model energy consumption as a function of cumulative global freezer production. First, we present an overview of all energy consumption data that we include in our analysis (Figure 114). The data seem to indicate a reduction of energy consumption between 1970 and 1977, a slight increase in energy consumption in the period 1977-1995, and a trend towards improved energy efficiency towards the year 2003. The energy consumption data are, however, relatively heterogeneous, spanning a wide range between the most and least efficient models. This finding can again be explained by the fact that Figure 114 shows data for the various freezer models, including chest and upright freezers. Due to their higher volume to surface ratio, the relatively large chest freezers are more energy efficient than the smaller upright-freezers. We therefore analyze the energy consumption of freezers separately for chest and upright freezers (Figure 115).

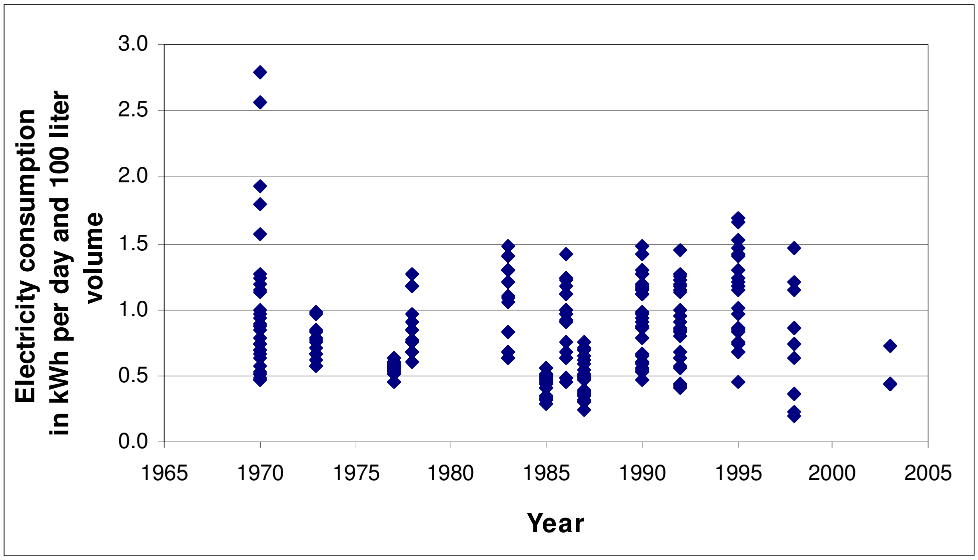

Figure 114: Overview of the energy consumption of freezers that are included in our experience curve analysis (Data source: Consumentenbond (various years))

We find that indeed chest freezers consume on average significantly less energy than upright freezers. The specific energy consumption of both freezer types reduces at rates of (15.7 ± 3.0)% and (10.8 ± 3.3)%, respectively with each doubling of cumulative production. We can, however, not identify *significant* differences in the learning rates for chest freezers and upright freezers.

To summarize, we identify reductions of production costs and improvements in energy efficiency for chest and upright freezers. The fact that we had to make assumptions for estimating the energy consumption of freezers, limit the applicability of the experience curve concept, given the data available to us. We furthermore argue that disaggregation of data into individual categories of freezers is necessary to assure meaningful experience curve analyses for this product category.

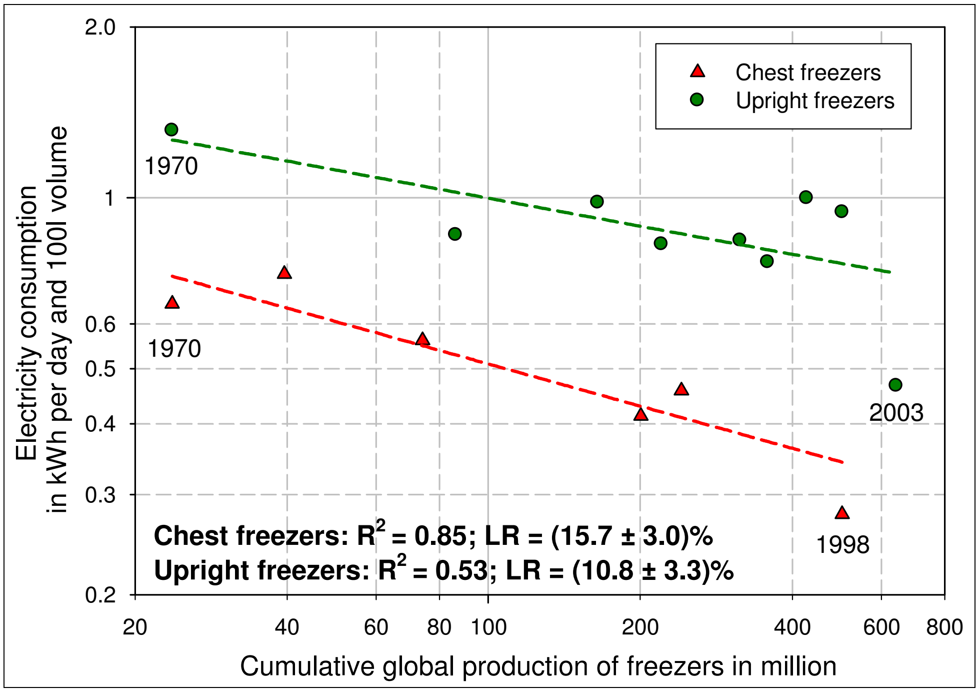

Figure 115: Experience curves for the energy consumption of chest and upright freezers covering the period of 1970-2003 (Principal data sources: Consumentenbond (various years), UN (2000, 2007))

4.6.5 Discussion of experience curve results for household appliances

In this section, we start out with an overview of the main drivers that lead to both cost reductions in the manufacturing of appliances and the observed reductions in energy and water consumption. For this, we first summarize the results of our experience curve analyses for appliances (Table 17).

Table 17: Summary of experience curve results for household appliances

	Learning rates in %		
	Production costs	Energy consumption	Water consumption
Washing machines	31.7 ± 7.2	24.7 ± 2.2	27.3 ± 6.1
Laundry dryers			
- Average	27.2 ± 4.9	19.9 ± 3.1	-
- Non-condensing	34.6 ± 3.8	19.9 ± 2.8	-
- Non-programmable	33.3 ± 8.2	20.3 ± 2.8	-
- No time clock	24.7 ± 6.3	21.6 ± 3.5	-
Refrigerators	9.1 ± 2.0	19.9 ± 2.4	-
Freezers			
- Chest freezers	7.7 ± 1.2	15.7 ± 3.0	-
- Upright freezers	8.7 ± 3.8	10.8 ± 3.3	-

Our results reflect the situation in the Netherlands and indicate a general trend towards both declining production costs and improving efficiencies of appliances, respectively. This trend is confirmed by studies analyzing prices and efficiencies of appliances sold in other parts of the world (Table 18).

Table 18: Average yearly price and efficiency changes of household appliances

Appliance category	Source	Country	Time period	Average yearly reduction in %		
				Price	Consumption of	
					Energy	Water
Washing machines	EES (2006)	Australia	1993-2005	2.2	1.2	-
	Dale et al. (2002)	USA	1993-2001	3.7	1.7	-
	Laitner and Sanstad (2004)	USA	1980-1998	3.4	-	-
	This study	NL	1965-2007	4.0	2.1	2.9
Laundry dryers	EES (2006)	Australia	1993-2005	0.9	0.6	-
	Laitner and Sanstad (2004)[1]	USA	1980-1998	3.2	-	-
	This study	NL	1969-2003	2.2	1.2	-
Refrigerators	EES (2006)	Australia	1993-2005	1.5	2.8	-
	Ellis et al. (2006)	Japan	2001-2005	4.5[2]	9.6[2]	-
	Schiellerup (2001)	UK	1989-2000	1.8	1.4	-
	Dale et al. (2002)	USA	1980-2001	1.6	2.2	-
	Laitner and Sanstad (2004)	USA	1980-1998	3.2	-	-
	This study	NL	1964-2007	2.1	3.3	-
Freezers	EES (2006)	Australia	1993-2005	1.8	2.2	-
	Schiellerup (2001)	UK	1989-2000	1.8	1.9	-
	Dale et al. (2002)	USA	1980-2001	1.6	2.2	-
	Laitner and Sanstad (2004)	USA	1980-1998	5.3	-	-
	This study	NL	1970-1998	1.3	3.0	-
	This study	NL	1970-2003	1.6	3.1	-

[1] Electric laundry dryers only
[2] Average for cold appliances

The reduction in prices, i.e., production costs can be generally attributed to the following reasons:

- continuous upscaling and streamlining of appliance production
- increasing the degree of automation in appliance manufacturing
- competitive sourcing of components
- technological improvement and miniaturization of components
- production shifts to low wage regions like China since the mid 1990s

The experience curve analysis for appliances is subject to uncertainties that mainly result from the heterogeneity of models, styles, and product specifications that are offered on the market. Appliance technology, characteristics, and the services provided to consumers changed over time (Table 19). This leads to inconsistencies in the system boundaries of our experience curve analyses and potentially explains the relatively large data variability in the case of laundry dryers, refrigerators, and freezers. Table 19 shows that appliances being offered on the market in the 1960s/1070s differ considerably from the ones produced today. The technological changes in appliance manufacturing have implications for both production costs and prices on the one hand and energy and water efficiencies on the other hand (Figure 116).

Table 19: Overview of main product innovations in appliances manufacturing

Period	Washing machines	Laundry dryers	Refrigerators and Freezers
<1960	Introduction of washer-dryer combination	Introduction of automatic drying termination cycle	Introduction of R-502 refrigerant
>1960	Introduction of washing programs (selection of cold and hot water, rinse and spinning programs)		Enhancement of interior space with laminated cabinet (combining fiberglass, polyethylene, saran, and kraft paper; cabinet-to-wall ratio declined
	Introduction of dispensing control unit for liquid detergents	Introduction of time-clocks	
	Introduction of two-spin motors		
>1970	Introduction of microchip-controlled automatic washing machines	Introduction of automatic drying programs	Introduction of non-chlorine-containing refrigerant HFC-134a
>1980	Introduction of centrifuge washer/dryer combination	First condensing dryers and tumble dryers with ventilation in the Netherlands	Introduction of ice-makers in refrigerators
	Introduction of electronic timers and automatic shut-off		
	Introduction of aqua-stop system		
	Introduction of washing machines that identify fabric types, provide voice feedback, and monitor the wash load		
>1990	Improved laundry detergents allowing to reduce water consumption and temperatures	Introduction of a wider range of different laundry dryers	Development of vacuum panels for insulation
	Digital age: wide application of electronic controls, improved user interfaces, and optimized appliance functionality	Introduction of gas-fired laundry dryers	Introduction of CFC free refrigerators using refrigerant 134a and 141b
	First washing machines with water consumption of less than 40 liters		CFC production phased out in the US
>2000	Introduction of washing machines with 6 kg capacity, vacuum system, and a comprehensive range of accessories	Introduction of energy efficient heat pump dryers, steam compression dryers	Introduction of antimicrobial-coated stainless steel

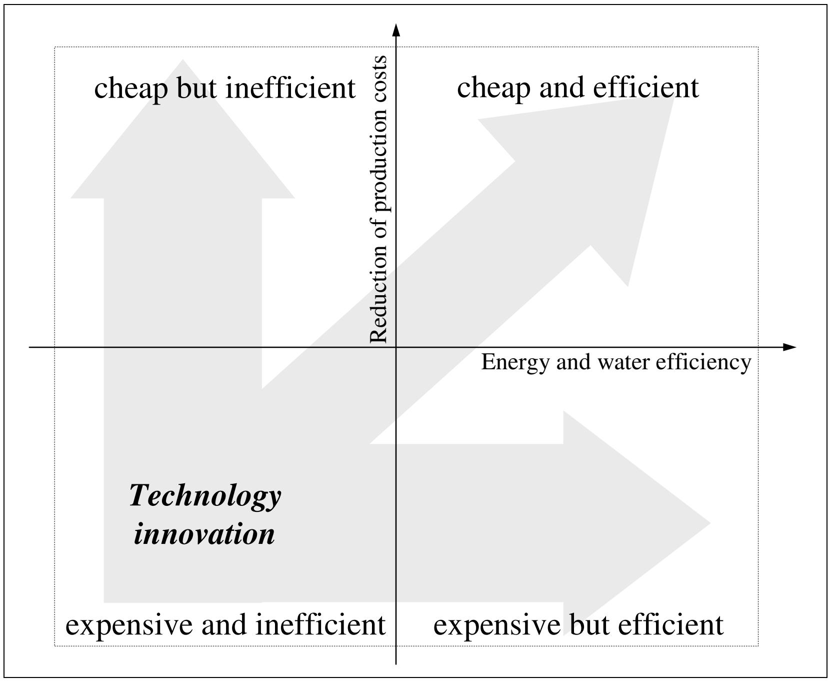

Figure 116: Technological innovation and its effect on production costs and efficiency of appliances

The observed reductions in electricity and water consumption of the analyzed appliances can be attributed to:

- improved wall insulation for refrigerators and freezers;
- reduced water consumption and lower washing temperatures for washing machines;
- improved efficiency of electric motors (e.g., compressors);
- improvements in the performance of components (e.g. insulation materials, control electronics);
- improvements in the performance of detergents in the case of washing machines;
- improvements in measurement and control.

Due to their relatively high variability, our data do not allow to identify any effect of the energy labelling of appliances in the EU (EU, 1992) on the price dynamics of appliances. The results presented in Figure 117 support, however, Ellis et al. (2007) who conclude that energy standards had no considerable effect on appliance prices because producers could meet additional energy performance requirements so far at little or no additional costs. It remains questionable, whether this will be also the case in the future with *low hanging fruits already being picked* and energy standards becoming stricter.

The relatively sharp drop of energy (and water) consumption in washing machines (and to some extent also the efficiency dynamics identified for laundry dryers and refrigerators) indicate that the EU energy label had a direct effect on efficiency improvements of appliances. Especially the case of washing machines indicates that policy measures are able to actively bend down the slop of the experience curve for energy and water efficiency. Such a phenomenon has so far not been observed for cost experience curves where policy intervention is generally seen as a measure for accelerating the *riding down* of the experience curve (i.e., facilitating cost reductions by stimulating cumulative production) but not as a measure for changing its slope.

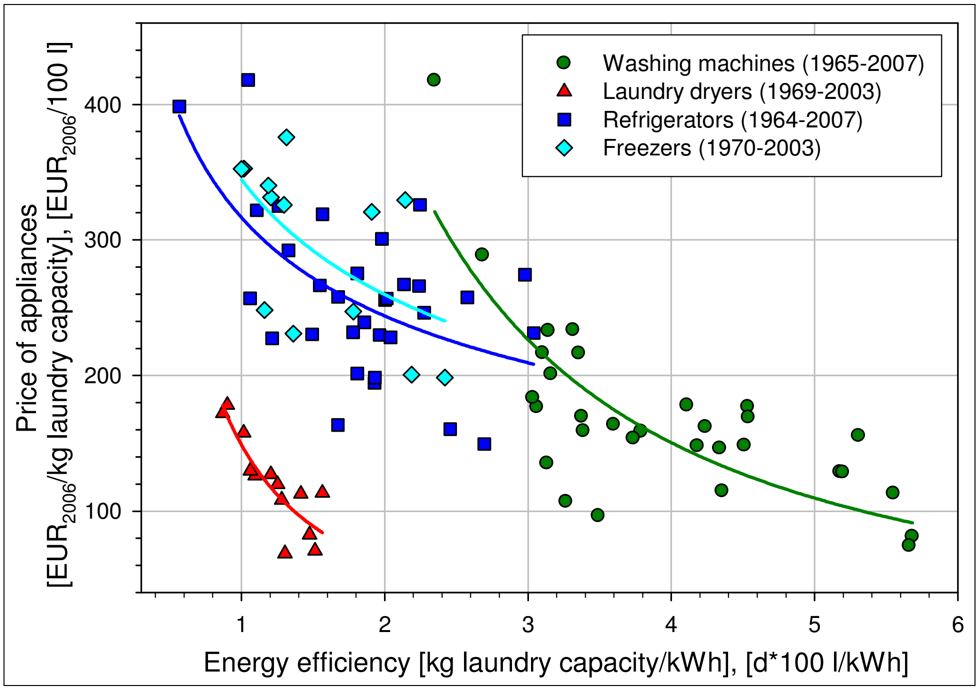

Figure 117: Appliance prices as a function of energy efficiency; in brackets time period analyzed

The data for washing machines and to a lesser also the ones for laundry dryers and refrigerators, point to another interesting phenomenon: After the year 2002, we find only relatively small reductions in the energy (and also water) consumption of appliances, which are in the range of autonomous efficiency improvements in the years before the introduction of the energy label. This finding might be attributed to the fact that label A products (in the case of washing machines and refrigerators) already have reached high market shares in the Netherlands and received very little incentives for further improvements. Our data for washing machines and refrigerators indicate a need for continuous adaptation of energy standards. Also ECEEE (2008) argues along these lines by stating that the energy labelling scheme has become obsolete for many appliances. ECEEE (2008), therefore, suggests (i) to update and revise the current labelling scheme and (ii) to complete it by minimum energy performance standards to enable market transformation towards higher appliance efficiencies. The updating of efficiency standards is also important because increasing global competition put producers under considerable price pressure that potentially makes reductions in production costs and thus market prices becoming first priority relative to efficiency improvements.

4.6.6 Household appliances – conclusions and outlook

We conclude that the experience curve concept is applicable for the four selected household appliances (i.e., washing machines, laundry dryers, refrigerators, and freezers). We identify a general trend towards declining production costs and increasing energy and water efficiencies. The main drivers for the reduction of production costs are the improvement, upscaling, automation, and streamlining of production processes, increasing competition in components manufacturing, and the shift of appliances production to low-wage regions. The experience curve analysis for (especially) washing machines and laundry dryers is to some extent complicated by the fact that we - strictly speaking - do not analyse a technology but a *black box* that provides services to the consumers. More general, our results are subject to uncertainties that result (i) from the use of price data to approximate production costs and (ii) from inconsistencies of the analyzed product system (i.e., changes in technology, changes in services, and heterogeneity of products).

5 DISCUSSION

5.1 Discussion of methodology

The reliability of our experience curve analysis and the related calculation of cost dynamics and improvements in energy and water efficiency depend on the quality of underlying data. The data sets provided by external sources were to some extent incomplete and had to be extended by interpolation and extrapolation. Data interpretation and expert judgement were also required to conduct the analyses presented in this report. This inevitably introduces uncertainties into our results, which can in most cases only insufficiently be quantified. We provide a qualitative overview of technology-specific uncertainties in Table 20.

Table 20: Overview of main sources of uncertainty

Technology	Main sources of uncertainty
Condensing gas boilers	• We use sales of condensing gas boilers as proxy for actual production. • Our estimates on subsidies granted for condensing gas boilers base on information given by Consumentenbond (various years) and Oude Lohuis (2004) because detailed data from governmental agencies were not available. • Average capacity of Dutch condensing gas boiler sales is calculated based on available data from Consumentenbond (various years) and Warmteservice (2007a,b) and might deviate from the average installed condensing gas boiler capacity. • We assume average capacities of boilers sold in the Netherlands for estimating the cumulative capacity of Western European condensing gas boiler sales.
Micro-CHP systems	• Experience curve results are based on scenario projections prepared by WGD (2007). • Underlying assumptions for cost reductions, market sales, and acceptable additional price level are highly uncertain.
Heat pumps	• Reliability of Swiss heat pump prices remains questionable.
Hot and cold storage systems	• On average coverage of only 40% of all hot and cold storage systems installed in the Netherlands. • Costs are to a large extent determined by exogenous, non-technology-related parameters.
Compact fluorescent light bulbs	• Estimates of cumulative global CFL sales are partly based on inter- and extrapolation of data.
Household appliances	• Inconsistencies regarding product system and services provided by appliances in the time period covered. • Relatively wide range of models and technical solutions. • Estimates for cumulative production based on inter- and extrapolation of available data.

In addition, there are several general uncertainties and limitations that concern all technologies; these include:

- the approximation of actual production costs by market prices;
- the use of mainly Dutch price data for constructing experience curves and estimating technology specific learning rates;

- inconsistencies in the estimation of cumulative production (e.g., geographical system boundaries and time periods considered for approximating cumulative production and sales).

These uncertainties result from the use of empirical data but they do not raise principle doubts about the method and its general applicability. We hence regard the experience curve approach as generally applicable for energy demand technologies and we consider the results of our analyses reliable. One important exception are hot and cold storage systems. Based on available data, we regard the results of our experience curve analysis for hot and cold storage systems unreliable because:

- the identified cost trends are statistically very weak;
- costs are to a large extent influenced by exogenous, non-technology-related factors, i.e., geological underground conditions.

For hot and cold storage systems, meaningful experience curve analyses could only be performed, if more detailed data were available allowing to normalize cost data with respect to deviations of on-site geological conditions.

With regard to household appliances, problems mainly relate to inconsistencies of product systems. In the relatively long time periods analyzed, (i) functions were added to appliances (e.g., centrifuge drying in washing machines), (ii) technologies changed (e.g., replacement of CFCs as refrigerants), and (iii) appliances became more diverse (e.g., condensing, non-condensing laundry dryers, freezers of different styles and sizes). This introduces considerable uncertainties into the results of our experience curve analysis for appliances.

Based on the insight gained in the course of this research, we postulate some criteria that should be fulfilled by a technology in order to be suitable for experience curve analyses. These criteria are summarized in Text Box 2. In practice, the postulated criteria are almost never entirely met. From the list mentioned, it is obvious that simple technologies, consisting of only a view components that provide only one rather than multiple services, and that are offered at a highly competitive market are very suitable for experience curve analyses. Technologies are unsuitable to be analyzed with the experience curve approach, if production costs are to a large extent determined by exogenous, non-technology-related factors, if there is major overlap with other technologies and if a technology shows considerable variation regarding functions and technological components within the time period analyzed.

We argue that energy supply technologies (in particular modular renewable energy supply technologies such as photovoltaics and wind energy) are generally more suitable for experience curve analyses than energy demand technologies because the former mainly provide a single service (producing electricity) while the latter often fulfil various and partly changing primary functions other than simply *consuming* energy.

Among all energy demand technologies that have been analyzed in this report, we regard condensing gas boilers and compact fluorescent light bulbs as most suitable for experience curve analysis. Despite the fact that the technology of both products changed in the period covered (e.g., magnetic ballasts have been replaced by electronic ones in the case of CFLs, both technologies are relatively simple, the boundary of the product system is well defined, the markets have been competitive, and the product functions provided to consumers remained constant (i.e., providing light and heat).

Text Box 2: Postulated success criteria for experience curve analysis

- The technology should be homogenous with respect to its technological characteristics, i.e., only incremental technological changes of components should occur in the time period analyzed. Ideally there should be limited overlap with other technologies using identical components (e.g., identical batteries or membranes) in order to avoid that the decrease in cost is primarily caused by developments in other product systems; strictly spoken, this condition is, however, hardly ever met.
- The technology should not change with respect to the functions and services it provides, e.g., a washing machine should only provide the service of washing clothes and not extend its consumer services by also centrifuging or drying them.
- Ideally, technology-related performance and costs should be independent from exogenous, non-technology-related factors. For example, technological learning for hot and cold storage systems cannot be analyzed with the experience curve approach because changes in geological underground characteristics (for which detailed information is not available) have much larger effects on the total installation costs than the gaining of experience in drilling and installation companies.
- Reliable values for prices (or preferably production costs) and cumulative production should be available for (preferably) long time periods.
- The boundary of the system studied (local, national, or global) must be sufficiently well understood. In other words, it must be clear how the technology has diffused geographically, and among which countries or regions knowledge exchange has occurred.
- Prices for production factors should ideally remain constant, i.e., prices of labour, energy, materials, and capital should not fluctuate strongly in the time period analyzed.

One critical aspect of all experience curve analyses refers to the last criteria mentioned in Text Box 2, i.e., that prices of production factors should remain constant. The production costs for a product are determined by quantity and price of production factors consumed in the manufacturing process (see also Section 3.2.6). Technological learning can influence the quantities of, e.g., labour, energy, materials, or capital that are consumed for production but generally not the prices for these production factors. Price changes that are exogenously imposed, e.g., by changing profit margins (changes in capital price), changing wages (outsourcing of production to low-wage regions), or changing material prices (variations in steel price) are incorporated into learning rates and can potentially have a considerable effect on the results of experience curve analyses. This is problematic because these factors are exogenous to the system studied. In that context, it is important to note that changes in production costs (from one unit to the other) are in early years (when production levels are low) strongly influenced by technological learning, i.e., the reduction of *quantities* of production factors that are consumed in the manufacturing process. However, cost reductions due to technological learning decrease with increasing cumulative production and the effects of *price changes* of production factors become increasingly important for determining total production costs. This is especially problematic, if the prices of production factors change strongly within a short time frame because such changes might cause changes in the slope of the experience curve. On the longer term, e.g., increasing raw material prices are likely compensated by more efficient use of material or material substitution. We observed such effects for example for the production of bulk chemicals until the end of the 1990s (Crank et al., 2004). Concluding, changing prices for production factors may lead to false conclusions, if experience curves are used for projecting future cost dynamics of a technology. Further research based on detailed and disaggregated data is recommended to quantify the effect of changing prices of production factors on the results of experience curve analyses.

The extension of the conventional experience curveapproach to model the COP of heat pumps, the luminous efficacy of CFLs, as well as energy and water consumption of household appliances as a function of cumulative production is novel and has not been executed in this way. We regard this methodological extension in general valid and suitable to reveal new insights into the dynamics of energy efficiency improvements.

A general application of the experience curve approach for modelling energy and water efficiency of products requires detailed empirical data analyses and should be underpinned by robust and more extensive research. Special attention should be paid to factors effecting market elasticity with regard to energy efficiency such as energy and commodity prices, secondary effects such as consumer discount rates, alternative investment opportunities for consumers, governmental policy, and other socio-economic factors. In the discussion of the results of this analysis, four points deserve special attention:

- Unlike for production costs, there are thermodynamic minimum energy requirements for processes (e.g., heating a defined volume of water to 60 °C in a washing machine), which cannot be overcome. This physical boundary for further energy and water efficiency improvements can only be ‘overcome’ by applying innovative and radically new technological solutions (e.g., replacing conventional laundry dryers by heat pump dryers; reducing the energy consumption in washing machines by reducing their water consumption and washing temperature).
- Energy and water consumption have been for a long time not relevant for the market success of products. Systematic improvements of these parameters, i.e., systematic and continuous technological learning with respect to energy and water consumption does only occur, if these parameters are critical for market success. We therefore argue that modelling energy and water efficiency in an experience curve framework is valid for recent decades but less justified for early years, e.g., before the first oil crisis. In these years, energy (and water) efficiency improvements might have been an *unintended* result of technological learning that

was aimed at improving other product characteristics. These so called *autonomous* efficiency improvements do not necessarily follow an experience curve because they might be easily reverted, if other product functions require such a development. A very recent example for such dynamics is the improvement of light chromaticity at the expenses of bulb efficacy in CFL manufacturing.

- The application of the experience curve approach for modelling COP dynamics of heat pumps seems to be justified because energy performance is next to product price *the* decisive criterion for the market success of this energy technology.
- Our results indicate that policy interventions might be able to actively bend down the slope of an experience curve for energy and water consumption (see, e.g., results for washing machines), while such a phenomenon has not been observed for cost experience curves.

5.2 Discussion of results

In this research project, we limit the application of the experience curve approach to efficient energy demand technologies that are relevant for the residential and commercial building sector. Although outlined in the initial research proposal, we exclude from our analysis products and technologies for which energy costs constitute a major cost component in the manufacturing process (e.g., bulk materials like steel or non-ferrous metals). This decision was made, based on three considerations:

- The availability of reliable and detailed data for the mentioned bulk materials is questionable.
- While the prospects for developing experience curves for energy consumption in manufacturing processes for these materials are generally good, experience curve analysis for production cost might be hampered by the strong dependency of production costs on energy prices (see also discussions in Chapter 5.1).
- The options for Dutch policy intervention and policy support for these materials are limited compared to the energy demand technologies analyzed in this report.

For the analyzed energy demand technologies, we identified a general trend towards lower production costs (Figure 118 and Figure 119). We regard the experience curve approach unsuitable for hot and cold storage systems (due to the large influence of exogenous, non-technology-related factors in the installation costs). Disaggregating our experience curve analyses yields the following results:

- The costs for medium size CFLs (60 W_e and 75 W_e capacity-equivalents) decrease significantly slower than the costs for CFLs with a capacity of 40 W_e and 100 W_e equivalents. We furthermore found that CFLs with a capacity-equivalent of 100 W_e have a significantly lower specific price [EUR_{2006}/W] than CFLs with a capacity-equivalent of 40 W_e.
- Water-efficient washing machines are on average more expensive and learn slower than water-inefficient washing machines.
- The prices of low efficiency laundry dryers decline faster than prices of medium- and high-efficiency laundry dryers.
- Chest freezers are cheaper than upright freezers.

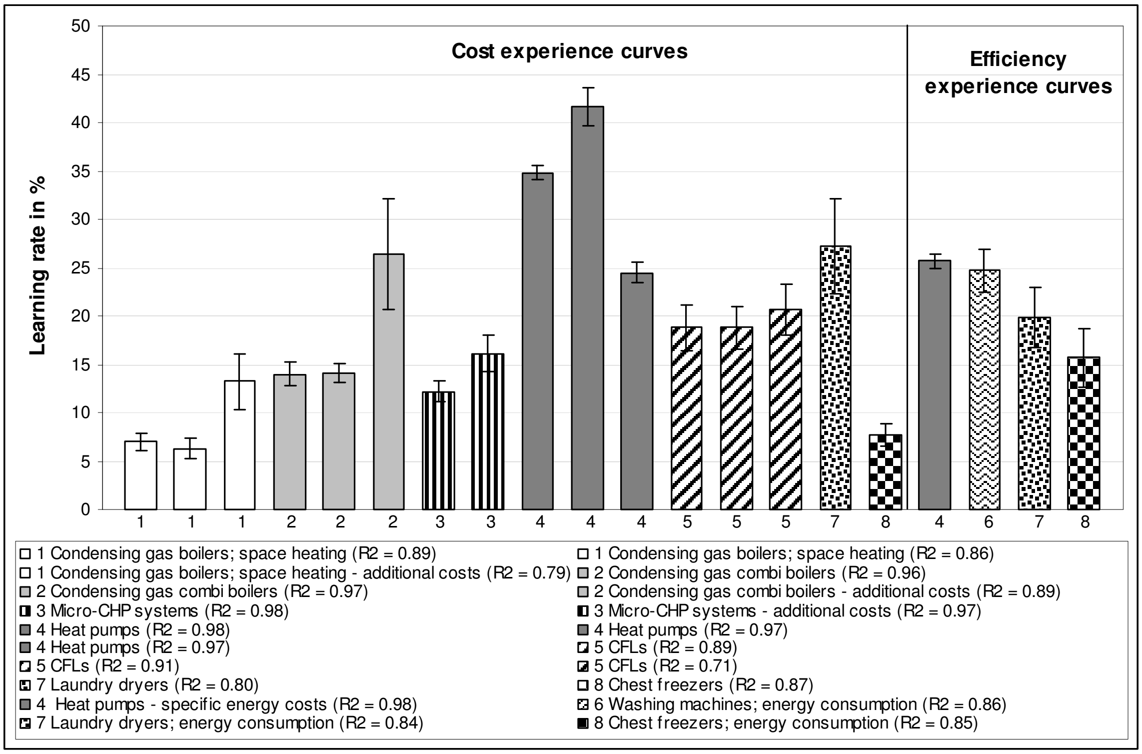

Figure 118: Overview of experience curve results; the error intervals represent regression errors only (we include here only experience curve results with a coefficient of determination larger than 0.7)[46]

By relating COP, luminous efficacy, as well as energy and water consumption to cumulative production, we identify a general trend towards increased efficiencies of heat pumps, CFLs, and household appliances. We identify the COP of heat pumps to increase at a learning rate of (13.8 ± 1.8)%. The relatively low coefficient of determination ($R^2 = 0.58$) indicates, however, that the applicability of the experience curve approach to model energy efficiency of heat pumps is subject to uncertainties. Combining the cost and COP experience curves, we construct an experience curve for costs per kWh heat produced. We find an average learning rate of (25.7 ± 0.7)%. This finding indicates a considerable drop in consumer costs for heat pumps per unit of heat produced. A comparison of the costs of roughly (0.14 ± 0.02) EUR/kWh heat in 2007 with the consumer costs of condensing gas boilers (0.08 EUR/kWh) shows, however, that heat pumps are not yet cost competitive in the Netherlands.

In the case of CFLs, the identified trend for efficacy increases (1.6 ± 1.3)% is statistically weak ($R^2 = 0.13$). Industry experts argue that CFL efficacies do not follow an experience curve pattern because rather than improving CFL efficacies, producers aim at adapting light chromaticity to match the light emitted by CFLs as closely as possible to the warm-coloured light of incandescent light bulbs. Improving the light quality of CFLs

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[46] Under the label 'additional costs', we include here the results of our experience curve analysis for the additional costs of condensing gas boilers relative to non-condensing gas boilers and micro-CHP systems relative to condensing gas boilers.

is generally regarded as being of paramount importance for obtaining higher market shares *despite* the fact that this strategy reduces bulb efficacies. In CFLs, we find hence a clear case for which further improvements in energy efficiency (i.e., bulb efficacy) are not regarded as crucial for the market success of a product. We therefore argue that the experience curve approach is *unsuitable* to analyze and project efficacy dynamics of CFLs.

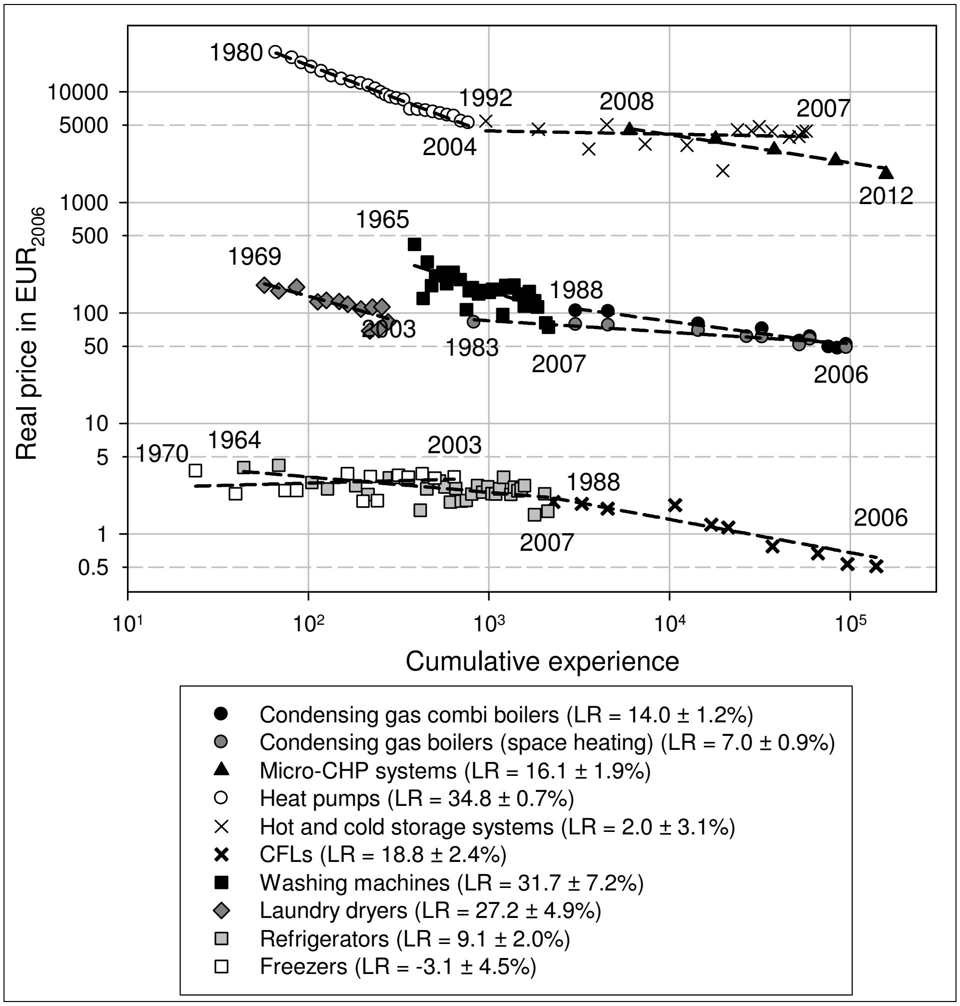

Figure 119: Overview of cost experience curves for selected technologies (numbers in the diagram indicate the time period of analysis; cumulative experience is equivalent to the sales and production data used for the experience curve analyses in the individual technology chapters)

Disaggregating the experience curves for energy and water consumption, we find:

- convergence of energy and water consumption in washing machines, i.e., we find that energy and water consumption in inefficient washing machines decreases considerably faster than in efficient ones;
- indication that the learning rates for energy and water consumption in washing machines change depending on the time period analyzed;

- indication that policy measures (i.e., the introduction of the energy label for household appliances) can actively bend down the slope of the energy experience curve (e.g., for washing machines) (see also discussion in Chapter 5.1);
- indication that chest freezers are significantly more efficient than upright freezers.

Applying the experience curve approach to novel energy demand technologies reveals insight into the cost and efficiency dynamics of these technologies. For effective policy guidance, it is however important to analyze both the novel technology but also the conventional reference technology. Only such comparative analysis allows evaluating the actual cost and efficiency potentials provided by novel and supposedly more efficient technologies.

5.3 Relevance of results for energy and environmental policy

After discussing methodological issues and presenting an overview of results of our experience curve analyses, we discuss in the final section of this chapter the potential policy relevance of our research. Based on the outcome of our analyses, we draw the following conclusions for policy makers:

1. The experience curve approach is generally applicable and can be a useful tool for analyzing past and future cost dynamics of many energy demand technologies.

The experience curve approach allows quantifying historic cost reductions and future cost reduction potentials for energy demand technologies. The experience curve approach allows estimating the additional costs up to the economic breakeven and can therefore provide a rationale for establishing subsidy schemes. The experience curve, furthermore, may assist the identification of potential over-support of technologies (see Junginger et al., 2008) thereby contributing to re-evaluation of governmental subsidy policies.

2. The experience curve approach is especially applicable for technologies, which remain homogenous with regard to technical components and provided services and for which costs are independent from exogenous, non-technology-related factors.

Modular energy *supply* technologies are generally more suitable for experience curve analyses than energy *demand* technologies; individual materials and technology modules (e.g., lamp ballasts for CFLs) are more suitable than complex, multi-component technologies. Technologies such as hot and cold storage, for which installation costs are to a large extent determined by exogenous, non-technology-related factors (e.g., geological underground conditions) are generally unsuitable for experience curve analyses unless detailed and highly disaggregated data are available.

3. Data quality and availability is a constant issue for experience curve analyses.

For policy makers, it is important to obtain a good understanding of quality, reliability, and system boundaries of data that have been used for experience curve analyses. Our results for, e.g., heat pumps and hot and cold storage systems indicate that changes in the system boundary of the analysis (e.g., national or European production data, changes in the physical unit of the independent variable on the x-axis) can have a considerable effect on the results of experience curve analyses. The approximation of production costs by market prices causes further uncertainty. A major point of uncertainty is related to possible fluctuations in the price of production factors (e.g., price of labour, raw materials, energy, and capital). These fluctuations can have a considerable impact on production costs and become increasingly important for mature products, for which learning effects (i.e., reduction of the quantity of production factors used in the manufacturing process) are marginal.

4. Our analysis confirms a general trend towards declining production costs for energy demand technologies. Based on the identified learning rates, we conclude that assuming learning rates of 10-20% for energy demand technologies seems to be reasonable for cost forecasting and modelling of future energy use and CO_2 emissions.

Our findings indicate that the rate of cost decline for energy demand technologies is comparable to many (renewable) energy supply technologies. For example, we regard the projected learning rates of 16% for micro-CHP systems to be reasonable. It is, however, very important to note that already small deviations in the projected learning rates (i.e., in the range of 1-2%) have considerable effects on long-term cost/price projections. This result is especially important for estimating subsidy requirements, which are hence attached with considerable uncertainties.

For effective policy guidance, it is important to analyze both the novel technology but also the conventional reference technology. Only such comparative analysis allows evaluating the actual cost and efficiency potentials of the novel and supposedly more efficient technology.

5. Our research confirms that economies of scale, increased specialization, automation of production processes, and the outsourcing of production to low wage regions are the main drivers for cost reductions in the manufacturing of energy demand technologies.

It is only to a very limited extent possible to determine the contribution of the individual factors mentioned above to the observed overall cost savings that are realized during the manufacturing of a product or technology. Such analysis would require far more disaggregated cost data that are generally not available due to confidentiality reasons. Cost reductions that have been realized by production shifts to low wage countries or declining energy or material prices are generally exogenous from the learning system. Such cost reductions can, in general, not be maintained continuously during the manufacturing of a product and have to be regarded as singular and often stochastic events that introduce considerable uncertainty into experience curve analysis.

6. The extension of the conventional experience curve approach for modelling COP dynamics of heat pumps, luminous efficacy of CFLs, and energy and water consumption of appliances is useful and reveals new insight into the dynamics of energy (and water) efficiency of household appliances.

We find a general trend towards increasing efficiencies of heat pumps, CFLs, and household appliances. The experience curve analysis is suitable to model COP dynamics of heat pumps because energy performance has always been an important sales criterion for this technology. The experience curve approach is, however, partly unsuitable to model and project luminous efficacy dynamics of CFLs because further improvements of already relatively high bulb efficacies is of minor importance for the market success of CFLs compared to changes of other product characteristics. CFL producers, for example, regard it more important to improve light quality rather than efficacy of CFLs. They therefore accept lower efficacies in order to generate a more warm-coloured light to match consumer preferences and thereby increasing CFL sales (Philips, 2007).

The energy and water experience curve analyses for household appliances indicate that the European energy labelling program temporarily accelerated the rate at which the energy efficiency of washing machines and refrigerators improved. Our findings indicate that policies may be able to actively bend down the slope of *efficiency* experience curves (i.e., accelerate the rate of energy efficiency improvements with each doubling of cumulative production compared to the autonomous trend), a phenomenon, which has so far not been observed for *cost* experience curves.

We regard this newly and innovative approach useful for evaluating the effectiveness of governmental policies that address the improvement of energy efficiency. We recommend its application also to other energy demand and supply technologies.

7. Policies supporting novel and efficient energy demand technologies might need a long breath.

The example of condensing gas boilers in the Netherlands, but also that of heat pumps and CFLs shows that novel and efficient technologies gained market shares relatively slowly in the past; i.e., the time periods required for achieving market break through are often 10 too even more than 20 years. The major obstacle for rapid market diffusion is often the high price of technologies, which requires additional investments from consumers. These consumer investments are often associated with uncertain prospects about whether the extra costs can be recovered through energy savings along the product life cycle. Both market perspectives of novel and efficient energy demand technologies and the cost effectiveness of governmental subsidy programs improve, if energy prices are high. Cost effectiveness of energy efficient demand technologies is however not a guarantee for the market success of a product. Potential cost savings have to be compared with other non-cost related consumer benefits of energy demand technologies as well as the potential revenue generated by other consumer investment alternatives. Price constraints (but also other market barriers such as consumer awareness, compliance with legal and technical requirements) have to be taken into account when evaluating, for example, the market potential of micro-CHP systems in the Netherlands.

In view of historic experience, we regard the projected market diffusion rates for micro-CHP systems as overoptimistic. Uncertainties related to technology specific learning rates as well as future dynamics of energy prices cause any estimates on governmental subsidy requirements to be highly uncertain.

8. Efficient energy demand technologies can save energy and CO_2 emissions in a very cost effective way.

Our cost calculations for condensing gas boilers and CFLs indicate that improving energy efficiency is very cost effective. This finding has two important implications: (i) improving energy efficiency and supporting innovative energy demand technologies should receive more attention, especially in view of the support given for relatively expensive renewable energy technologies and (ii) intelligent and tailor-made support programs individually for each product or product group have to be initiated to circumvent high initial consumer investment costs. To that end, leasing programs with utility companies or retailers might be successful alternatives to conventional product sales policies. Such programs might be especially useful to resolve existing landlord-tenant dilemmas, which remain an important barrier to energy efficiency improvements in the residential sector.

9. The subsidies spent in support of condensing gas boilers enabled major cost savings at the consumer side and provided incentives for product innovation in the Netherlands.

The example of condensing gas boilers shows how product innovation can successfully improve energy efficiency, thereby contributing to a decrease in consumer costs as well as in overall energy consumption and CO_2 emissions in the Dutch residential sector. Limited subsidies of roughly 70 million EUR contributed to product innovation, made the Netherlands technology leader in boiler manufacturing, and strengthened the position of Dutch boiler producers on a competitive European boiler market. While it cannot be stated that this Dutch policy support was the single determining factor enabling the break-through of condensing gas boilers, it did probably contribute considerably to the success of this technology.

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

Considerable governmental budgets are spent to support the diffusion of efficient energy demand technologies. It is however often unclear to policy makers, to what extent this support will lead to cost reductions. The achievable cost reductions depend to a large extent (i) on the already existing accumulated experience, i.e., mainly global sales or production and (ii) on the additional production that will be generated through policy support. Since the Netherlands is a small country, the influence of national policy measures on the experience curves for global technologies might be limited. On the other hand, the example of condensing gas boilers has shown that national policy support can generate first-mover advantages by opening up markets for new and innovative technologies. There could hence be different rationales for a small country to support certain technologies. The aim of contributing to technology development and rapid cost reductions can probably only be achieved, if technologies are supported for which one or few pilot projects already mean a substantial increase of cumulative production. Early mover countries that build up a domestic market and that support their industry in developing export markets can gain a considerable competitive advantage within a certain technology area, if they continue policy support over a considerable time period. An example for such a technology would be micro-CHP systems. Dutch subsidies for micro-CHP systems can have a considerable effect on the reduction of production costs because worldwide sales are so far negligible. Market diffusion in the Netherlands can, therefore, quickly generate several doublings of cumulative production.

If the market for a certain technology is already substantial, 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 and R&D will be in general best positioned at the market of novel and innovative technologies. Economic analyses of broader scope (e.g., incorporating also the government's perspective) should, however, also account for secondary effects such as lost tax revenues (in the case of energy savings), employment opportunities, or potentials for private domestic and foreign investments.

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