Technical and economic characterization of selected energy technologies

Contributions to the EU SAPIENTIA project

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Acknowledgement/Preface

This report gives the final outcome of the research performed under task 1.1, 1.3 and 1.5 of the SAPIENTIA project. This task was carried out by ECN and IER and with contributions from IIASA and IEPE. This project has been carried out as part of contract No ENK6-CT-2002-00615 within the 5^{th} Framework Programme of the European Commission and with support from the Dutch Ministry of Economic Affairs (ECN project nr 7.7492).

Abstract

This document provides the background for exploration of the impact of a two factor learning curve (learning by doing and learning by searching) for specific technologies and technology components. A clustering approach is used, where technology spill over can be analysed. The research covered the characterisation of technologies outside the power sector; applying and extending the methodology of the precursory SAPIENT project. The wide variety of technology deployment, the lack of data and of data accessibility however proves to be a remaining barrier for a complete analysis and for a full assessment of the impact of two factor learning for non power technologies.

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Summary

The SAPIENTIA project is a follow-up of the SAPIENT project with the aim to explore the impact of a two factor learning curve (learning by doing and learning by searching) for specific technologies and technology components. These components form technology clusters in which technology spill over, both intra-sectoral as cross sectoral, can occur. By means of a two factor learning curve a distinction is made between the deployment and R&D efforts as driving forces behind cost reductions of technologies.

The presented report gives an overview of the results of the research performed. The research covered the characterisation of technologies outside the power sector; power sector technologies were largely covered by the SAPIENT project. Unlike the power sector, which is characterised by a relatively homogeneous technology description, the non-power sectors, seen their inherent less homogenous technology representation, are less suited for technology spill-over. This does not mean that technology learning can not occur in these sectors,. It does appear but on a different level and with less spill-over compared to the key components in the power sector.

For a number of selected technologies, capacity and cost development is analysed, and where possible the R&D expenditure development is determined. Unlike R&D expenditures in the power sector, detailed data on R&D expenditures for all non-power technologies proved to be scarce, incomplete and when existing, these data are mostly confidential. This made this task within the project, although conceived to be ambitious but achievable at the time of the design of the project, a real challenge and hard to fulfil. Nevertheless from the scattered and incomplete data gathered, sufficient material can be deducted to formulate a two factor learning approach. This two factor learning is reported upon by NTUA in the same SAPIENTIA project. The wide variety of technology deployment, the lack of data and of data accessibility however proves to be a remaining barrier for a complete analysis and for a full assessment of the impact of two factor learning for non power technologies.

1. Introduction

This report describes the outcome of the tasks of WP1 of the SAPIENTIA project assigned to deal with the characterisation of technologies outside the power sector (T1.1, T1.3 and T1.5). Technologies in the power sector were largely covered by the SAPIENT project. Unlike the power sector, which is characterised by a relatively homogeneous technology description, the non-power sectors, seen their inherent less homogenous technology representation, are less suited for technology spill-over. This does however not mean that technology learning cannot occur in these sectors, it does appear but on a different level and with less spillover compared to the key components in the power sector.

Within this work package an extensive inventory of non-power technologies with good prospects for improvement has been compiled. Technological data was collected by joint efforts from IER, IIASA and ECN. The R&D data were not as available as foreseen at the moment of design of the project. The non-power sectors prove to be less transparent concerning these R&D data compared to the power sector for which IEA collects all relevant data. The effort in performing and finishing this task, especially on the R&D data side, caused considerable delay in timing for the rest of the project.

From an initial long list, very soon a selection of technologies based on the data availability and their opportunity for the project had to be made. The focus remained on non-power technologies with a prospective wide area of application. The list was changed and reduced furthermore through the duration of the project, at some points suggestions to include new options were also made but since the difficulties in finishing the work on the existing list of technologies, it was jointly among all partners decided to focus on the agreed list.

This report describes in detail the results of the extensive research concerning the short listed technologies. Chapters 2 till 5 deal with end-use technologies in transport and in building environments (stationary fuel cells, heat pumps, condensing boilers); Chapter 6 deals with a novel technology, the organic rankine cycle (ORC); Chapter 7 treats CO_2 capture and storage (CCS) and finally Chapters 8 and 9 deal with liquefied natural gas (LNG) liquefaction and electrolysis as mean for hydrogen (H_2) production.

Finally, in Chapter 10, an overview of the R&D methodology developed within this project for a number of specific technologies from the POLES database is given. These technologies focus on the hydrogen energy chain, production and use. Automotive technologies are chosen as example for the R&D database. Also the methodology to set up an R&D time series from scarce and incomplete data is explained.

2. Automotive technologies

The transport sector is a major contributor to the emission of greenhouse gasses (GHG). Thus, when extending the analysis of GHG reduction schemes to sectors other than the power sector, the transport sector is a prime candidate, in particular passenger transport. This holds even more if one considers the development of fuel cell technologies, and especially the spill over between applications of fuel cell technologies in the power sector and other sectors. Fuel cells are expected to play a substantial role in future developments in the transport sector, and the opportunities for such technologies are conditional on the development of competing technologies. Hence, it is imperative that one treats these competing technologies consistently.

The automotive industry is strongly centralised. Thus, efforts towards technological advances are concentrated in a few large companies, if not in actual work then at least financially. This simplifies the data collection, as one need only focus on a small number of firms. On the other hand, because the automotive industry acts in a highly competitive market, data is valuable. Many consulting companies aim at serving interested parties with specific data. What's more, economical data is specifically *not* considered to be a public good, so whenever time series on this type of data is required, one can either purchase existing data sets, or go through the painstaking exercise of collecting the data anew. In the SAPIENTIA project, the first option was ruled out because of the huge expenses involved, amounting to a multitude of the overall budget. Therefore, we tried the second option.

2.1 Technologies

The technologies under consideration are the Otto engine (internal combustion engine, or ICE, running on gasoline), the Diesel engine (ICE running on diesel), the electric engine using batteries and a fuel cell engine. Mixes between these may also be eligible for inclusion, but these will be considered as explicit hybrids. Of these options, only the Otto and Diesel engines can be considered as commercial options. The phases of the other two options can be described as demonstration (electric) and pilot (fuel cell), respectively.

2.1.1 Internal combustion engine

In automobiles, the most commonly applied concept of internal combustion engines is the four stroke engine (Wikepedia, 2004). In such an engine, a mixture of fuel and air is drawn into a cylinder through a first (downward) stroke of a piston. Next, the intake valve is closed, and the ensuing (upward) stroke compressed the fuel-air mixture. The mixture is ignited at (approximately) the top of the upward stroke, and the resulting expansion of burning gasses forced the piston down in a third stroke. In a final fourth stroke, the spent exhaust gas is exhausted through the then opened exhaust valve. The four-stroke process is illustrated in Figure 2.1.

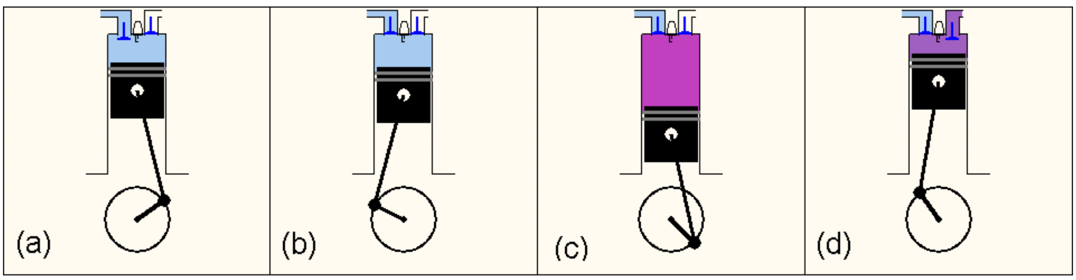

Figure 2.1 *Cycle of a four-stroke engine*
(a) intake of fuel and air, (b) compression of combustible mixture, (c) expansion after combustion, and (d) exhaust
Source: (Moros, 1998)

The development of the Otto engine has been a gradual one ever since it became the dominant ICE type used in the automotive industry. At the same time, the diesel engine has developed in parallel to the development of the Otto engine. While the Diesel engine served mainly as a heavy-duty engine until the nineteen-seventies, from then on the market share of diesels started to increase world-wide, mainly as a result of the oil crises. In the United States this increase has been interrupted as the impact of the oil crisis slowly faded away. In contrast, the penetration of the diesel engine in Europe has seen extended growth, due to tax support schemes. This is illustrated in the figure below. In Japan, the diesel engine so far has not had a major share in personal transport. Thus, while the Otto engine remains the predominant engine type in the world as a whole, increased scarcity of fossil fuels in combination with an inherent higher efficiency of the Diesel engine may shift the balance in the years to come.

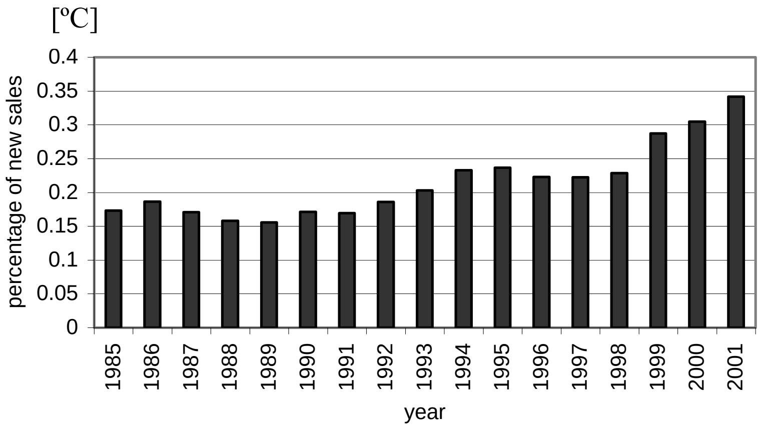

Figure 2.2 *Diesel penetration in Europe measured by percentage of new sales.*
Source: Odyssee

Over the more than hundred years of its existence, the ICE in general has developed from a simple mechanical device to a complicated electronic system (Atzler, 2001). This development has led to considerable improvements in performance (Feirrera, 1998; Odyssee, 2004). However, as the rest of the automobile has also seen extensive changes, the improved performance has neither led to improved efficiencies (particularly in the previous ten years), nor to a decrease of costs for the car as a whole (in constant prices). Nevertheless, the improvement in cars, such as increased average power output of the engine, should actually be considered as implicit price decreases. In Figure 2.3 the development of average power in European new car sales is shown.

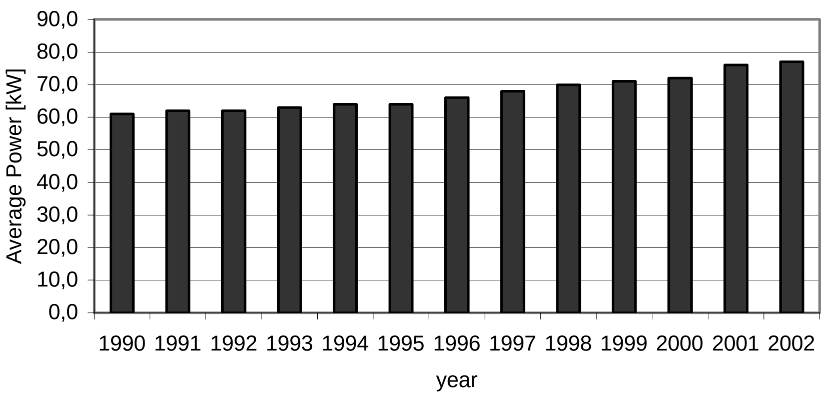

Figure 2.3 *Average power of new passenger car registrations in Western Europe (EU+EFTA).*
Source: ACEA

2.2 Cost development for passenger cars

As mentioned above, the price of a passenger car has hardly seen improvements, measured on an absolute scale. This shown in Figure 2.4, where the cost development in the past decade for the average price of a new car is given, calculated as the turnover of the largest car companies divided by their sales. This shows a roughly constant value, of approximately € 21,500 per car.

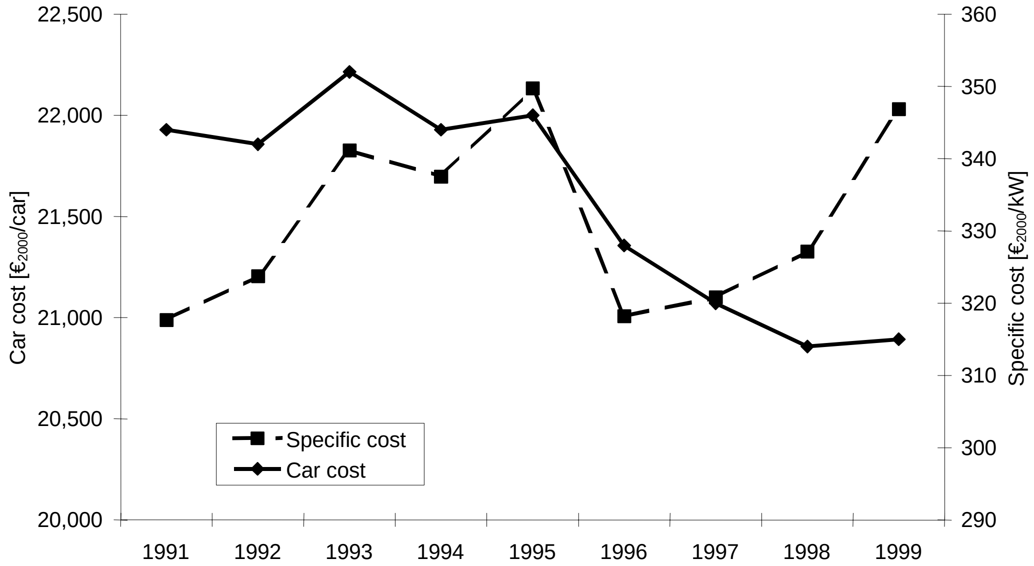

Figure 2.4 *Passenger car cost, per car and per kW of engine output*

That the average price of a car would be the proper measure to assess future cost reduction potential is highly questionable, though. This is illustrated by second series shown in Figure 2.4, giving the average cost of new sales per kW. Here, a clear cost reduction can be seen, from some 350 €/kW to a little over 310 €/kW. The use of engine output power is used as a proxy for the capacity of the car, and the costs per kW are seen as specific costs of a car. Then, the trends in specific costs in principle can be analysed by comparing these to cumulative capacities[1].

Table 2.1 *Parameters used in estimation of cumulative capacities and specific costs, global number summing or averaging over all types of cars*

Parameter	Unit	Start	1991	1992	1993	1994	1995	1996	1997	1998	1999
Cumulative # cars	[mln cars]	430	441	452	463	474	485	496	508	521	534
Cost per car	[€2000/car]		20988	21205	21827	21697	22133	21007	21100	21327	22031
kW-price	[€2000/kW]		344	342	352	344	346	328	320	314	315
Power/car	[kW]	61	62	62	63	64	64	66	68	70	71

[1] Strictly speaking, the specific costs should be fitted to the cumulative installed capacity, which here would translate into sum of the product of number of cars sold per annum times the average engine capacity in that year. Unfortunately, there is insufficient data to do this.

2.3 R&D in automotive technologies

Although other types of engines, and in particular also other types of fuels, have been available for quite some time, the major market share has been taken by the combination of gasoline and diesel cars. In some niche markets, small amounts of alternative fuels have been used (e.g. ethanol in Brazil, and LPG in the Netherlands) but on a world scale these have been negligible. Only in recent years, due to climate change concerns, alternative fuels have received increased attention. This is particularly clear from the R&D expenditures by companies, which can be deduced from the R&D budgets of companies combined with patent data. The patent data are shown in Figure 2.5 (absolute numbers) and Figure 2.6 (indexed numbers).

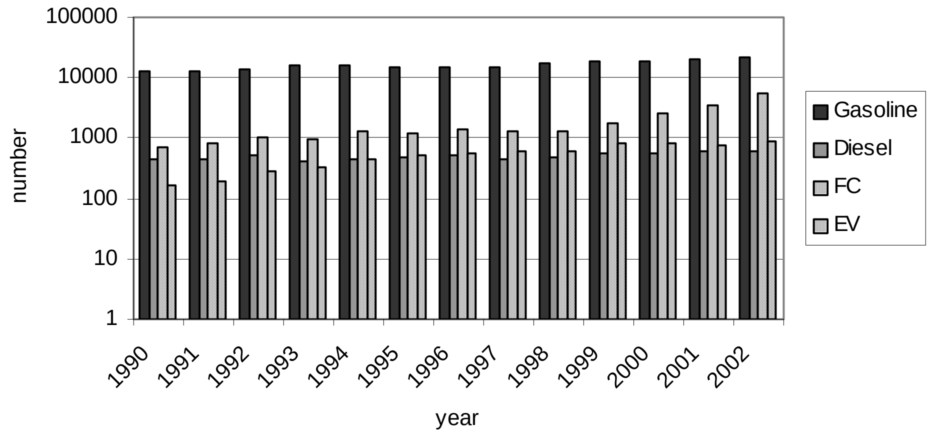

Figure 2.5 *Number of patents for Otto engine (gasoline), diesel engine, Fuel cell and electric vehicle engine. Note the logarithmic scale.*
Source: esp@cenet

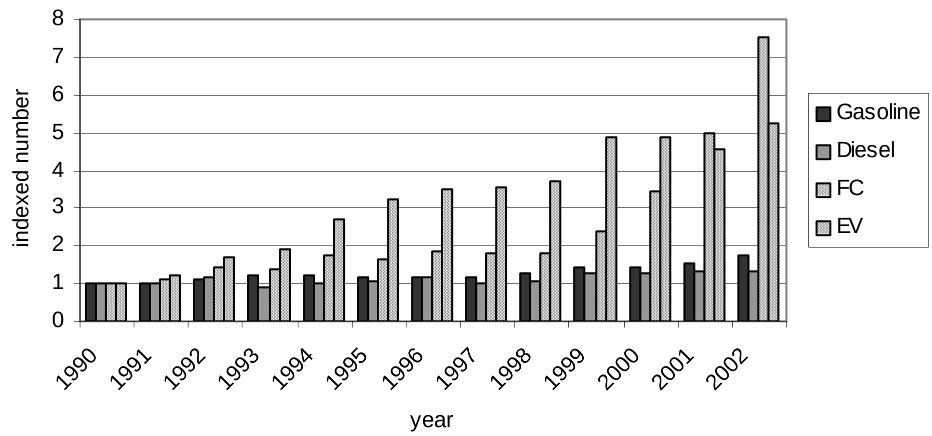

Figure 2.6 *Indexed number of patents for various car types*
1990 = 1
Source: esp@acenet

At present, dedicated electric vehicles are in a prototype stadium (Atlas, 2004; IEA-HEV, 2004). Japanese producers have focussed on the hybrid concept as a successfull means of introducing affordable (partial) electric drive automobiles, and have indeed managed to do so, as the introduction of the Toyota Prius (Toyota, 2004) and Honda Insight and Civic hybrid (Honda, 2004) have shown. Nevertheless, at the present production rate of a few tens of thousands per year world wide, a lot of effort needs to be put into further development of the electric vehicle.

The number of fuel cell cars at present is extremely limited, a total number quoted is around 100 (Atlas, 2004). This is partially due to the high price of fuel cell cars, which are far from commercial. Some car companies lease out fuel cell vehicles, but the lease price is not likely to be representative of the production costs. For example, car cost is quoted to be of the order of 80,000 $ at present (Tsuchiya, Kobayashi, 2002) on the one hand, and a similar price is quoted only in ten years time (IHT, 2002). Introduction of fuel cells on a larger scale will require substantial political interference, in particular as ongoing developments in more conventional options complicate the market position of alternative fuels.

As mentioned above, R&D efforts are ongoing in all of the car types considered. This is reflected in the number of patents shown above, which can be used to disaggregate the R&D expenditures by car companies. The total budget is more or less a constant in the last decade, the estimate ranging between € 33 bln and € 37 bln. Plotted against the annual sales, we find a negative correlation. This is shown in Figure 2.7, where we show the research expenditures by major car manufacturers as a function of their sales. An actual fit would lead to a positive correlation, but the two higher values are clearly outliers.

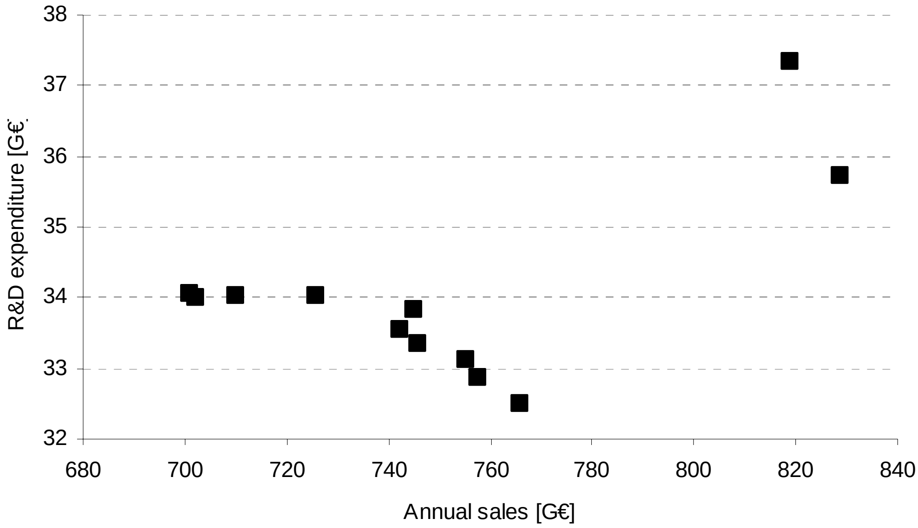

Figure 2.7 *Research expenditure of car manufacturers as a function of annual sales*

The data given in these sections is incorporated in the R&D database, which has been set up as a separate Excel file distributed to the project partners.

As data on the specific commitment of R&D expenditure by companies generally is considered as sensitive information, it is impossible to construct a database containing exact figures. In stead, one can try to deduce the expenditures by using an auxiliary variable (or proxy). In the present study, data on patents is used to disaggregate the R&D expenditures. Although for government spending (GERD) this does not necessarily hold, specific data is sparse, and an auxiliary variable may be used to improve estimates. The combined results of deducing Government R&D and business R&D expenditures are below.

Table 2.2 *Estimated cumulative R&D expenditures by government and business*

Year	Cumulative Government R&D [M€$_{2000}$]				Cumulative Business R&D [M€$_{2000}$]			
	Otto	Diesel	FC	EV	Otto	Diesel	FC	EV
1990					27,594	584	771	339
1991					31,225	648	919	451
1992					35,057	724	1,101	573
1993					39,039	774	1,255	734
1994	1,448	47		600	42,610	830	1,447	917
1995	1,575	50	541	776	45,656	890	1,608	1,104
1996	1,696	55	633	948	48,517	956	1,780	1,281
1997	1,810	58	710	1,112	51,195	1,008	1,933	1,454
1998	1,912	60	788	1,259	54,029	1,063	2,076	1,680
1999	2,015	64	896	1,405	57,133	1,131	2,296	1,886
2000	2,109	67	1,012	1,542	59,955	1,197	2,606	2,064
2001	2,206	70	1,143	1,682	62,868	1,270	3,008	2,264
2002	2,301	72	1,275		66,098	1,339	3,634	2,451

3. Stationary fuel cells

3.1 Market survey

On a global scale, an estimated 650 large stationary fuel cell systems (>10 kW) had been produced and installed by September 2003 (Internet source 1). The average output of these systems is estimated at ~200 kW_e. In the first half of 2002, the number of systems stood at 530 (Internet source 2).

Most of the stationary fuel cell systems installed today are Phosphoric Acid Fuel Cell (PAFC) systems (Internet source 3): around 260 units of the 200 kW_e PC25™ PAFC system of UTC Fuel cells have been installed around the world since the system was launched in the early 1990s. The PAFC working temperature is about 200°C. For PAFC systems, the allowable impurities for CO in the fuel gas are 1%. Further limit values for different kinds of fuel cells are mentioned in Table 3.1.

Table 3.1 *Fuel gas component limits for utilization in fuel cells*

Substance	PAFC[1]	MCFC[2]	SOFC
Sulphur	1 ppm	0,1 ppm	1 ppm
Chlorine	1 ppm	0,1 ppm	1 ppm
Fluorite	n/a	0,01 ppm	n/a
Heavy metals	n/a	0,1 ppm	n/a
Particles		1 µm	n/a
Excess pressure	n/a	≈ 200 mbar	n/a
CO	1%	fuel gas	fuel gas
Mercury	n/a	30-35 ppm	n/a
N_2	4%	nda.	n/a
NH_3	0,2 ppm	1 vol.-%	n/a
CH_3OH	500 ppm	nda	n/a

[1](Weindorf, Bünger, 1997)
[2](mtu, 1999; USDOE, 2000)

The largest PAFC system built was an 11 MW_e system manufactured by Toshiba and UTC Fuel Cells (then known as International Fuel Cells). The cumulative installed capacity of stationary PAFC systems around October 2001 is estimated at approximately 75 MW (Table 1.1).

Table 3.2 *Cumulative installed capacity and size distribution of PAFCs*

		50 kW_e	100 kW_e	200 kW_e	500 kW_e	1 MW_e +	Total
Number		75	23	245	2	5	350
Capacity	[MW]	3.75	2.3	49	1	20	76

Estimate, 2001

Also suitable for stationary applications is the Molten Carbonate Fuel Cell (MCFC, operating temperature 650°C). The smallest MCFC systems are rated at 250 kW_e. During the last few years PAFC technology has been giving way to more prospective stationary fuel cell technologies: MCFC, Proton Exchange Membrane Fuel Cell (PEMFC, working temperature ~100°C), and Solid Oxide Fuel Cell (SOFC, operating temperature ~850°C). In 2003, PAFC systems were outrun by MCFCs as the dominant type of fuel cell (in terms of numbers installed) (Figure 3.1).

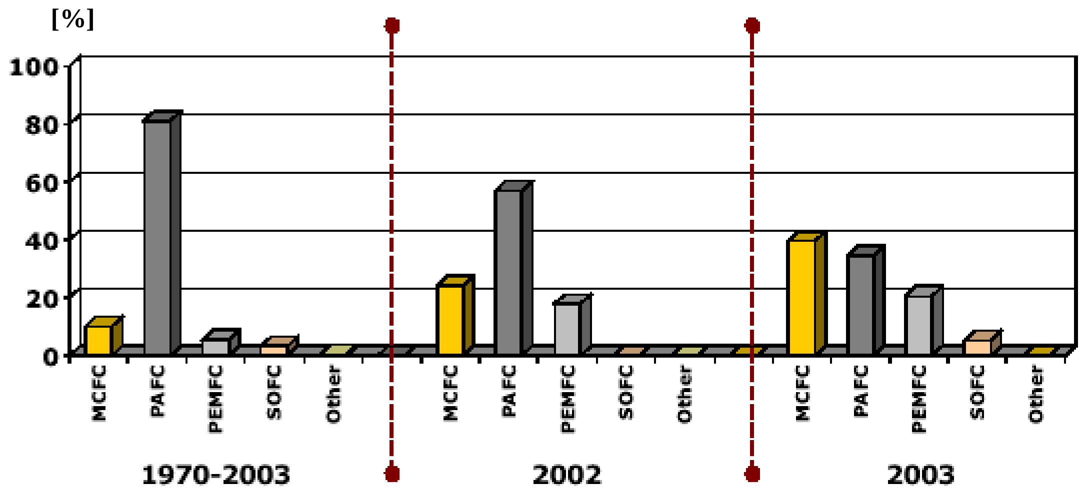

Figure 3.1 *Stationary fuel cells by technology type*

Figure 3.2 gives an indication of the cumulative capacity of (stationary) fuel cell systems installed by the end of 2002 and 2003.

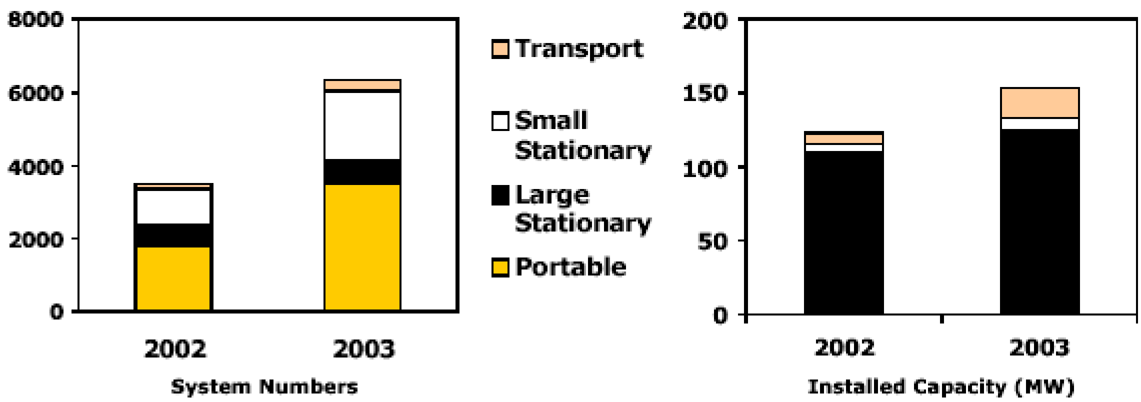

Figure 3.2 *Cumulative number and capacity of fuel cell systems by the end of 2002/2003*

The capacity of large stationary fuel cell systems was about 110 MW_e by the end of 2002. It is estimated that this capacity was approximately 130 MW_e by the end of 2003. Figure 3.3 shows the distribution of fuel cell types among large stationary fuel cell systems by the end of 2001.

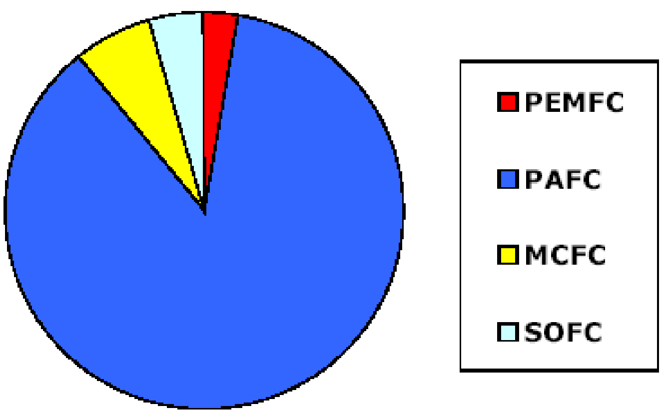

Figure 3.3 *Distribution of technology types among large stationary fuel cell systems*

It turns out that by the end of 2001 the leading technology – by percentage of systems installed – was PAFC (~83%), followed by MCFC (~8%), SOFC (~6%), and finally PEMFC (~3%).

Table 3.3 gives an estimate of the cumulative capacity and the cost of stationary fuel cells.

Table 3.3 *Cumulative capacity and specific investment cost of stationary fuel cells in 2003*

	Number (cumulative)	Capacity (cumulative) [MW_e]	Specific investment cost [€/kW_e]
PAFC	520	104	4,500-7,000
MCFC	70	10	6,000
SOFC	30	6	9,000
PEMFC	30	5	~12,000
Total	650	125	

Data for this table are from sources cited before, (Internet source 4), (Blesl, 2003) and (Manitoba, 2003). General Motors plans to install a 500 unit, 35 MW_e fuel cell power plant at the Freeport industrial complex of Dow Chemical in the USA (The hydrogen & fuel cell letter T, 2003). This power plant will use automotive fuel cell stacks, if the test phase of the project will prove successful. The size of (automotive) PEM fuel cell units is approximately 70 kW_e.

The US Department of Energy (DoE, 2003) has the following view on stationary FCs:

> *Over the last several years, phosphoric acid, tubular SOFC, and MCFC systems > 200 kW have been demonstrated at costs of $4000-12,000 per kW. As further R&D improves cost and reliability, Federal and State governments can team with private industry to share risks and costs of limited prototype tests. Cost reduction and technology improvement managed by partnerships are critical in the current phase of technology development. Only technologies that have the potential to approach an installed cost target of $400/kW would be pursued through further RD&D. This cost target is based on 5 kW modular systems at a production volume of 100,000 units.*

3.2 Learning curve examinations for MCFC and SOFC

Target investment costs for high temperature fuel cell systems in the 200-2000 kW_e range in order to prevail in the market are 1200-1500 €/kW_e. Figure 3.4 and Figure 3.5 give information about the cumulative capacities required to reach investment cost targets for assumed learning rates of MCFCs and SOFCs. Whereas for demonstration plants learning rates are 0,6-0,65, the impact of learning after market entry is expected to shrink. Then for MCFC systems learning rates are assumed to be 0,85 and 0,9 for the USA and Europe respectively. These learning rates require cumulative capacities of 100 GW_e respectively 250 GW_e to reach the cost target.

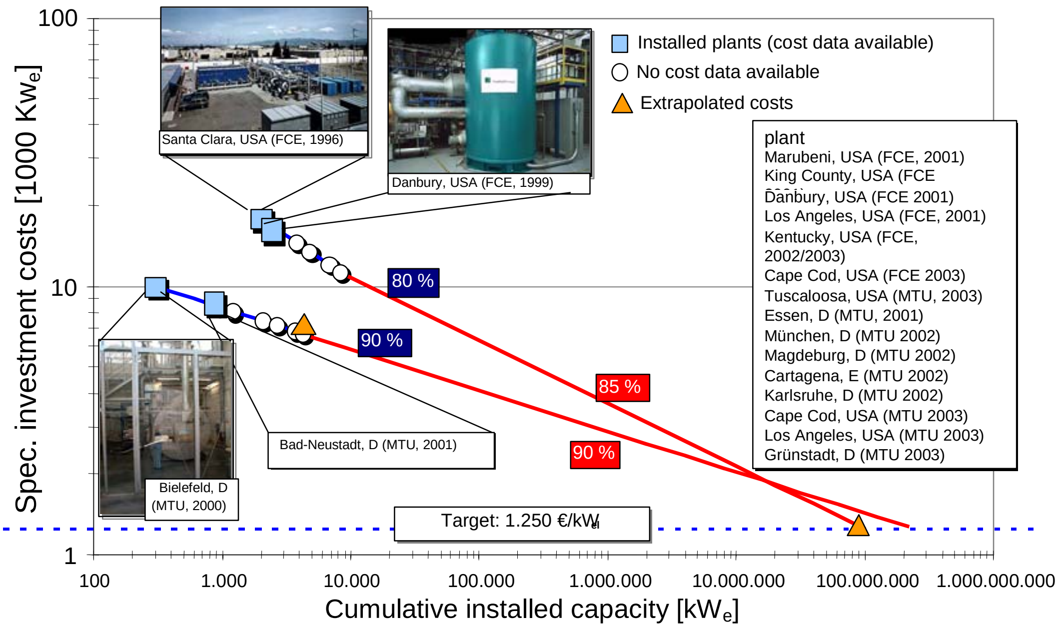

Figure 3.4 *Learning curve for MCFC systems in the USA and in Europe*
Source: Blesl et al., 2004

For SOFC systems a future learning rate of 0.85 was assumed. With this learning rate a cumulative capacity of 35 to 130 GW_e is necessary to meet the target investment costs.

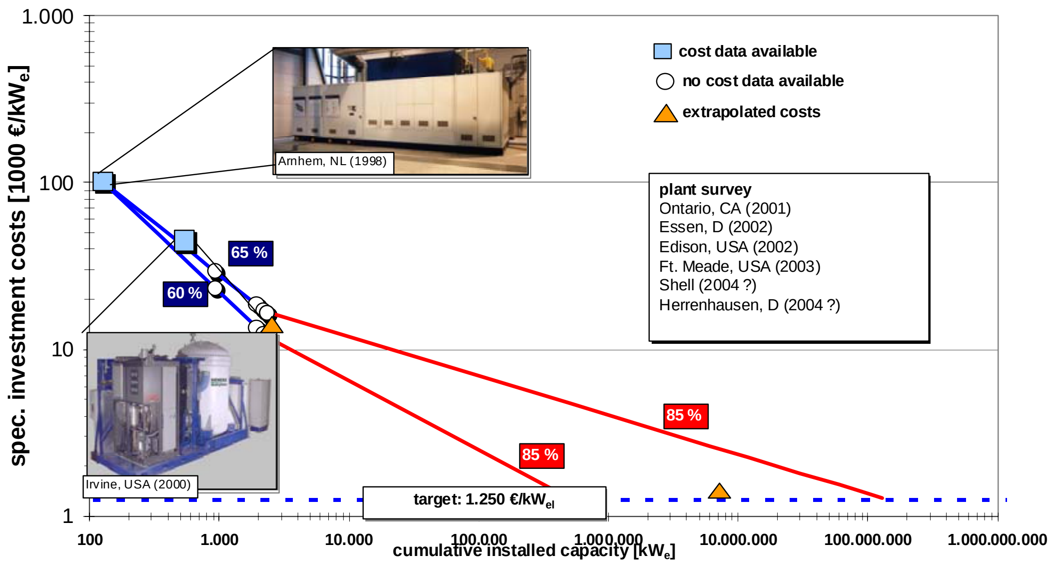

Figure 3.5 *Learning curve for SOFC systems in the USA and in Europe*
Source: Blesl et al., 2004

Anyhow, there may be limitations to the learning curve approach like excessive public subsidizing or the customers´ willingness to accept high prices. Both factors can keep investment costs on a high level despite considerable rises in cumulative production, as seen in the field of wind power generation (Blesl et al., 2004).

Besides the learning effect by growing cumulative capacities, the effects of scale-up are considered. Therefore the MCFC and SOFCs were fractionalised into their components.

As most of the components of high temperature fuel cells, e.g. pumps, heat exchangers, or inverters, have also been applied in other, established technologies, mass production of these parts has already been existing. So the investment costs for conventional application can be taken as bottom-line costs of these components. Only a few components of fuel cells, like the stack, are only used for fuel cell application. For these components no target costs can be derived from any application in other technologies.

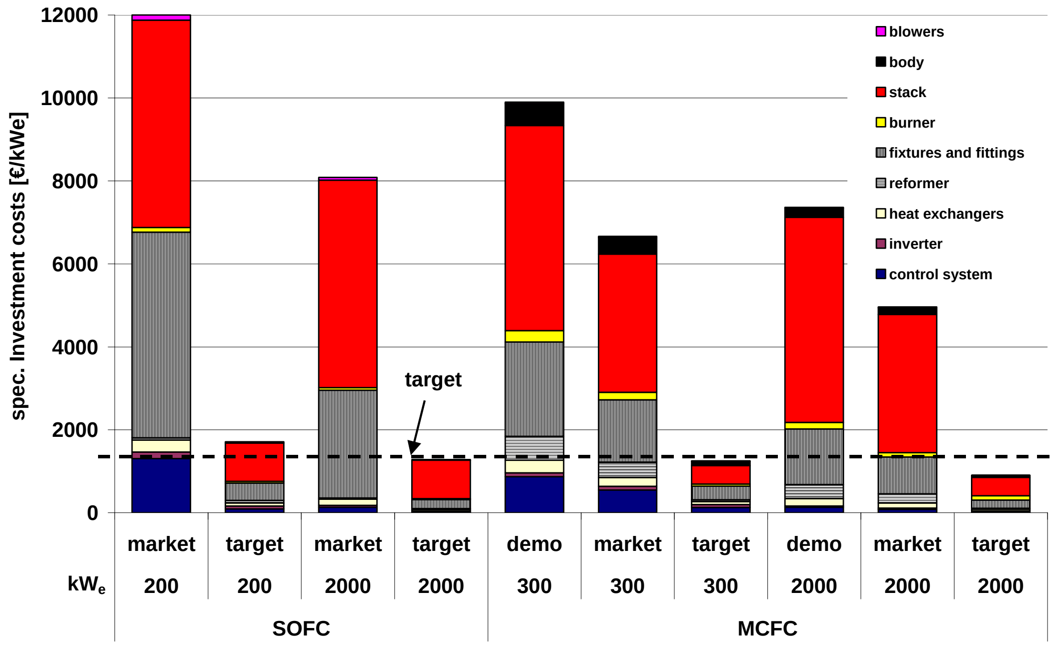

Figure 3.6 *Influence of learning on specific costs of MCFCs and SOFCs*
Source: Blesl et al., 2004

With the overall investment costs of different development stages allocated to the single components for different capacities of high temperature fuel cell systems MCFC and SOFC, IER (Blesl, 2003) presents specific cost targets in the range of 962-1712 €/kW$_e$ (Figure 3.6).

It turns out that for some plant capacities, esp. the smaller ones, target costs can not be reached without further progress in the process scheme. So, for example, the reformation unit might be replaced by producing the hydrogen inside the MEA.

3.3 Public R&D expenditures

Figure 3.7 presents an overview of public R&D expenditures on fuel cells in world regions (The Clean Fuels and Electric Vehicles Report, 2003a).

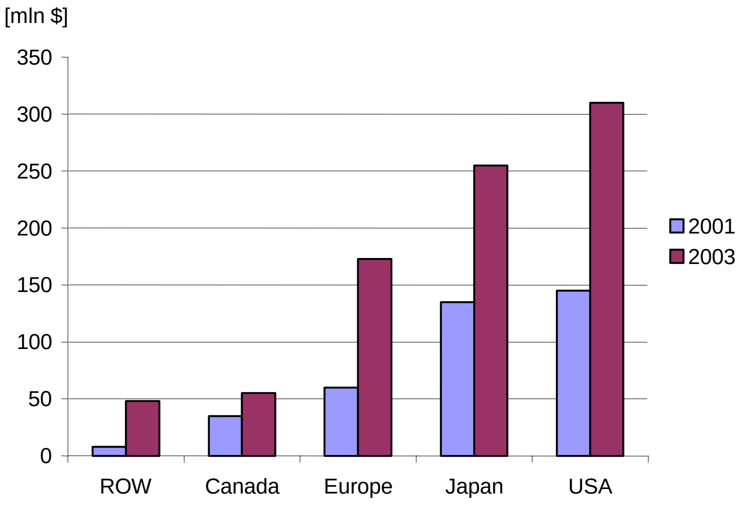

Figure 3.7 *Public R&D expenditures on fuel cells*
Sources: The Clean Fuels and Electric Vehicles Report, 2003a; Http://www.fuelcelltoday.com.

For the U.S. detailed data is available for the years 1996-2002, with a distinction between public and private R&D expenditures (Internet source 5) (Figure 3.8 and Figure 3.9).

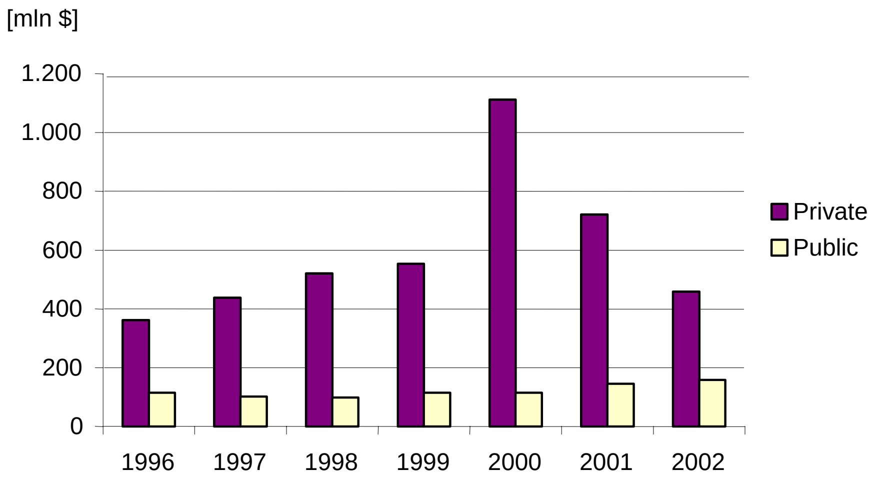

Figure 3.8 *Public and private fuel cell R&D expenditures in the USA*

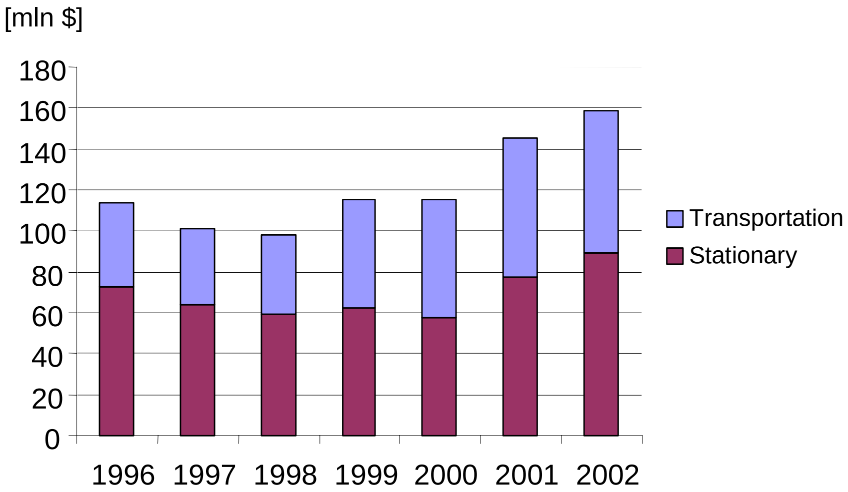

Figure 3.9 *U.S. federal fuel cell R&D expenditures by market*

According to the 'Breakthrough Technologies Institute', federal R&D expenditures on fuel cells rose from $ 114 mln in 1996 to $ 159 mln in 2002. Federal expenditures on stationary fuel cell R&D showed a 'dip', whereas expenditures on transportation fuel cell R&D rose steadily.

Private sector R&D expenditures of in the US were much less stable, and showed a peak of some $ 1.1 bln in 2000 (Figure 3.8). These private R&D expenditures have not been disaggregated into stationary fuel cell R&D and transportation fuel cell R&D. In 2001, Europe's industry invested some $ 120 mln in joint fuel cell R&D programs with governments.

4. Heat pumps

4.1 Introduction

Heating and/or air conditioning of buildings have been the preferred areas of application for heat pumps. Besides those, there is also a number of commercial applications for heat pumps, e.g. heat supply for food processing or for the chemical industry. A very interesting field for the deployment of heat pumps can be drying processes, such as in the paper or textile industries, and the dehydration of sludges. Heat recovered by heat pumps can be used for drying goods; the cooling that is produced simultaneously is capable of separating steam fractions from air or gas flows.

For industrial purposes heat pumps with a thermal range from 200 kW_{th} up to 2 MW_{th} are available; for domestic heating, plants start from as little as single digit kW_{th} capacities. There are two operational modes for heat pump plants: monovalent mode, if the heat pump is the only heat supply in the circulation system, and bivalent mode, if another source of heat is integrated (e.g. an oil-fired boiler). Bivalent mode can optionally be performed with an alternative ('substitute'), parallel ('add-on') or mixed operation of both sources.

Both heat pumps and refrigerating machines are based on the same thermodynamic principle. Heat is absorbed at low levels of pressure and temperature, and mechanical work is added to the system, so that the heat can be delivered at higher levels of pressure and temperature. Thus heat from the environment (ground, air or water) can be utilised, making the primary energy demand decrease (30 to 60%), which can save both costs and CO_2 emissions.

The particular application of the thermodynamic principle determines which term is used to describe the system. If the hot side of the system is utilised, it is called a heat pump; with the cold side utilised, it is called a refrigeration machine. The most common application of a refrigeration machine, of course, is the refrigerator that one can find in almost every European household.

Heat pumps can reach a thermal maximum of 150°C on their heat-output side. They are especially suitable for the climatisation of buildings. Besides providing heat the heat pump then produces cold by cooling water flows that can be used for cooling purposes. Generally, heat pumps consist of four essential components connected to each other by pipes (see Figure 4.1): Vapouriser, compressor, condenser and expansion valve. A liquid working fluid (refrigerant) with a very low boiling point runs through this system. Common refrigerants are, since the prohibition of the CFCs, ammonia, fluorocarbons, carbon dioxide and various types of hydrocarbons, e.g. propane, propene or pentane.

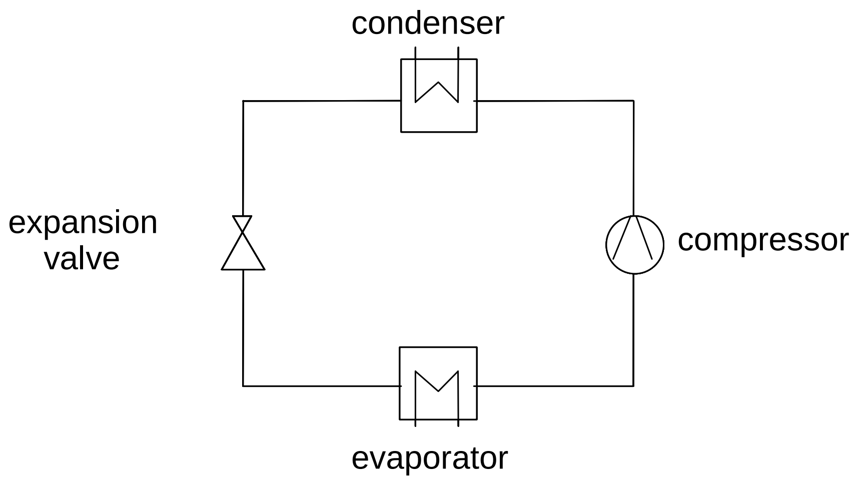

Figure 4.1 *Major components of a heat pump*

In the vapouriser the refrigerant absorbs heat from the environment to evaporate. The vapour runs into the compressor, where both pressure and temperature are raised by adding mechanical energy. In the condenser the vapour is condensed completely, releasing all the heat absorbed for further utilisation, e.g. for heating purposes.

Besides the sources and sinks of heat, the method of refrigerant compression is also variable. Smaller plants usually have electric or, from 100 kW_{th} on, gas engine compressors. These plants are called compression heat pumps. Larger plants on industrial scales are able to apply waste heat flows for a thermal compression of the refrigerant. These plants are called absorption heat pumps. Thereby refrigerant vapour is blended with water, condensed and further heated by the waste heat flow (maximum temperature 180°C), with pressure continually rising. The lower boiling point of the refrigerant enables the water fraction to separate from the blend. By cooling down water and refrigerant flows, the entire heat absorbed can be utilised. By analogy there are absorption and compression refrigerating machines.

The quality of a heat pump plant can be expressed by several ratios. The coefficient of performance (COP or ε) is defined as the ratio of the overall output of useful heat and input power of an electric powered compressor. The COP is an indicator for the efficiency of a heat pump process.

Similarly the primary energy ratio (PER or ζ) is the quotient of the overall output of useful heat and input power of the fuel. The PER gives information about current fuel efficiency in combustion engine and absorption heat pumps. Gas engine heat pumps can reach primary energy ratios between 1.5 and 3, whereas electric heat pumps for domestic heating have values between 3 and 4, due to the generally lower temperature level of their heat demand (Blesl, 2002; Leven et al., 2001).

According to both ratios, it is necessary for the heat source to have a rather high temperature level, and for the return to have the lowest temperature level possible, in order to reach maximum efficiency.

The seasonal performance factor (SPF or β), which is the quotient of overall output of useful heat and overall input energy, is the basis of the long-term economics of the plant, generally calculated as the annual performance factor. Heat pumps connected to plate heat exchangers have annual performance factors of some 3.8; if connected to floor heating systems the number is about 4.3, due to their temperature level being 20 K lower. Large plants with small temperature differences can peak at annual performance factors of some 7.2 (Bertuleit, 2000). Because the heat taken from the environment is only contained in the numerator, yet not in the denominator, it is possible for all three ratios to have values higher than 100%.

A new opportunity for a rational use of energy arises from the combination of a compression heat pump and combined heat and power unit (CHP). Hence the constant power-heat-ratio of the CHP can be varied and an independent energy supply system providing electricity, heat and cooling can be realised.

The idea of using environmental heat is not quite new: the concept of using the ground as the heat sink for a geothermal or ground-source heat pump dates back to the 1940’s (Sanner, 2001). The first ground-source heat pump in the U.S. was installed in a house in Indianapolis in 1945. (Rawlings, 1999). During the last 30 years heat pumps have made considerable progress, also in terms of energy efficiency. So COPs of small residential heat pumps soared from 1,5 in 1973 to 3,24 in 2000. For 2004 COPs larger than 5 were predicted. The development of heat pump energy efficiency is shown in Figure 4.2.

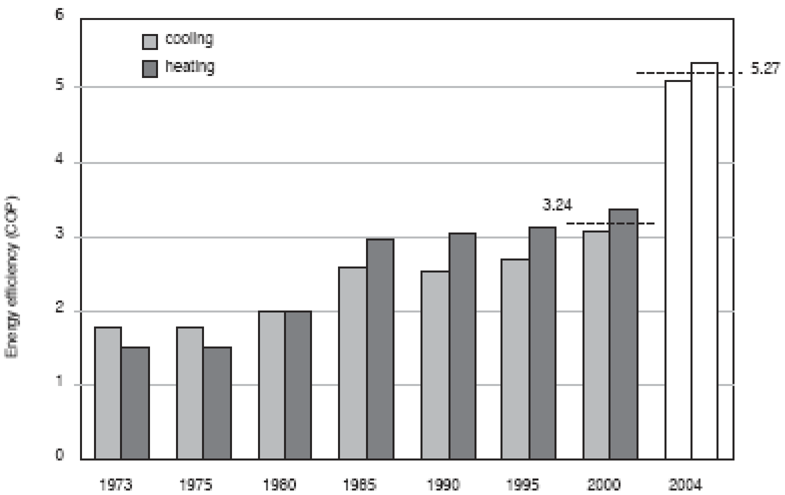

Figure 4.2 *Trend of energy efficiency for residential heat pumps up to 2,5 kW$_{th}$*
Source: IEA Heat Pump Centre Newsletter, vol. 21, 1/2003

Current research topics in the heat pump area concern the use of natural refrigerants, smart control systems, and cost reduction. Also on the agenda are items like extended maintenance rates, advanced flue gas cleaning and optimised components.

4.2 Market survey for selected countries

The following chapter describes the development of international heat pump markets during the last 25 years. Emphasis is put on countries in Western Europe plus Japan. Besides, there will be a glance at the North American and the upcoming Chinese market. For markets with sufficient data available, learning curves were constructed.

4.2.1 Austria

In Austria, the first heat pump systems installed in the early 1980's were either monovalent systems with groundwater as heat source and a low-temperature heat distribution system (floor heating) or bivalent systems with outside air as heat source and a high-temperature heat distribution system using radiators. Monovalent systems were installed in new buildings; bivalent systems were mainly used for retrofitting existing heating systems (Halozan, 2003). In the early 1980's, oil was the main fuel for space heating in the residential area. The price ratio of electricity to heating oil per unit of energy delivered was roughly 2.5. In order to stimulate the introduction of heat pumps, the government provided subsidies in the form of tax deductions. The result was not only a rapid rise and peak in the number of units sold and installed, but also in the number of heat pump system failures. The integration of the heat pump in the heat distribution system of the building proved to be the cause of most failures.

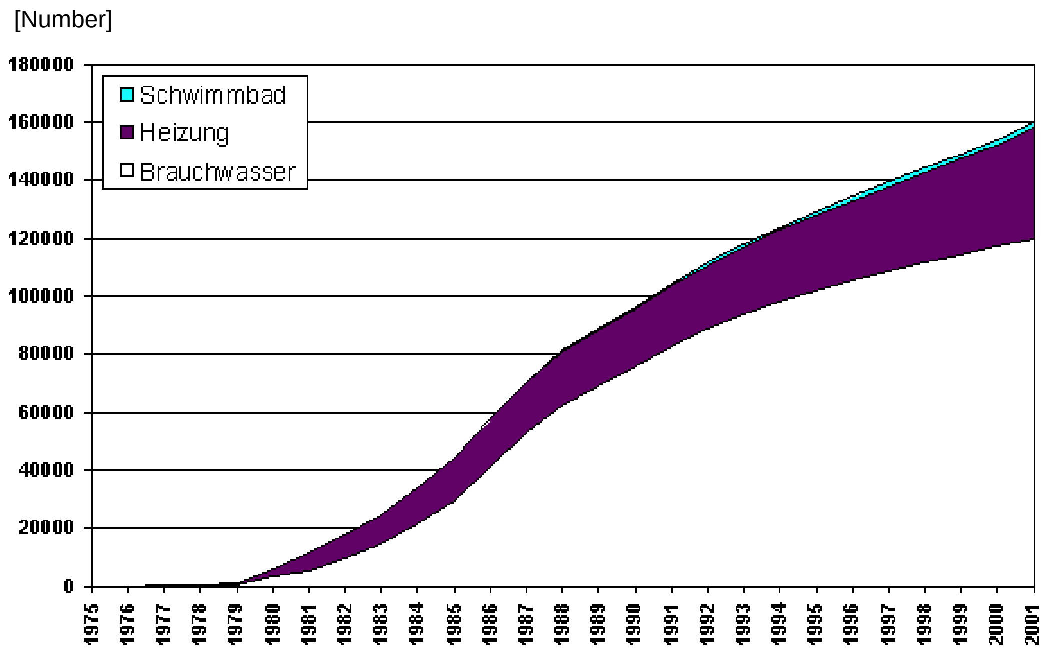

Figure 4.3 *Cumulative sales of heat pump units in Austria 1975-2001*

By the end of 2001, nearly 160,000 heat pumps (for space heating, warm water supply, swimming pools) were in operation in Austria, about 77% of which for hot water, and the balance for space heating. In 2001, the capacity of heat pumps (space heating, hot water, etc.) amounted to 834 MW_{th}, and the annual heat production was nearly 2,000 GWh_{th} (Internet source 9).

Figure 4.4 shows the development of heating-only heat pumps. (Halozan, 2003; Bach, 2003) After a steep reduction in numbers of heat pumps installed in 1982, energy companies focused on solving the problem of servicing customers with heat pump systems. In 1985, international oil prices tumbled and government subsidies for heat pump systems were cancelled. Bivalent systems, which until that date had formed the main market, were not cost-effective any more. The heat pump market focused on monovalent systems for new buildings. Later on, the ground was also introduced as a heat source. Ground coils were mainly horizontally installed collectors.

Since 1990, the heat pump market showed a steady recovery. The ground (or groundwater) became the main heat source and, due to better building codes (i.e. better insulated houses, improved compressors and heat exchangers), SPFs in the range of 4 and more have been achieved, especially with direct expansion systems.

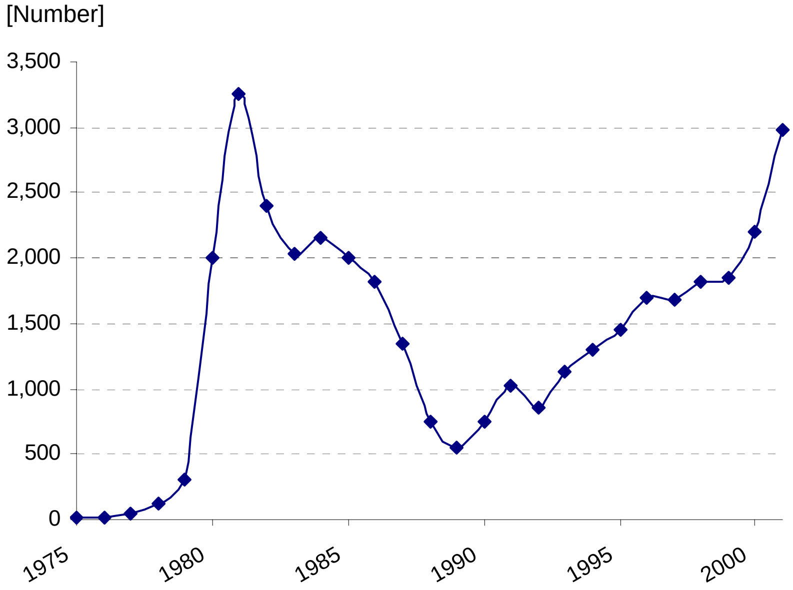

Figure 4.4 *Annual sales of heating-only heat pumps in Austria 1975-2001*

Heat pump capacities installed in Austria from 2000 to 2003 are shown in Table 4.1

Table 4.1 *Heat pump installations in Austria 2000-2003 according to field of application*

Year	Water for domestic/industrial use	Heating	Air conditioning	Swimming pool	Total
2000	2700	2000	80	90	4890
2001	2400	2200	120	120	4840
2002	2300	2800	160	100	5360
2003	2200	3500	180	100	5980

Source: (Faninger, 2004)

From 2002 on, the figures for water for domestic/industrial use and for heating applications were extrapolated, the data for air conditioning and swimming pools are based on estimations

Figure 4.5 shows the environmental benefits of heat pump application for Austria in terms of CO_2 reduction by heat pumps (space heating, hot water, etc.) in Austria. In 1996, for example, the production of some 130,000 t of CO_2 could be avoided by heat pump operation.

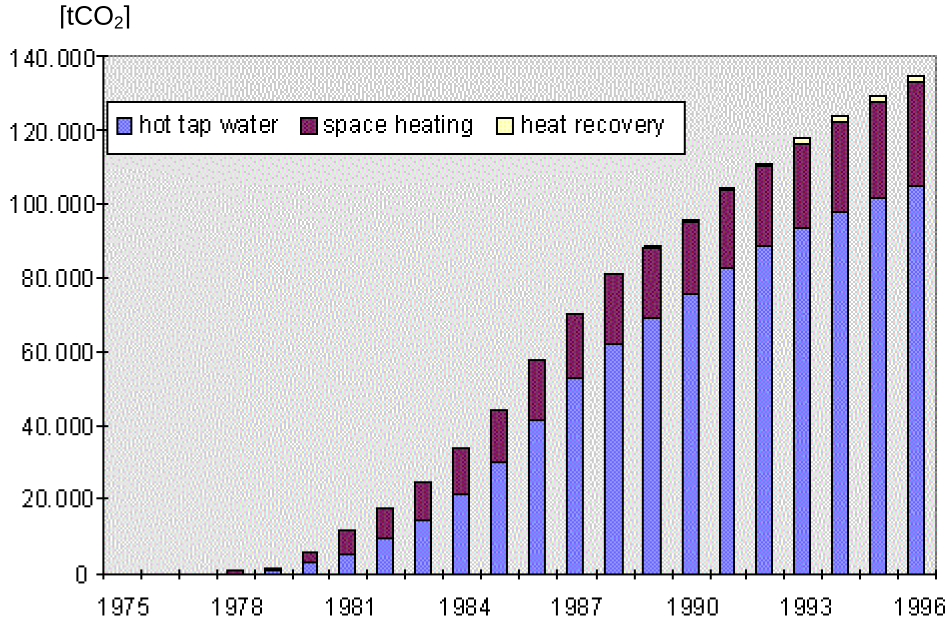

Figure 4.5 *Cumulative CO_2 reduction by heat pumps in Austria*

4.2.2 Canada

The former Canadian Earth Energy Association reported that about 30,000 ground-source heat pump units had been installed in Canada in the nineties. Annual sales peaked in the early 1990s, primarily as a result of a utility incentive program in the province of Ontario, enabling installation of approximately 6700 residential ground-source heat pumps. (Internet source 10) The Geothermal Heat Pump Consortium (GHPC)[2] is a partner and counterpart to the Canadian GeoExchange Coalition. In March 2000, Natural Resources Canada (NRCan) proposed to pay $ 0.87 million over three years to the GHPC. (Internet sources 11 and 12).

4.2.3 China

The Chinese heating market is, to a large extent, characterised by the absence of central heating systems. Instead, room air conditioners (RAC) are usual. Due to its large population, China has the biggest residential air conditioning market in the world.

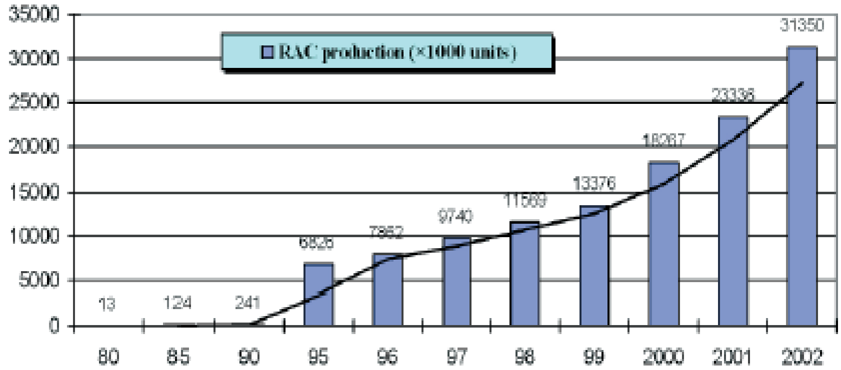

Figure 4.6 *Room air conditioner production in China*
Source: IEA HPC Newsletter vol. 22, 4/2004

[2] The Washington based GHPC is a non-profit organisation (partnership) of government, industry and over 240 utilities.

Therefore, the production of RACs in China ranks first in the world. For example, penetration of residential air conditioning in Shanghai has reached 96.8%. However, the usage ratio is still low due to high energy costs. Use of large numbers of RACs has already caused enormous pressure on energy supply and the environment of China. Electrically driven RACs have created the biggest unstable power grid load and the biggest source of CO_2 emissions in most Chinese metropolises. The residential air-conditioning trend in Chinese metropolises should be DHC with combined cycle heat and power unit (CCHP) using natural gas as an energy source. Household central air conditioning will become the main type of air conditioning for individual houses or town houses. RACs will still have a broad market (IEA HPC Newsletter vol. 22, 4/2004).

4.2.4 Finland

The cumulated sales of heat pumps in Finland 1994-2002 is shown in Figure 4.7. A steady growth of the Finnish heat pump market can be confirmed. This increase of sales does yet not apply to all kinds of heat pumps offered: Whereas the outlets of ground source and exhaust heat pumps have almost been stagnating since 2000, air/air heat pumps have shown dynamic growth, especially after 1999.

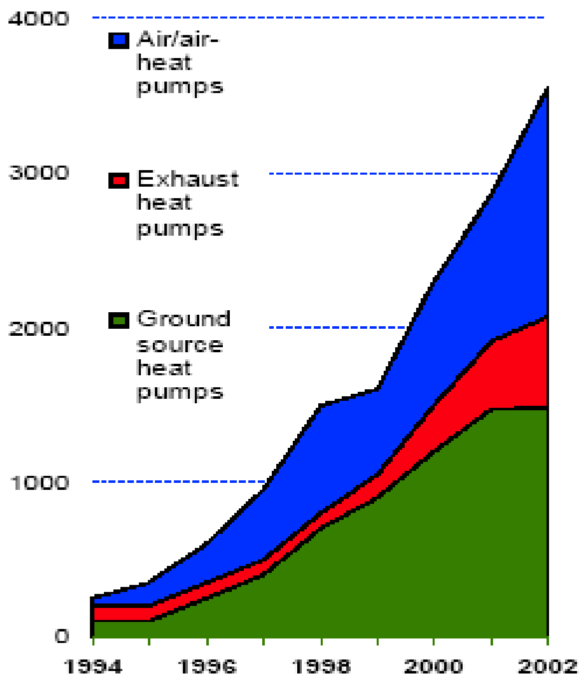

Figure 4.7 *Heat pump sales in Finland for different heat sources*
Source: Hirvonen 2003.

There are a couple of reasons for the general growth of the heat pump sector, like rising energy prices, the tough Finnish climate conditions, etc. Besides, electricity is the only energy carrier with a nationwide distribution system. As Finnish homes have high air change rates, air/air systems recovering heat from waste air are very attractive. Thus, this kind of heat pump has outperformed the other heat pump technologies in terms of sales and market growth during the last few years.

The factors mentioned above make Finland a very attractive market for heat pumps in the future, and so further growth is expected for the next years. Furtherly, Finland has a great many of lake and rock areas, where solar heat is stored. The ongoing trend towards heat pumps will additionally be fanned by the chance to utilize these sources.

4.2.5 France

Table 4.2 compares the investment and operating costs of various types of heat pump systems with a heating/cooling floor under French conditions. (Olivier, 2001)

Table 4.2 *Comparison of the costs of heat pumps for a heating/cooling floor application*

Type	Investment cost [€/m² floor area]	Operation and maintenance cost [€/m² floor area/year]
Vertical ground-coupled system	137	2.6
Horizontal ground-coupled system	115	2.6
Air-to-water heat pump	92	3.8

The seasonal COP during the heating period varies from 3.6 to 3.9 for heat pumps in France. Table 4.3 shows investment cost of ground-source and air-to-water heat pumps and that of an oil-fired heating system. (Internet source 13; EHPA, 2003)

Table 4.3 *Investment cost of heat pump systems compared with oil-fired central heating*

	Heat pump system based on floor heating[1]		Oil-fired
	Air-to-water heat pump [€]	Ground-source heat pump [€]	central heating [€]
Drilling on turn-key basis	-	7,000	-
Heat pumps	n/a	6,000	-
Installation of heat pump	n/a	1,200	-
Oil-fired boiler	-	-	4,800
Control	-	-	800
Fuel tank + installation	n/a	2,500	3,800
Chimney	-	-	4,000
Total	10,000	16,700	13,400

[1] Based on a heat demand of 7 kW_{th} and an average COP of 3.

According to Table 4.3, the additional investment cost in case of a ground-source heat pump is € 3300, and the cost saving in case of an air-to-water heat pump is € 3400.

Figure 4.8 shows the annual sales of heat pumps in France according to (EHPA, 2003). In 2002, sales of heat pumps soared to 20,000.

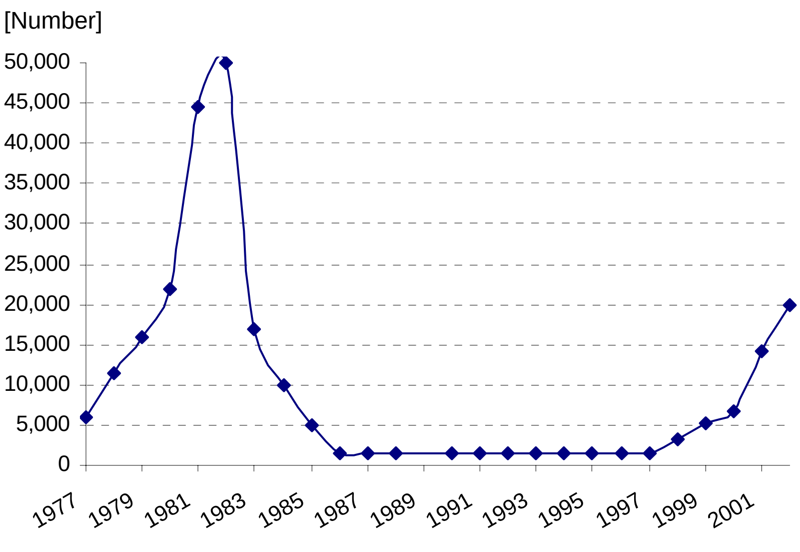

Figure 4.8 *Annual sales of heat pumps in France 1977-2002*

In 1996/1997 ADEME and the Ministry of Housing supported development and field tests by manufacturers of prototypes of engine driven heat pumps for individual housing with a budget of 300 k€. Details about the financial incentives for heat pumps for the residential sector are presented in (EHPA, 2003). EdF has decided to develop both heating and cooling solutions. However, no data with regard to private R&D (e.g. by EdF) have been disclosed.

4.2.6 Germany

Information of the heat pump sales figures, as shown in Figure 4.9, points out substantial differences especially in the early eighties. Since the foundation of a governmentally supported heat pump centre in 1991, information on sales figures is collected centrally and used for general statistics. The heat pump peak in Germany was at the beginning of the eighties, but after some years, the sales figures collapsed downright. In the late eighties and the early nineties, they ranged at a few hundred heat pumps. Since the middle of the nineties, an upward trend appeared, although the sales figures still lag behind the numbers of the early eighties. (Nilsson, 2003; Internet sources 14 and 15)

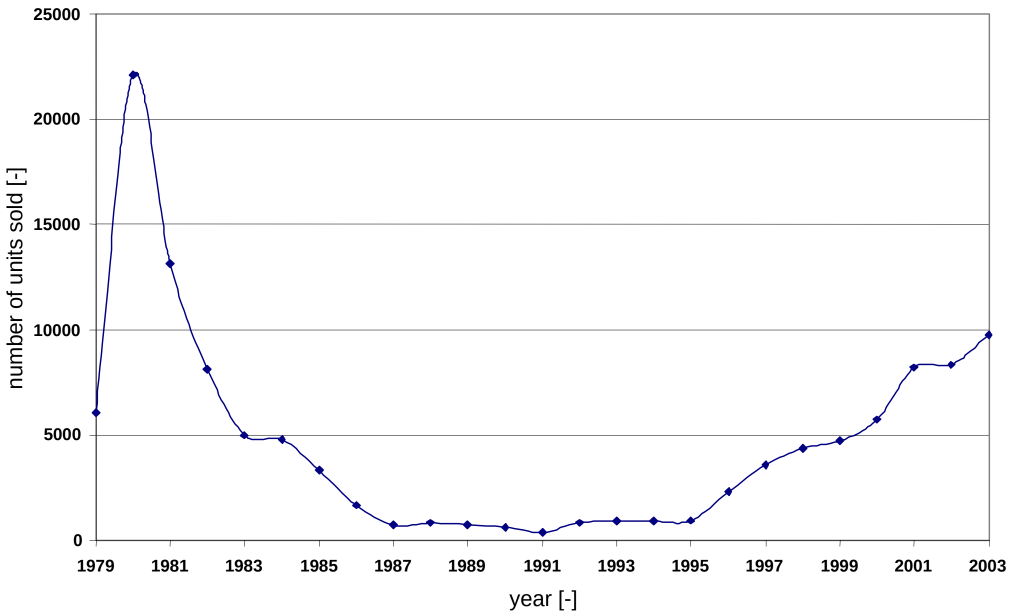

Figure 4.9 *Annual sales of heating-only heat pumps in Germany 1979-2003*

In 2003, not only 9745 heat pumps for heating were sold (as shown in Figure 4.9), but also another 3,776 systems for warm water supply were installed. This totals to 13,521 sales, reaching closely to the all time high of 1980. The largest growth in 2003 was performed by air/water heat pumps (+57%), followed by heat pumps using ground heat (+16%), whereas heat pumps using heat from water showed a 20% decline (Wärmepumpe aktuell vol. 6, 1/2004).

Federal R&D support for heat pumps declined after a peak since the early 1980's, just like R&D support in general. Funds were used to promote R&D by research institutes, manufacturers of heat pumps, etc. Federal R&D support from 1974 to 1998 amounted to DM 15 mln (≈ € 7.5 mln).

Although the Federal government no longer supports heat pumps by grants, there are attractive loans for heat pumps. Grants are awarded in the framework of the CO_2 reduction programme and the buildings retrofit CO_2 programme of the KfW bank (Kreditanstalt für Wiederaufbau). (Internet source 16).

In 1997, the investment cost of an electric heat pump system based on 5 vertical borehole heat exchangers (double-U), each 50 m deep, amounted to € 23,300 (DM 45,600). The heat pump supplies the heat demand and the demand for hot water. Some cooling may be provided using the floor heating coils. The floor area is 180 m^2 in two storeys, with a nominal heat demand of 11.5 kW_{th}. Thus, the specific investment cost was about € 2000/kW_{th} in 1997, including drilling costs. (Internet source 14)

The investment costs of heat pumps have increased slightly during the past few years. For industrial applications (see Figure 4.10) they were in a range between 1250 €/kW and 450 €/kW (EWU 1992, 1994, 1999).

For residential application, typical annual operation costs consist of a 77.6% share for capital costs (€ 2023), 2.9% fixed costs (€ 508) and 19.5% variable costs (€ 77) (example for a single occupancy house equipped with steel panel radiators erected in 1995) (Leven et al., 2001).

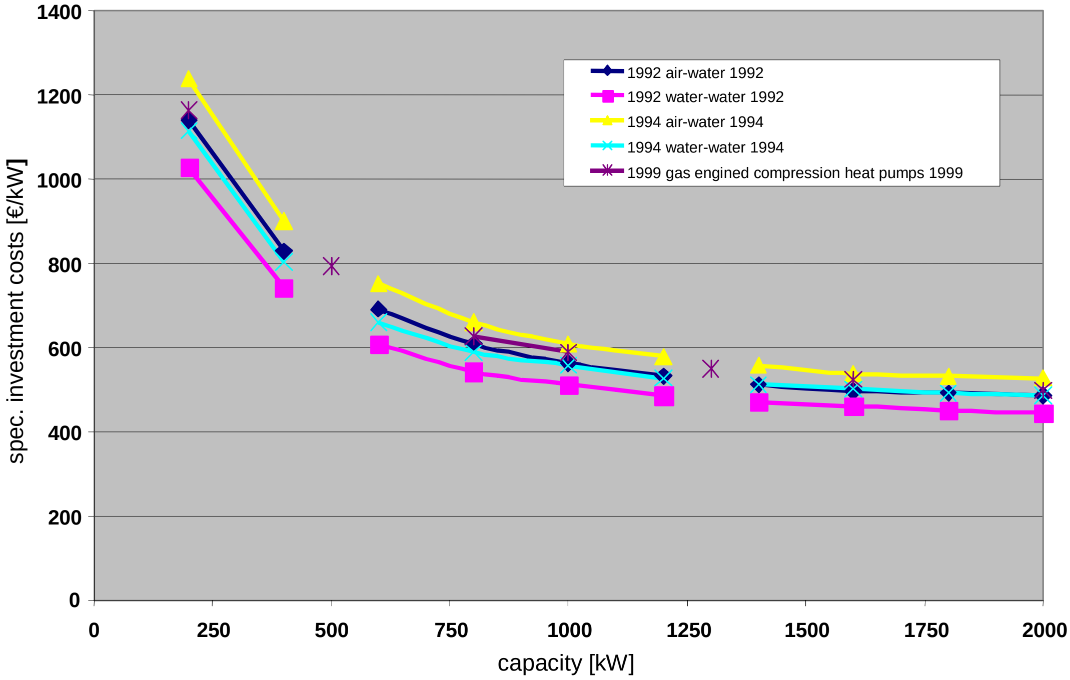

Figure 4.10 *Investment costs for different types of heat pumps for industrial use in different years*
Source: (EWU 1992, 1994, 1999).

From the data for cumulated sales and the investment costs associated, a learning curve for Germany´s heat pump market can be derived. This learning curve is shown in Figure 4.11. With increasing cumulative sales, a inflation-adjusted contemplation of investment costs shows a steady decline. So, the learning factor arising for the years 1980-2002 is 0,70. In Figure 4.18 there is another learning curve given, now for the Swiss heat pump market, and can be compared to the result for Germany.

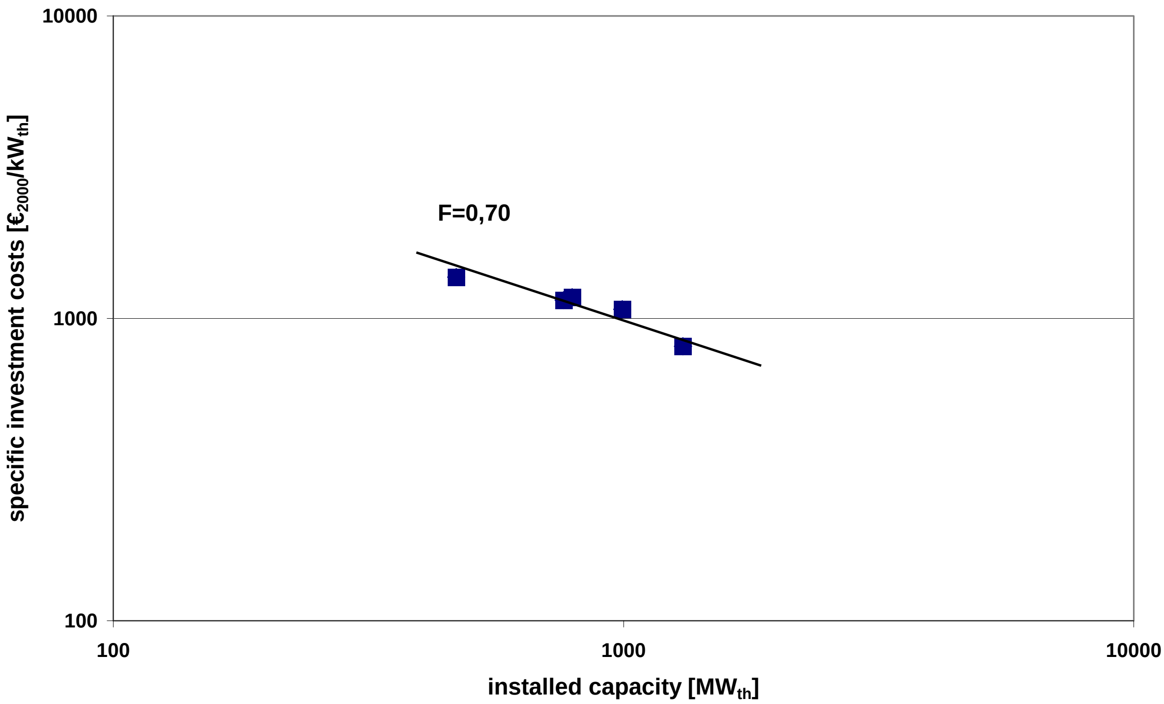

Figure 4.11 *Inflation-adjusted learning curve of the German heat pump market 1980-2002*
Source: cost data from EWU and BWP.

4.2.7 Japan

The Heat Pump & Thermal Storage Technology Center of Japan (HPTDJ) is a public organisation functioning under the auspices of the Ministry of Economy, Trade and Industry (METI). As a national centre for heat pumps and thermal storage, the HPTCJ promotes the use of thermal storage systems and carries out many projects aimed at improving technology. Thermal storage systems combine the advantages of heat pumps and thermal storage, so they meet the need for the effective storage and utilization of energy. CO_2 heat pump water heaters sold in Japan are of the storage type that store the hot water produced with cheap night-rate electricity in a tank.

The HPTCJ is actively involved in promoting systems and technologies in this field, and they conduct a wide range of surveys and research. Government subsidies are available to support the installation of ice thermal storage air conditioning systems. Subsidies apply to decentralised systems (Internet source 17).

A relatively small use of heat pumps is indicated which is concentrated in the cold and snowy Prefecture of Okayama. Hot spring water above 150°C is available all over the country so there is little demand for heat pumps (Lund, 2000a) .

Figure 4.12 shows the cumulative number of heat pumps in Japan (Halozan, 1998).

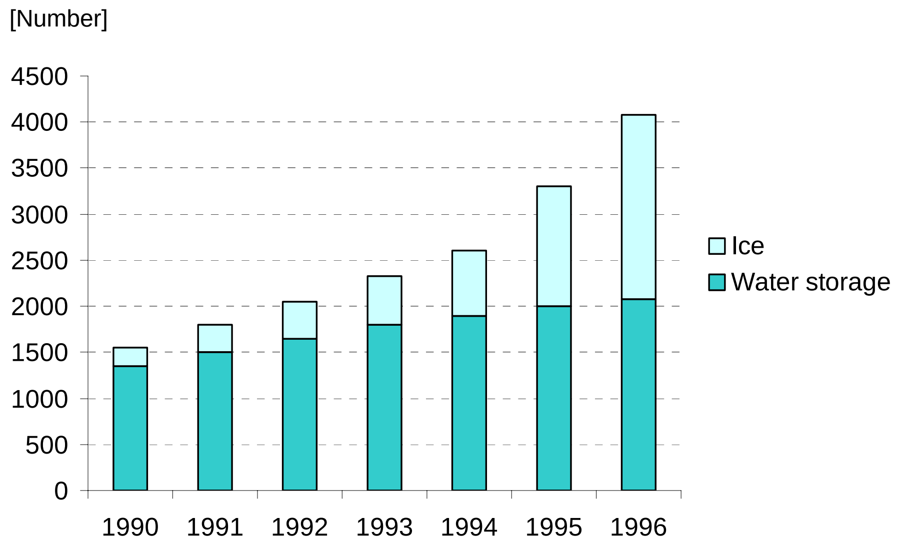

Figure 4.12 *Cumulative number of thermal storage type heat pump systems in Japan 1990-1996*

4.2.8 The Netherlands

According to (NeoScan Warmtepompen, 2003) and (Joosen, 2003) at the end of 2002 the heat pump capacity in the Netherlands amounted to 274 MW_{th}. The cumulative number of heat pumps was approximately 33,200, including about 8400 heat pump boilers. (Graus, 2003). The annual sales of heat pumps are represented in (Figure 4.13).

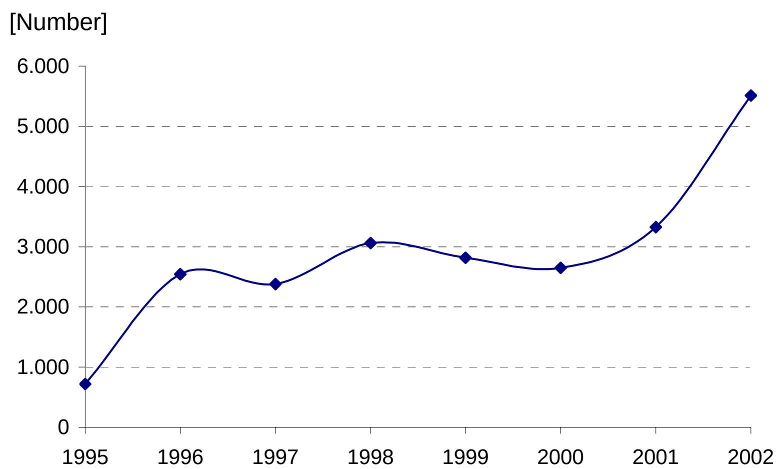

Figure 4.13 *Annual sales of heat pumps in the Netherlands 1995-2002*

R&D and the quality of prototypes and commercial heat pump technology in the Netherlands has improved dramatically in the last few years. Seven years ago (in 1998), the international position of the Netherlands was rather poor. In the meantime, however, heat pumps have been introduced successfully in the horticultural sector and several very interesting heat pump applications in the residential (domestic) sector have been observed recently. This has been realised by a coherent approach both from the government and SenterNovem, the Dutch organisation for promotion of R&D on energy and environment, and several Dutch manufacturers (Kleefkens, 2004).

4.2.9 Norway

In 2003, sales of heat pumps in Norway reached 56,000 units (after 21,300 in 2002 and 6400 in 2001, 94% of which in the residential sector). Since 1997, market sales show a rising trend. Higher electricity prices in the Nordic energy market were the main reason for increased sales of heat pumps in Norway in the last few years. A substantial part of the production in this market is hydropower and periods with cold and dry weather are resulting in higher prices. By the end of 2002, approximately 58,300 heat pumps were in operation in Norway (Internet source 18) (Figure 4.14).

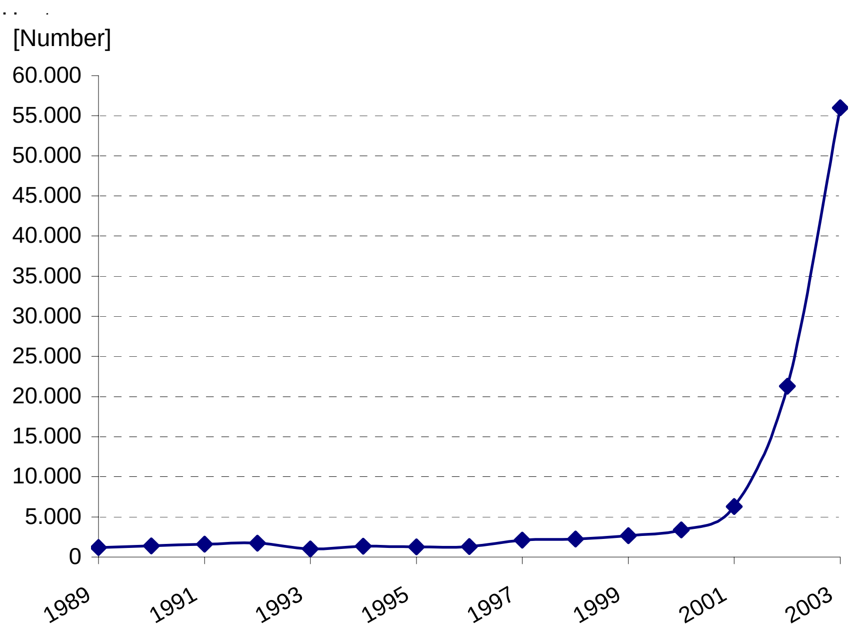

Figure 4.14 *Annual sales of heat pumps in Norway 1989-2003*

The Norwegian Heat Pump Association, NOVAP, (Internet source 19) assumes that the best way to promote market expansion is by:

- quality assurance activities, i.e. certification of sellers/buyers, standard contracts and guarantees, and product information to potential buyers,
- buyer support through insurance and loan arrangements,
- information for potential buyers on the impact of heat pumps on energy consumption,
- good statistical data on sales, etc.

4.2.10 Spain

The Spanish heat pump market has increased considerably in the past few years. Sales increased by 250% between 1997 and 2000 and about 2,000,000 heat pumps are installed at present. This growth rate is expected to continue for the next few years.

The air-to-air heat pump is the most successful type in Spain, especially in mild climate zones. The most common heat pump used is the electrically driven reversible compression unit, but gas companies are strenuously promoting gas-driven heat pumps. Heat Pumps have been installed in all sectors, but market penetration has been different in each one.

The residential sector has the largest number of installed heat pumps, followed by the commercial sector, with the industrial sector having the smallest number of sales. One of the most important barriers that must be overcome by the heat pump is the confusion in the minds of users. Most of them perceive the heat pump as air conditioning because equipment sold in Spain is normally reversible. In addition, the Spanish are not used to heating by air and prefer heating systems such as radiators. Heat pumps are normally installed as refrigerating equipment and a complementary heating system. Nevertheless current promotional campaigns are focussing on public information and people are becoming increasingly interested in new heating systems, such as under-floor or ceiling heating (Internet source 20).

The Spanish National Team on Heat Pumps (ENEBC) was created on 1st April 1996 at the request of the Ministry of Industry and Energy, through the State Energy Planning Office, for the research, development and dissemination of the heat pump technologies (Internet Source 21).

Figure 4.15 shows the annual sales of heat pumps in Spain (European Heat Pump News, 2002b; IEA Heat Pump Centre Newsletter, 2003).

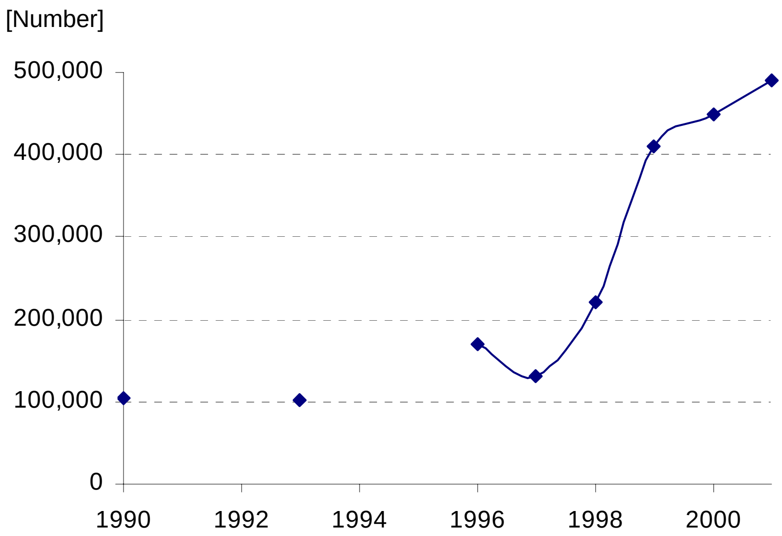

Figure 4.15 *Annual sales of heat pumps in Spain 1990-2001*

As shown in Figure 4.16, heat pumps have the largest market shares for air conditioning applications. It also shows, that not only heat pump sales are rising, but there is also a steady growth in the entire market for air conditioning systems.

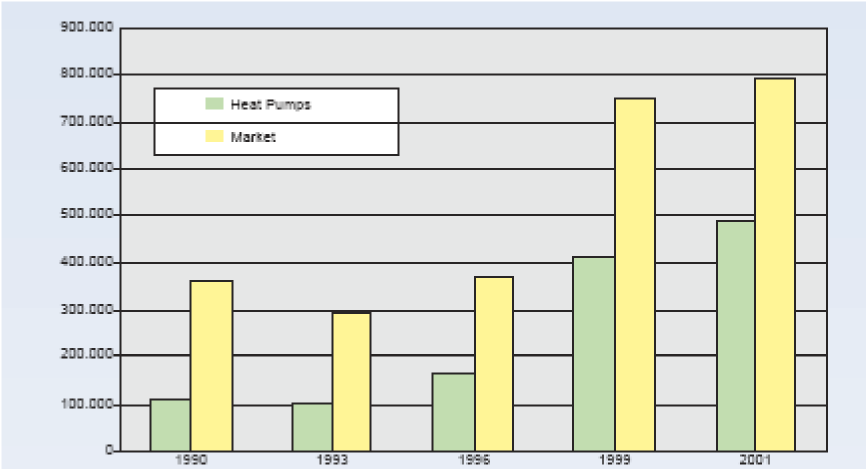

Figure 4.16 *Heat pump and total air conditioner market of Spain (in units sold)*
Source: IEA Heat Pump Centre Newsletter, vol. 21, 2/2003.

By the end of 2001, close to 2.5 million heat pumps were in operation in Spain.

4.2.11 Sweden

The Swedish heat pump market is one of the largest in the world. In 2002, total sales of heat pumps approached the level of 40,000. In the 1980's and 1990's Swedish market had its ups and downs illustrated by Figure 4.17 (Karlsson, 2003).

During the first half of the 1980's horizontal ground-source heat pumps and open systems were quite common in Sweden. During this period the heat pump market was supported by governmental subsidies. Around 1985, the heat pump market showed a substantial decrease, mainly due to the withdrawal of governmental subsidies. What is more, the international oil price decreased by some 50% at that time. During the period 1985-1990, the market consisted mainly of ordinary, non-expensive, heat pumps. Direct expansion systems were used for ground-source units. Air-to-water heat pumps were still quite common.

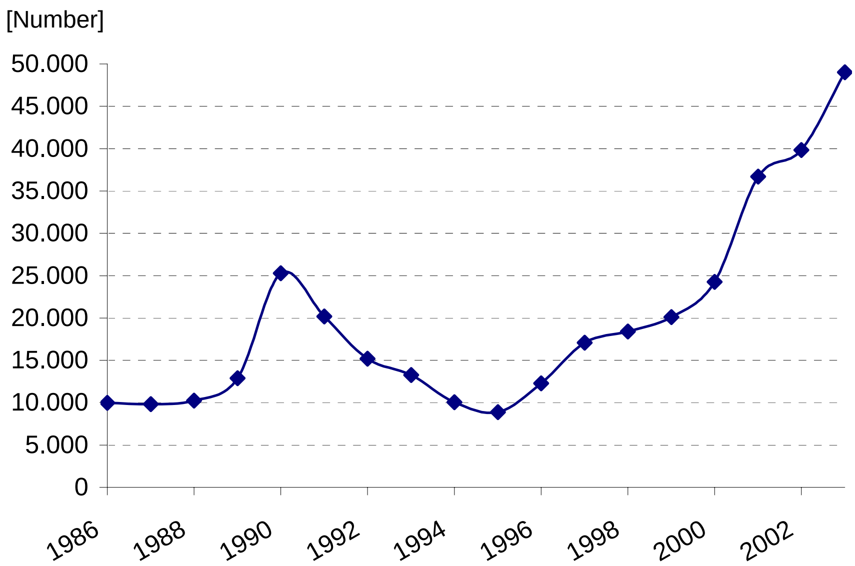

Figure 4.17 *Annual sales of heat pumps in Sweden 1986-2003*

Around 1990-1991, the heat pump market expanded again because of increased sale of air-to-air heat pumps. These were installed in houses with direct-acting electric heating. In 1994-1995, the Swedish National Board for Technical Development (NUTEK) issued a technology procurement on heat pumps. Consequently, sales of heat pumps increased rapidly.

4.2.12 Switzerland

Switzerland claims position number two in the European heat pump market, after Sweden. With 40% of new single-family homes equipped with a heat pump system, the market continues to grow. Fifty percent of the heat pump systems extract heat from the air, 39% from the ground, using deep boreholes (300 meters), and 11% from ground and surface water.

Figure 4.18 shows the increased share of heat pumps in new single-family dwellings in Switzerland. (Internet sources 23 and 24).

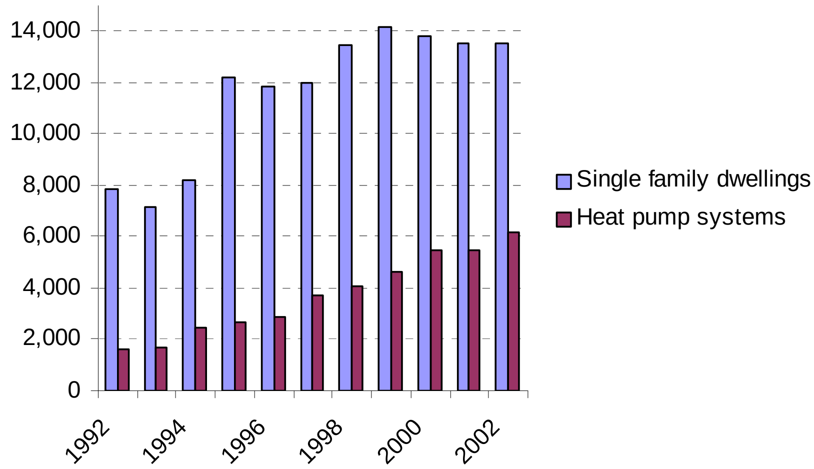

Figure 4.18 *Penetration of heat pumps in new single-family dwellings in Switzerland*

The Swiss try to ensure that in the next ten years more than 50% of new dwellings and 10% of the existing ones will use heat pumps. Training of installers and designers is a key element of the Swiss strategy (IEA Heat Pump Centre Newsletter, 2002). Table 4.4 gives an overview of the Coefficient of Performance (COP) that may be achieved with different heat pump configuration. (Heat Pump Test Centre Töss, 2003).

Table 4.4 *COP's for different heat pump configurations measured in Töss (Switzerland)*

Type	Temperature [°C]	Temperature heat source [°C]	Average COP
Air-water	35	-7 - 20	2.6 - 5.0
Brine-water	35	-5 - 5	3.7 - 5.0
Water-water	35	10 - 15	5.5 - 6.2

Table 4.5 compares the costs of an electric heat pump to those of an oil-fired central heating system (Internet source 22).

Table 4.5 *Comparison of installation and operational costs of an electric heat pump system with an oil-fired boiler (central heating system)*

		Heat pump system with borehole heat exchanger	Oil-fired boiler
Base: heat demand 6.5 kW			
Heat demand	[kWh/yr]	13,600	13,600
System efficiency	[%]	95	80
Seasonal Performance Factor		3.5	-
Effective energy used	[kWh/yr]	4,090	17,000
Fuel consumption	[l/yr]	-	1,703
Space required	[m^3]	2.6	23
CO_2 emission	[tonne/yr]	-	
Installation costs			
Complete system incl. storage	[€]	8,700	11,150[1]
Borehole heat exchanger	[€]	7,530	-
Space in house	[€]	710	6,290
Miscellaneous (trenches, chimney)	[€]	1,110	1,090
Total installation cost	[€]	18,050	18,530
Energy costs			
Electricity, high tariff	[€/yr]	230.75	33.50
Electricity, low tariff	[€/yr]	153.85	15.00
Basic payment	[€/yr]	69.75	5.50
Fuel cost	[€/yr]	-	792.00
Total energy cost	[€/yr]	454.35	846.00
Running costs			
Maintenance	[€/yr]	102.60	253.00
Chimney cleaning, flue gas control	[€/yr]	-	123.00
Total running cost	[€/yr]	102.60	376.00

[1] Two tanks 2000 l.

The investment costs of the ground-source heat pump in Table 4.5 is about 8% higher than the corresponding cost figure in Table 4.3. The investment cost of conventional central heating system is 40% higher, as Table 4.5 includes € 6290 for space required for the oil-fired boiler. Figure 4.19 illustrates the development of the Swiss heat pump market. During the last 12 years a steady upward trend in heat pump sales can be seen.

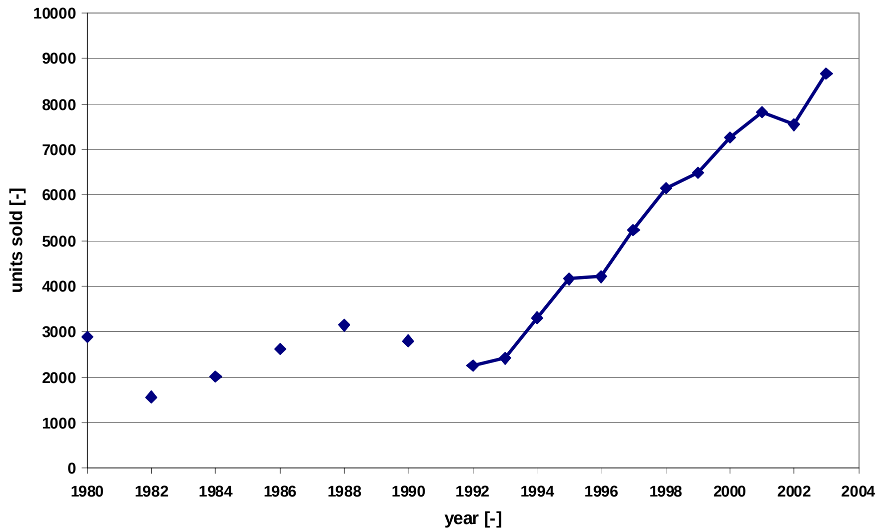

Figure 4.19 *Annual sales of heat pumps in Switzerland 1980-2003*
Source: (Beyeler, 2004).

At the end of 2003, 86,000 heat pumps were in operation in Switzerland, with a total capacity of approximately 1440 MW_{th}. At the end of 2000, the number of heat pumps was 61,606, with an installed capacity of 1038 MW_{th}. (Rognon, 2002) Rybach et al (Internet source 22) expect that the market will further expand in the leading countries like Sweden and Switzerland.

The inflation-adjusted development of the investment costs for a 7,6 kW_{th} heat pump, boreholes and connecting pipes from 1980 to 2004 is shown in Figure 4.20.

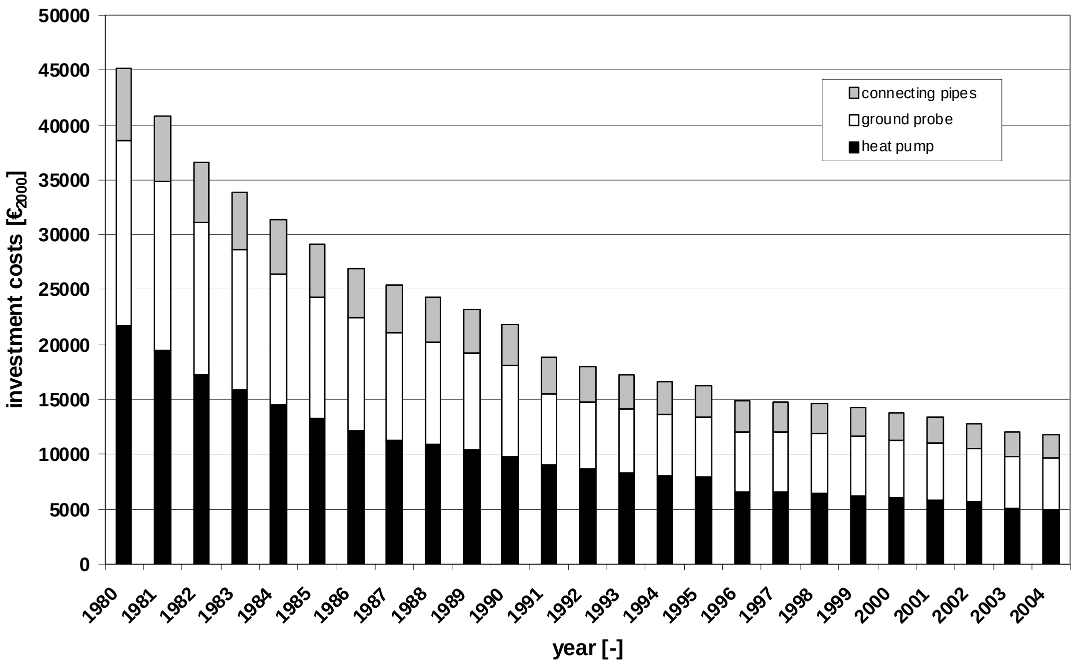

Figure 4.20 *Inflation-adjusted development of investment costs for a 7,6 kW_{th} B0/W35 heat pump in Switzerland (base year 2000)*
Source: (Beyeler, 2004).

Utilizing data from Figure 4.19 and Figure 4.20, a learning curve for the Swiss heat pump market can be calculated (see Figure 4.21). The resultant average learning factor for the Swiss market is 0.74.

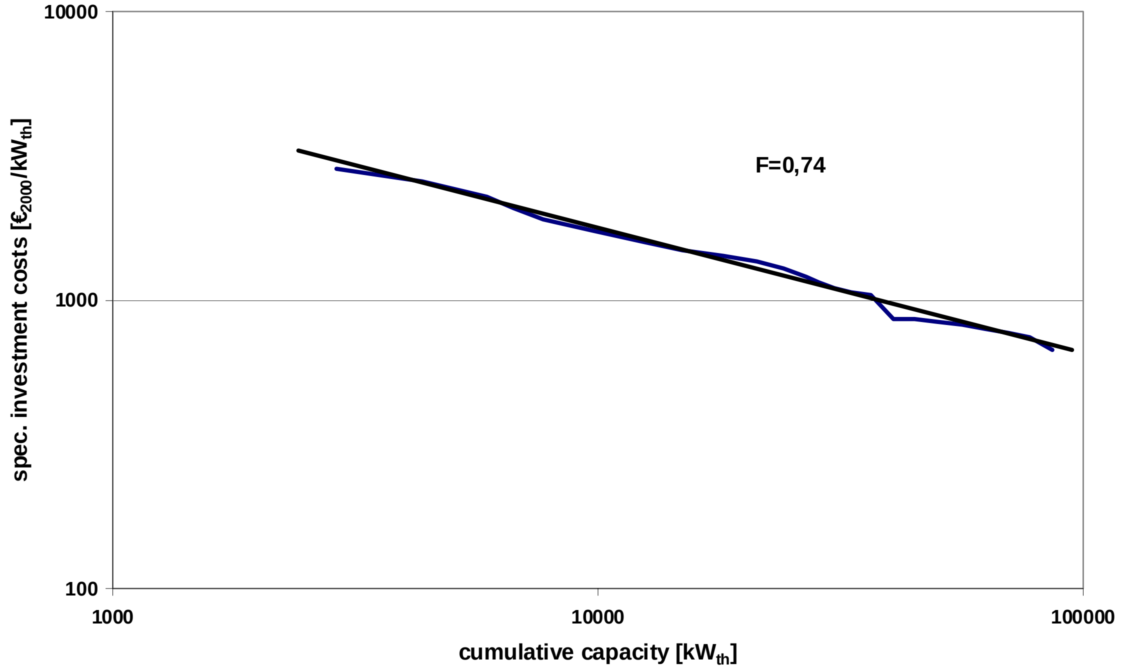

Figure 4.21 *Inflation-adjusted learning curve of the Swiss heat pump market 1980-2003*

This comes close to the result for the learning factor of the German heat pump market, which is 0.70. Due to the larger scale of heat pump production in Germany the advantage from learning is even a little better there.

Figure 4.22 illustrates the development of geothermal heat production in Switzerland.

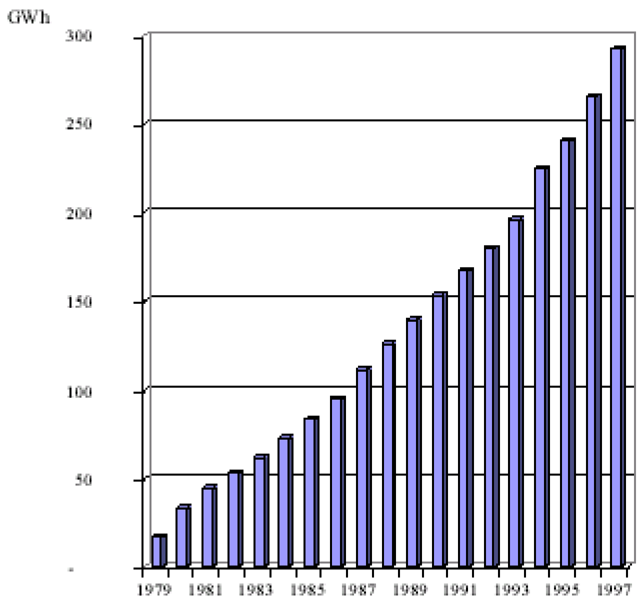

Figure 4.22 Geothermal heat production (before the heat pump) in Switzerland

In 2001, the budget of the Swiss government for R&D on heat pumps ('Umgebungswärme') amounted to some CHF 1.5 mln (≈ €1 mln) (Internet Source 25).

4.2.13 United States

In the United States, geothermal heat pump installations have steadily increased over the past 10 years with an annual growth rate of about 12%, mostly in the mid-western and eastern states from North Dakota to Florida. Relatively few heat pumps have been installed in the west. At the end of 1999, a total number of 400,000 units installed, with 45,000 installed annually. Today these figures are 450,000 and 50,000, respectively (Internet sources 26 and 27).

Historically, the fortunes of the electric heat pump have varied inversely with the fortunes of natural gas. Unitary heat pumps got a boost in North America in the mid 1970's when the oil crisis and the moratorium on new natural gas hook-ups led to the proliferation of heat pumps in the newly developing suburban areas. However, poor installations and reliability problems kept heat pumps from becoming as popular as they might have been. Heat pump shipments tumbled by one third in the four years from 1978 to 1982. When the gas moratorium was lifted soon after, the natural gas utilities had to invest to get gas service to the newest construction areas. Competition continues to be fierce, and the North American heat pump market continues to grow at a slow but steady pace (Internet source 28).

The biggest improvement in recent years has been to use of higher efficiency scroll compressors in many lines of heat pumps and air conditioners. Also, variable speed drives for compressors and fans help achieve better part load efficiencies. These are utilised in some of the higher end equipment. Most individual measures to improve efficiency are small, but they add up. There are research projects being undertaken by the industry's 21st Century Research program that show promise of adding efficiency, reliability and comfort.

Financial incentive schemes have been introduced by several electric utilities in the U.S. encouraging house owners to use groundwater heat pumps for space cooling/heating purposes and thus, reduce the peak loads on their electric systems. (Fridleifsson, 1998) The Geothermal Heat Pump Consortium (GHPC), a partnership of government, industry and over 240 utilities, has shown that an important first step to sustainability of the geothermal heat pump industry is a commitment from government to support market development and to build alliances and initiatives within a coalition of stakeholders. The GHPC has established the following goals:

- To reduce annual greenhouse gas emissions by 1.5 Mt annually by the year 2005.
- To increase annual unit sales of geothermal heat pump systems from 58,000 to 400,000 by the year 2005.
- To help the technology reach sufficient market penetration that it becomes self-sustaining without further help or incentives from government or utility sources.

To that end, the GHPS established a 6-year program. Until March 2001, the GHPC has invested more than $ 50 mln to develop the geothermal heat pump market. (Internet sources 29 and 30)

4.3 International collaboration and targets

Since its inception, the primary purpose of IEA's Heat Pump Program (HPP) has been to foster continued and increased deployment of the heat pump technology to achieve improved energy efficiency and environmental benefits. Consequently, the Programme is established and designed to be a link between the R&D community and the market, a body that should facilitate a higher degree of market penetration for heat pumps. The basic idea behind the HPP is that different countries face many common challenges, and that these challenges are most effectively solved through international collaboration and pooling of resources (IEA Heat Pump Centre Newsletter, 2002).

Under the auspices of the IEA the so-called Annexes are executed, e.g. Annex 25, Annex 26, and Annex 27. Annex 25 covers 'Year-round Residential Space Conditioning and Comfort Control Using Heat Pumps'.

After three years of operation, Annex 25 has been finalised. Annex 26 covers ‘Advanced Supermarket Refrigeration/Heat Recovery Systems’. Countries involved are: the USA, Canada, Denmark, Sweden, and the UK. The total value of the research work under Annex 26 is approximately \$5 mln. This represents a leveraging of each participant’s funds of up to 10:1. Therefore, the total R&D budget from the IEA countries involved amounts to approximately \$ 50 mln.

The recently finalised Annex 27 covered ‘Selected Issues on CO_2 as Working Fluid in Compression Systems’. The main objective of this Annex was to bring CO_2 technology closer to commercialisation, by adding critical issues of both a basic and applied character. It is important to involve industry, especially manufacturers, as well as research organisations. The budgets of Annex 25 and 27 are unknown. Annex 28 deals with ‘Test Procedure and Seasonal Performance Calculation for Residential Heat Pumps with Combined Space Heating and Domestic Water Heating’ and is in the stage of start-up (IEA, 2003).

In an effort to contribute substantially to the increased use of renewable energies, to energy saving and to CO_2 emission reduction in Europe, the European Heat Pump Association (EHPA) intends to double the number of heat pumps that are expected to be installed in the year 2010, i.e. roughly 7.3 million (Internet source 31).

4.4 Summary of sales and R&D data

Figure 4.23 and Table 4.6 present annual sales of heat pumps in a number of countries. Sales of heat pumps in Europe are estimated at close to 600,000/year, in Japan at 2000/year, in Canada at 4000/year, and in the U.S. at 58,000/year. Global annual sales could amount to 660,000 or more.

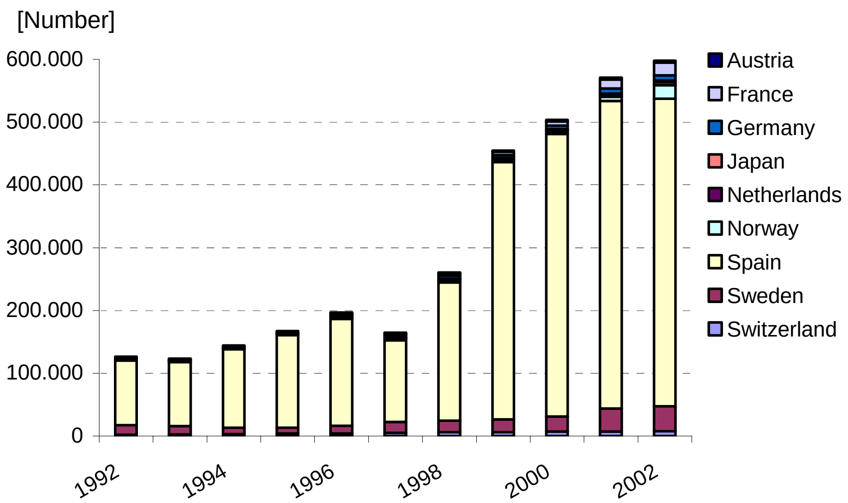

Figure 4.23 *Sales of heat pumps in Europe and Japan (indicative)*

Table 4.6 *(Indicative) sales of heat pumps in Europe and Japan (1992-20003)*

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Austria[1]	850	1125	1300	1450	1700	1675	1825	1850	2200	2980	2980	3500
France	1500	1500	1500	1500	1500	1600	3200	5200	6800	14200	20000	
Germany[1]	850	900	900	1200	2310	3580	4367	4717	5737	8213	8315	13521
Japan[2]	250	275	275	700	775	900	1050	1250	1500	1850	2250	
Netherlands	721	721	721	721	2543	2381	3061	2818	2650	3327	5512	
Norway	1750	1000	1350	1275	1300	2100	2250	2650	3395	6300	21300	56000
Spain[2]	103000	102000	124667	147333	170000	130000	220000	410000	450000	490000	490000	490000
Sweden	15200	13250	10040	8900	12300	17100	18400	20100	24250	36700	39825	49000
Switzerland	2260	2420	3309	4160	4207	5225	6155	6160	6943	7168	7554	8677
Total	126381	123191	144062	167239	196635	164561	260308	454745	503475	570738	597736	

[1] Heating-only heat pumps.
[2] Sales in Japan were extrapolated after 1996; sales in Spain were assumed to remain stable after 2001.

Figure 4.23 and Table 4.6 also show the recovery of international heat pump market during the nineties, when sales almost quintupled from 126,000 in 1992 to 598,000 in 2002. Table 4.7 shows that the total number of installed heat pumps in the regions considered – Western Europe, Japan, and North America – could amount to approximately 4.5 million.

Table 4.7 *Indicative numbers of installed heat pumps (2002) for selected countries*

	Ground-source heat pumps	Air-to-water/air-to-air heat pumps	Total
Austria	27,200	137,800	165,000
Canada	30,000	-	30,000
France	500	247,500	248,000
Germany	21,200	87,200	108,400
Japan	300	12,500	12,800
Netherlands	1,200	32,000	33,200
Norway	58,300	-	58,300
Spain	-	3,000,000	3,000,000
Sweden	73,500	231,000	304,500
Switzerland	25,400	60,000	85,400
United States	450,000	-	450,000
Total	687,600	3,808,000	4,495,600

The Electric Power Research Institute (EPRI) estimated that 800,000 heat pump units (of all kinds) were installed annually in 1988, 25,000 of which geothermal heat pumps (Lund, 1990). Table 4.8 gives an overview of the global development of geothermal heat pumps in 2000 based on (Lund, 2003a) and (Internet source 8).

Table 4.8 *Worldwide geothermal heat pump installations in 2000*

Country	Capacity [MW_{th}]	Energy produced [TJ/a]	Energy produced [GWh/a]	Heat pump installations	Equivalents of demand of 12 kW_{th}
Australia	24	57.6	16	2,000	2,000
Austria	228	1,094	303.9	19,000	19,000
Bulgaria	13.3	162	45	16	1,108
Canada	360	891	247.5	30,000	30,000
Czech Republic	8	38.2	10.6	390	663
Denmark	3	20.8	5.8	250	250
Finland	80.5	484	134.4	10,000	6,708
France	48	255	70.8	120	4,000
Germany	344	1,149	319.2	18,000	28,667
Greece	0.4	3.1	0.9	3	33
Hungary	3.8	20.2	5.6	317	317
Iceland	4	20	5.6	3	333
Italy	1.2	6.4	1.8	100	100
Japan	3.9	64	17.8	323	323
Lithuania	21	598.8	166.3	13	1,750
Netherlands	10.8	57.4	15.9	900	900
Norway	6	31.9	8.9	500	500
Russia	1.2	11.5	3.2	100	100
Poland	26.2	108.3	30.1	4,000	2,183
Serbia	6	40	11.1	500	500
Slovak Republic	1.4	12.1	3.4	8	117
Slovenia	2.6	46.8	13	63	217
Sweden	377	4,128	1,146.7	55,000	31,417
Switzerland[1]	300	1,962	545	21,000	25,000
Turkey	0.5	4	1.1	23	43
UK	0.6	2.7	0.8	49	53
USA	4800	12,000	3,333.3	350,000	400,000
Total	6,675.4	23,268.8	6,463.6	512,678	556,282

[1] Internet source 8.

Table 4.9 shows a few data regarding government expenditures on R&D on heat pumps, based on the preceding paragraphs on IEA countries and the IEA Heat Pump program.

Table 4.9 *Government expenditures on R&D with regard to heat pumps*

	1974	1995	1996	1997	1998	1999	2000	2001	2002	2003
France			300 k€							
Germany		€ 7.5 million (1974-1998)								
Switzerland								€ 1 mln		
IEA Annex 26									(€ 50 mln)	

The budget for IEA Annex 26 is shown between brackets as the R&D involved is related to ‘Advanced Supermarket Refrigeration/Heat Recovery Systems’, which is not identical to R&D on heat pumps.

5. Condensing Boilers

5.1 Technology description

Saving primary energy has been energy technology´s main purpose for the last decades.
A very significant part in reaching this target can be played by condensing boilers. Condensing boilers are an evolution of conventional boiler systems, with additional heat production by condensation of the steam fraction from the flue gas stream. Thus, the utilisation of the fuel´s energy content can exceed the lower heating value LHV, which is a limit to conventional systems. This means efficiency rates higher than 100% (relative to the LHV) are possible, as condensing boilers are capable of also utilising the enthalpy of evaporation concealed in the steam fraction of the flue gas by condensing. Using natural gas as a fuel 10 to 11 percents of efficiency can be gained by a condensing boiler compared to a non-condensing system; using oil the advantage over conventional systems is just 5.5 to 6 percents - the difference in potential usually makes gas-fuelled condensing boilers the more attractive alternative.

Further advantages of condensing boiler technology comprise fuel variability (either oil or/and different kinds of gas), low space demand, low emissions, low noise, high degree of modulation, and good cost/performance ratio due to high degrees of systems integration of burners and boilers. Besides, the lower flow rates allow the integration of downsized fittings, thus reducing investment costs. In combination with the savings from lower fuel consumption a high economic efficiency can be obtained, including short payback periods. Figure 5.1 gives an overview of a condensing boiler`s main components and their functions.

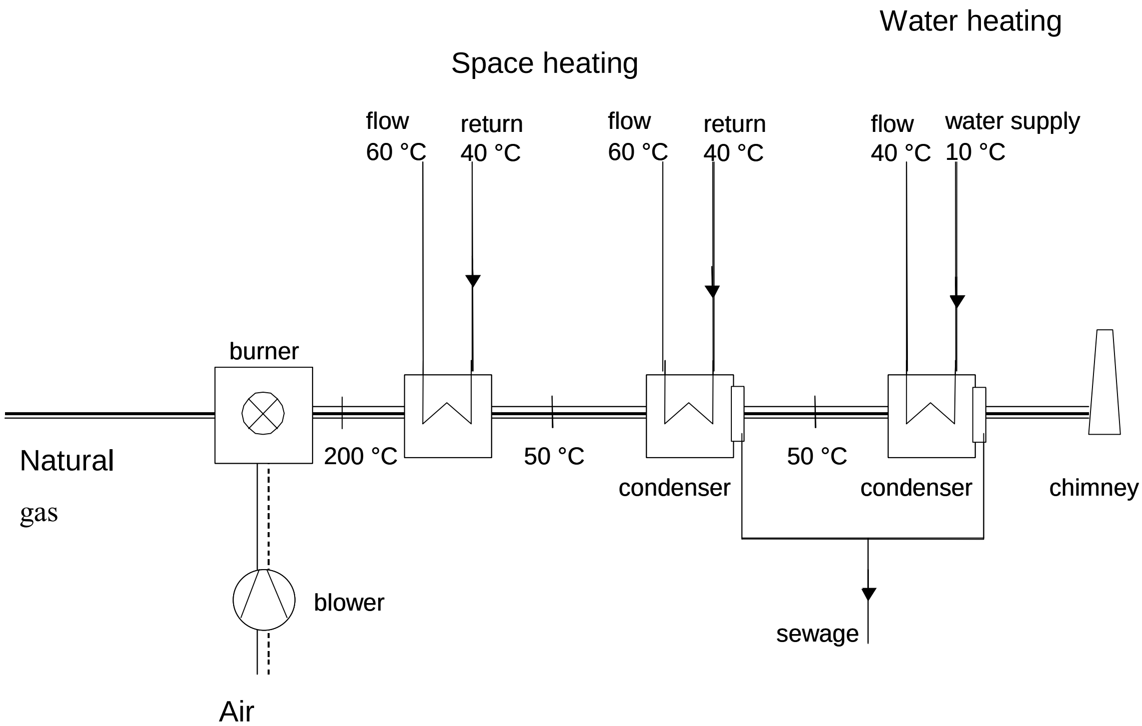

Figure 5.1 S*cheme of a gas-fuelled condensing boiler*

Condensing boilers primarily were designed for large systems with capacities of several hundred kW to meet with industrial demands. Meanwhile, suitable capacities for residential space heating have been offered. From their market introduction in the early 1980s, condensing boilers have continuously made their way towards becoming a considerable factor in the heat supply market. In 2002 condensing boilers for residential space heating have reached market shares of 89% of all gas boilers for residential space heating in the Netherlands (1996: 56%), 62% in Germany (1996: 18%), 13% in the UK (1996: 4%), 3% in Italy, 44% in Austria, 16% in Denmark, and 21% in Belgium (Pfannstiel, 2003; Haug et al, 1998). However, the statistics is led by Switzerland, where condensing boilers in 2002 have made 100% of all gas boilers sold for residential space heating (Pfannstiel, 2003).

5.2 Cost and capacity development

A first examination of condensing boilers` investment costs has been given by (Blesl, 2002) (see Figure 5.2), with a comparison of investment costs for condensing boilers and conventional systems over capacity.

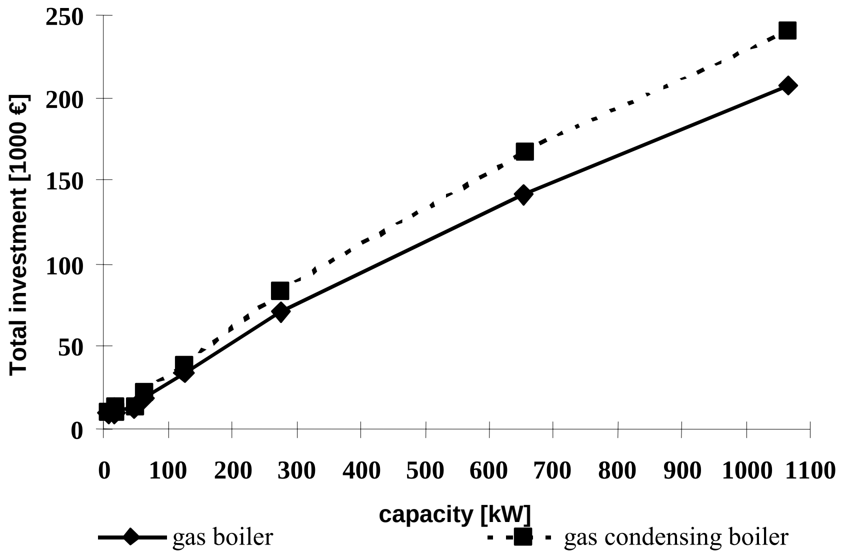

Figure 5.2 *Comparing investment costs of low temperature gas boilers and gas-fuelled condensing boilers over capacity, construction of district heat stations included*
Source: Blesl 2002.

Further cost data are available through EWU for the years 1992, 1994, and 1999, as illustrated by Figure 5.3. Additionally, the cumulative capacities of condensing boilers in the German market are depicted in Figure 5.4.

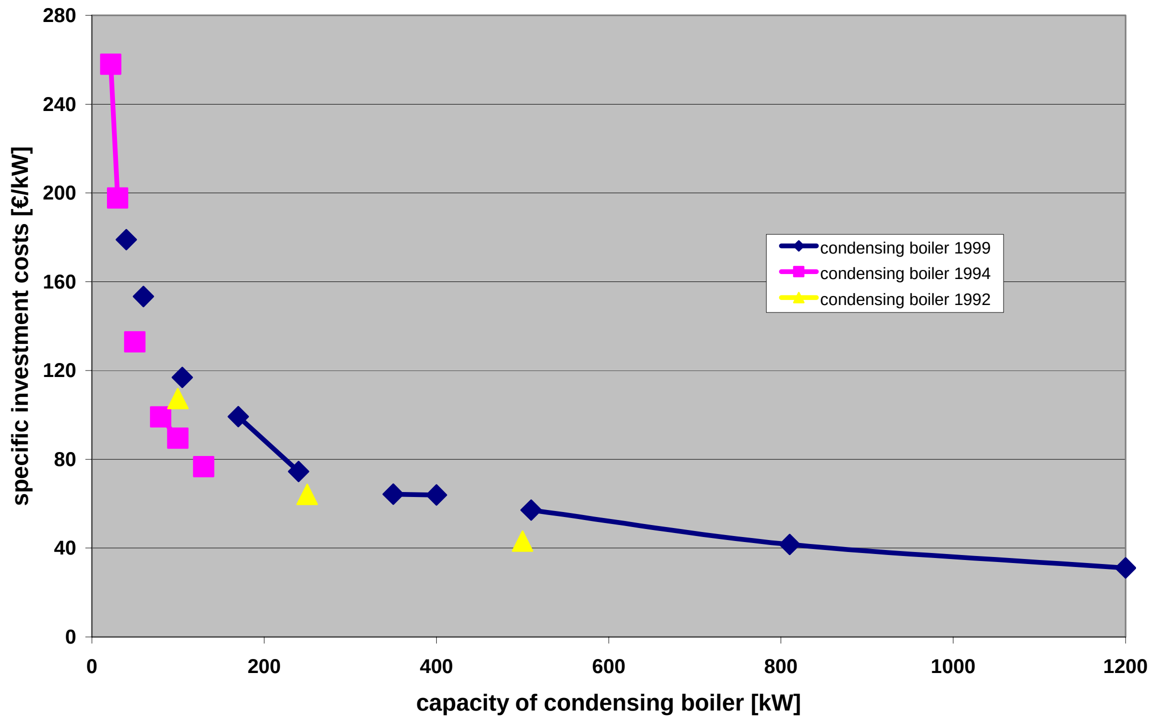

Figure 5.3 *Specific investment costs of condensing boilers in Germany for different years*
Source: (EWU 1992, 1994, 1999).

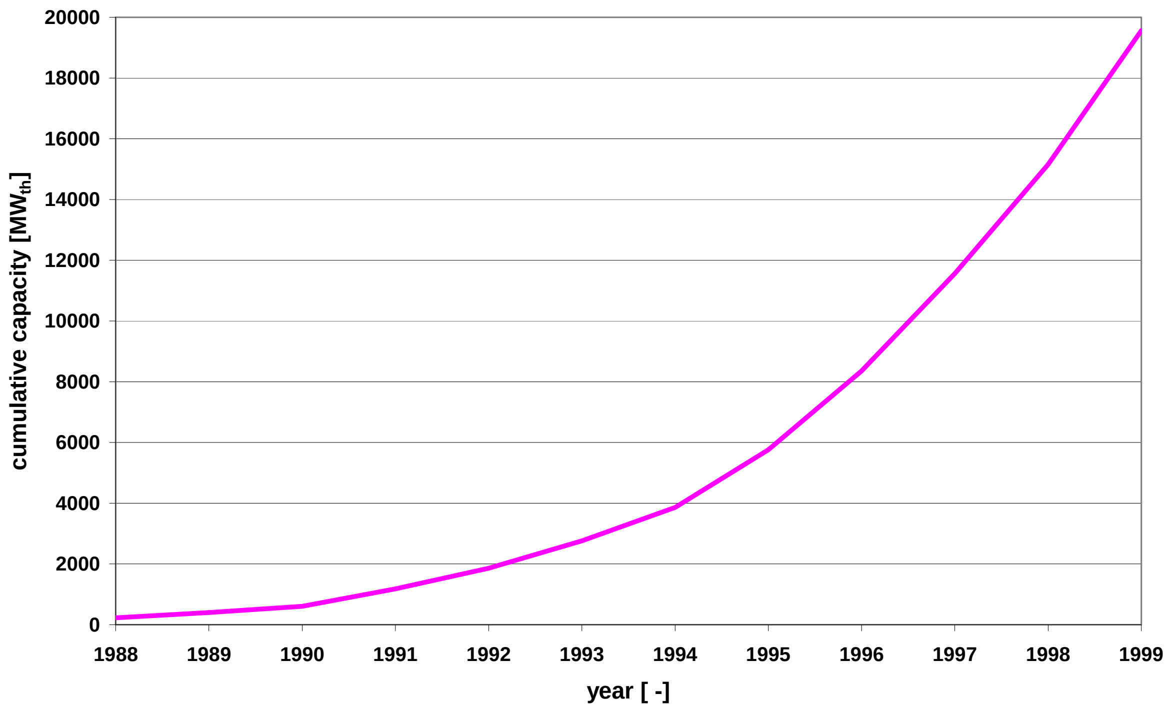

Figure 5.4 *Cumulative capacity of condensing boilers installed in Germany 1988-1999*
Source: (Beckervordersandforth, 2001).

With the information delivered by the two diagrams a learning curve can be constructed (see Figure 5.5).

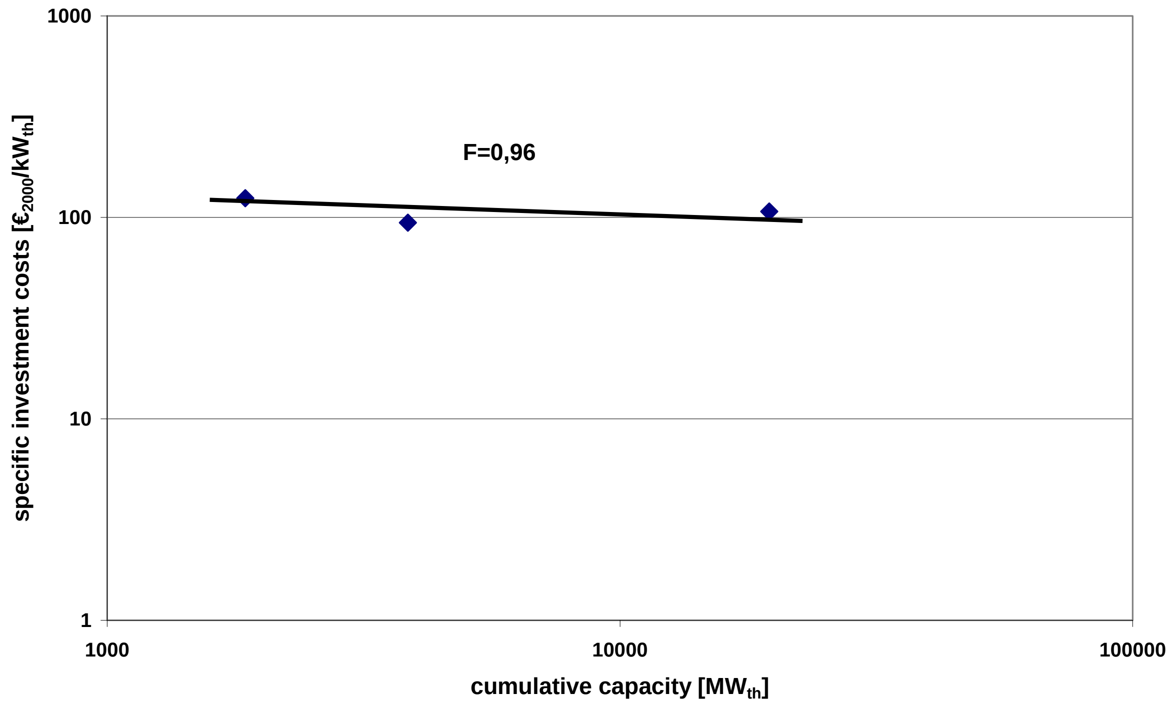

Figure 5.5 *Inflation-adjusted learning curve for the German condensing boiler market 1992-1999*

For the German market the learning factor of condensing boilers is 0,96 (see Figure 5.5).

Haug et al. 1998 have dealt with the development of investment costs of condensing boilers over cumulative sales for several European markets. For the Dutch market (see Figure 5.6) there was sufficient data available to examine learning effects.

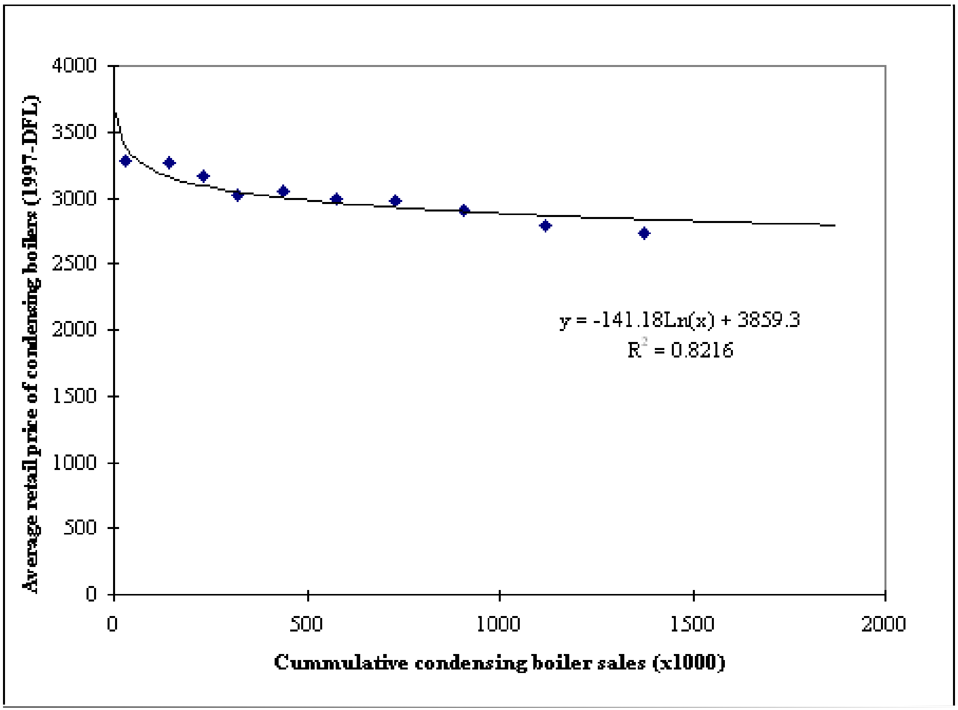

Figure 5.6 *Development of investment costs of condensing boilers in the Dutch market over cumulative sales for capacities between 15 and 25 kW*
Source: (Haug et al., 1998)

The learning curve for the Netherlands is shown in Figure 5.7.

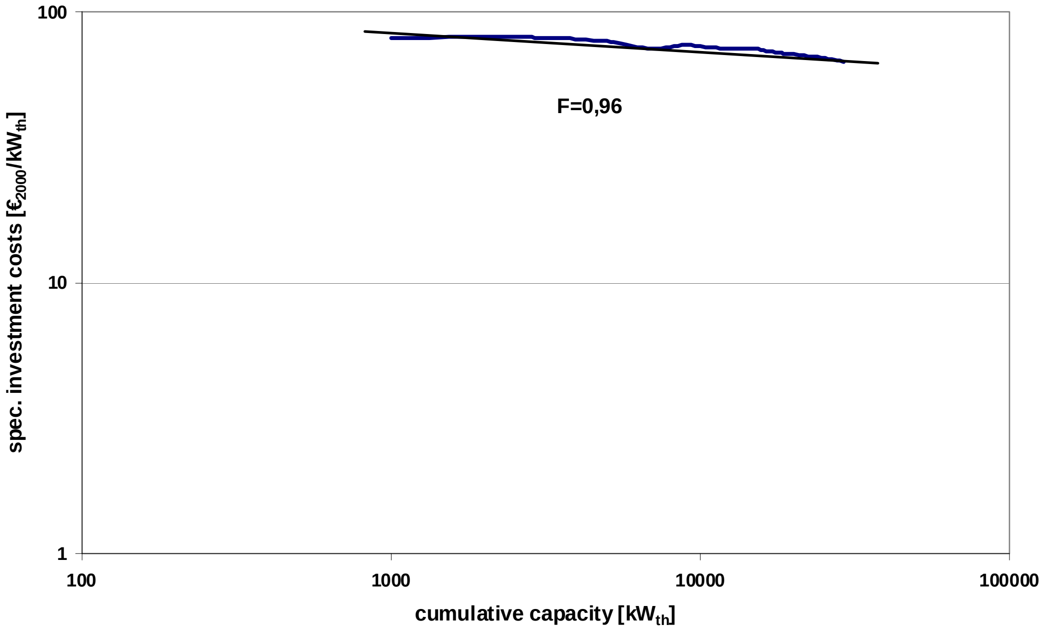

Figure 5.7 *Inflation-adjusted learning curve of condensing boilers in the Netherlands 1983-1997*

Exactly like for the German market, the learning factor for the Netherlands is 0,96. This is a pretty small learning factor, that proves that the condensing boiler is a mature and established technology with very little opportunities for further cost reductions left unless by a continuous widening of production.

A first comparative overview of operational costs of 12 and 60 kW_{th} low temperature gas boilers and condensing boilers is given by Table 5.1

Table 5.1 *Overview of basic data for low temperature gas boilers and gas condensing boilers*

		Low temperature gas boilers		Gas condensing boilers	
Capacity	[kW_{th}]	12	60	12	60
Annual use efficiency	[%]	90	89	96	94
Spec. investment costs	[€/MWh_{th}]	345	165	445	193
Spec. fixed operational costs	[€/MWh_{th}]	17	8	17	8
Spec. other variable costs	[€/MWh_{th}]	1.15	1.05	1.1	1.14

It becomes obvious that conventional low temperature gas boilers have lower specific investment costs than gas-fired condensing boilers. Instead, the annual use efficiencies of condensing boilers are higher. Whereas the fixed operational costs (e.g. for maintenance) are the same for both types of boilers, the spec. other variable costs of condensing boilers can be 4,3% lower for small capacities (12 kW_{th}), due to better fuel utilisation. For larger capacities (60 kW_{th}) with a lower annual use efficiency (in compare to the smaller-sized condensing boiler), spec. other variable costs can be higher than for conventional boilers.

6. Organic Rankine Cycle

6.1 Technology description

Organic Rankine Cycle (ORC) is a rather new technology for the production of heat and electricity. ORC plants are particularly suitable for the utilisation of heat from geothermal sources or biomass combustion. ORC´s technical principle resembles the conventional Rankine process as used for electricity production by steam turbines. The basic difference is the application of liquid (organic) hydrocarbons, like toluene, isopentane, isooctane or polysiloxane oil as a working fluid, instead of water. The respective plant layouts are accordingly similar. With biomass fed ORC plants, biomass is combusted with air supply in a boiler. The heat produced thereby is transferred to a thermo-oil cycle by a heat exchanger. Another heat exchanger evaporates the working fluid in the ORC circulation system to drive the turbine. A generator connected to the turbine turns the turbine´s mechanical energy into electricity. The heat left in the ORC circulation system is transferred to a heat consumer cycle by a condenser, e.g. for a district heating application. This cycle also takes up the waste heat from the flue gas of the combustion, thus enhancing thermal overall efficiency. The basic process of a (biomass-fueled) ORC plant is shown in Figure 6.1. An advanced version of an ORC plant operating with combustion air preheated by the flue gas is depicted in Figure 6.2.

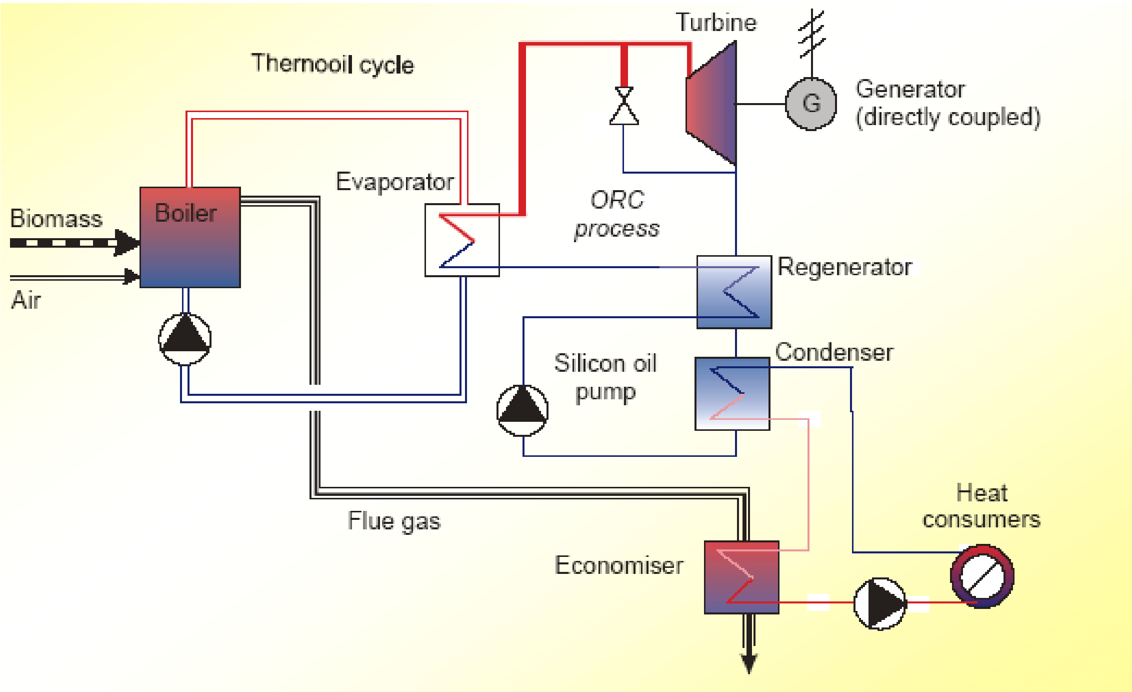

Figure 6.1 *Process scheme of a biomass-fueled ORC plant*
Source: Obernberger, 2003.

When utilising geothermal heat in an ORC plant, the thermo-oil cycle is dispensed with, so that the hot water from the well is directly used for the evaporation of the organic working fluid. The rest of the layout is similar to that of biomass fed plants, yet without the additional components for the recovery of the heat from the flue gases. One of the advantages of the ORC concept, compared to a steam based Rankine process, is the lower boiling temperature of the organic working fluids. Hence heat of a temperature level even below 300°C can be used for electricity production. Turbine efficiency is 85% with good controllability and excellent properties of the turbine under part load (operating range 10-100%) (Obernberger, Hammerschmied,1999). The turbine has a very short start-up period enabling flexible temporal operation. Overall efficiency including waste heat utilisation can be from 70 up to 105%, if a flue gas cooling system is applied to condense the steam fractions of the flue gases. By choosing an appropriate working fluid, the process can be adjusted to the conditions both on the hot and the cold side of the plant, thus achieving the maximum efficiency. The plants can be operated in a completely automated mode, and ORC technology already has positive operational records. Moreover, ORC plants have very low maintenance costs.

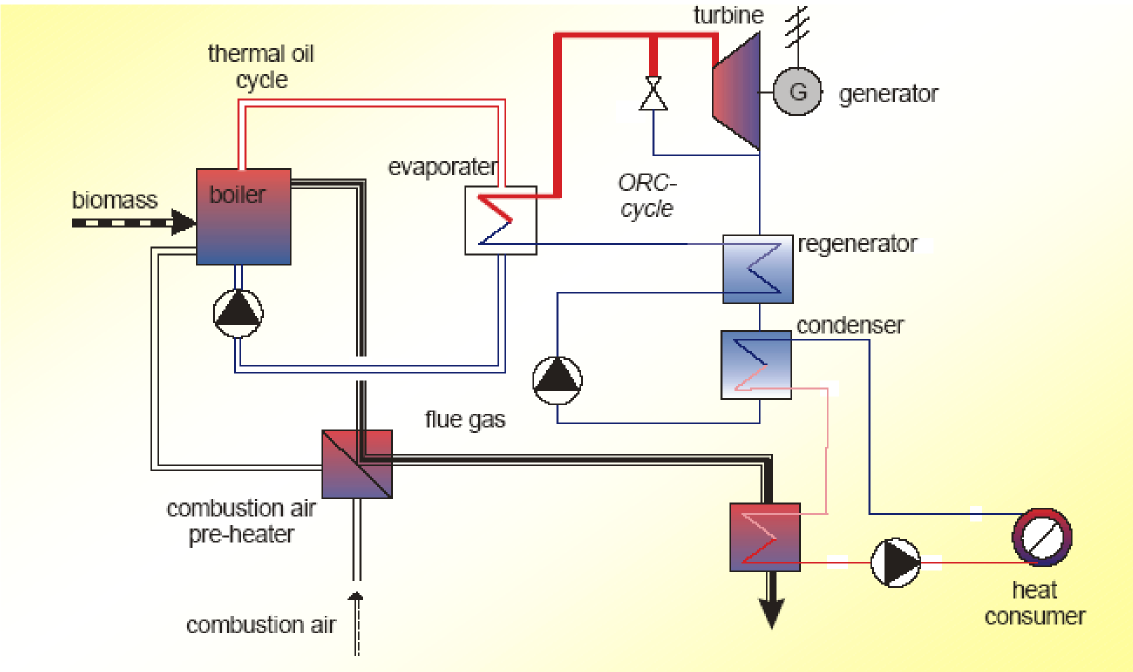

Figure 6.2 *Advanced ORC plant with combustion air pre-heater*
Source: (Obernberger, 2003)

The essential disadvantages of ORC plants concern their high demand of heat exchanger surface if thermo-oil is involved in the process and the fact that there is only a heat-conducted operation mode possible. Beside these points, ORC plants need high full load operation periods of 4000-6000 hours per year for cost effectiveness, and their electrical efficiency of 13-18% (relative to the energy content of the fuel) is very low. The electricity-heat ratio of ORC plants is 0.23, which is also very low compared to competitive power generating technologies. Current overall investment costs are 7475 €/kW$_{el}$ (reference: Admont ORC plant, Austria), which is severalfold higher than investment costs of conventional power plants. Using geothermal sources has specific investment costs of 2529 €/kW$_{el}$ (Kaltschmitt et al., 2003) with a range of electrical efficiency between 4 and 13%, relative to the heat content of the hot water pumped from the ground. Most significant technical data, classified by different sources of heat, is summarised in Table 6.1.

Table 6.1 *Basic data on the utilisation of heat from different sources in ORC plants*

		Heat source		
		Geothermia	Biomass combustion	Industrial processes (1985)
Range of capacities available	[kW$_e$]	100-1200	100-2000	100-10000
Electrical efficiency	[%]	4-13	13-18	15
Spec. overall investment costs (reference value)	[€/kW$_e$]	2529 (850 kW$_e$)	7765 (400 kW$_e$)	1235-2556 (960 kW$_e$)
Thermal range of heat source	[°C]	100-240	max. 1100	100-400

6.2 Current capacity

Currently plant capacities between 100 kW_e and 1,5 MW_e are available. In Germany, nine plants with a total of 6500 kW_e are operating (reference year 2004) (Gaderer, 2002; Mrowald, 1999; Kohlbach, 2004) plus one 1500 kW_e plant being under construction. Throughout Europe there are another 23 plants with a total of 28100 kW_e in service or under construction (see Table 6.2).

Table 6.2 *ORC plants in Europe*

Country/location	Capacity [kW_e]	Commissioning year	Comments
Germany			
Lengfurt	1200	1999	Utilisation of industrial waste heat from cement production.
Sauerlach	480	2001	District heating; overall investment costs 8900 k€.
Weimar	500	2002	
Friedland	500	2001	
Wurzbach	400	2001	
Lobenstein	500	Unknown	
Ostfildern	1000	2002	Wood chip combustion as heat source; overall investment costs 5202 k€, investment costs ORC 1607 k€.
Hengersberg	1500	Under construction	
Neckarsulm	1000	002	District heating; investment costs ORC 1400 k€, overall investment costs 6000 k€.
Ploessberg	1100	2003	Wood combustion; heat supply for the drying process of a pellet factory.
Austria			
Admont	400	1998	Overall investment costs 3200 k€.
Lienz	1000	2002	District heating: investment costs ORC 1360 k€.
Fussach	1000	2001	Incl. absorption chiller (1350 k€), CHP 6140 k€.
Seyring (Vienna)	1000	2002	Incl. absorption chiller.
Altheim	1000	2001	Utilisation of geothermal heat, overall investment costs 5 M€ incl. drilling.
Klosterneuburg	200	2002	
Großarl	600	2004	District heating.
Hall (Tyrolia)	1000	2005	District heating.
Leoben	3·1500	2005	Heat supply for a drying process.
Bregenz	1000	2002	Integrated in a PET bottle plant, incl. absorption chiller.
Siezenheim	1500	2004	District heating.
Lofer	600	2004	District heating.
Abtenau	1100	2004	Heat supply for the drying process of a pellet factory.
Längenfeld	1100	2004	District heating.
Thal Aue	1100	2004	Heat supply for a drying process.
Theurl	1000	2004	
Switzerland			
Bière	300	1998	District heating.
Crissier	500	2001	Heat from waste wood combustion.
Hungary			
Kaszó	1100	Under construction	
Italy			
Tirano	1000	2003	District heating.
Dobbiaco/Toblach	1500	2003	District heating.
Nocera Inferiore	450	2004	Heat from waste incineration utilized.
Schluderns	450	2005	
France			
Soultz-sous-Forêts	6000	2005	Utilisation of geothermal heat.
Czech Republic			
Trhove Sviny	600	2005	District heating.

Source: Gaderer, 2002; Mrowald, 1999; Kohlbach, 2004; Turboden, 2004)

Besides the heat sources mentioned, ORC plants can also be operated using waste heat from industrial processes. For example, the ORC plant at Lengfurt, Germany, is supplied with heat from cement production (about 275°C) (Mrowald, 1999).

6.3 Investment Costs And Learning Curve Approach

Investment costs of the most significant ORC components are shown in Table 6.3. Compared to other technologies of large-scale heat production, ORC plants result to be quite expensive. Therefore the operation of ORC plants is still depending on public subsidies.

Investment costs of a technology do not grow proportionally with plant capacity. The capacity-related investment costs of a technology though can be calculated by the formula

$$I_1 = \sum_{j=1}^{J} i_{j,0} \cdot \left(\frac{c_{j,1}}{c_{j,0}} \right)^{n_j}$$

with:

- I = investment costs of plant,
- I = investment costs of component,
- J = number of components
- c = capacity
- n = exponent of degression
  - index 0: data of base capacity
  - index 1: plant/component to be examined

Table 6.3 *Current investment costs for ORC plant components*

Component	Base capacity	Investment costs [€]	Exponent of degression
Thermo-oil boiler incl. ash removal and control system	5000 kW$_{th}$	784000	0,48
Fuel supply incl. silo	5000 kW$_{th}$	52000	1,40
Electrostatic flue gas filter	5000 kW$_{th}$	165000	0,34
ORC module incl. generator and control system	1200 kW$_{e}$	1250000	0,68

As there is quasi just one manufacturer of ORC core technology in the market, it is no use to examine European ORC applications split up into national markets. Instead, the European ORC market is regarded as one.The learning curve of European ORC technology is shown in Figure 6.3. As the data for this curve come from different countries (Germany and Austria) no inflation-adjustment could be performed.

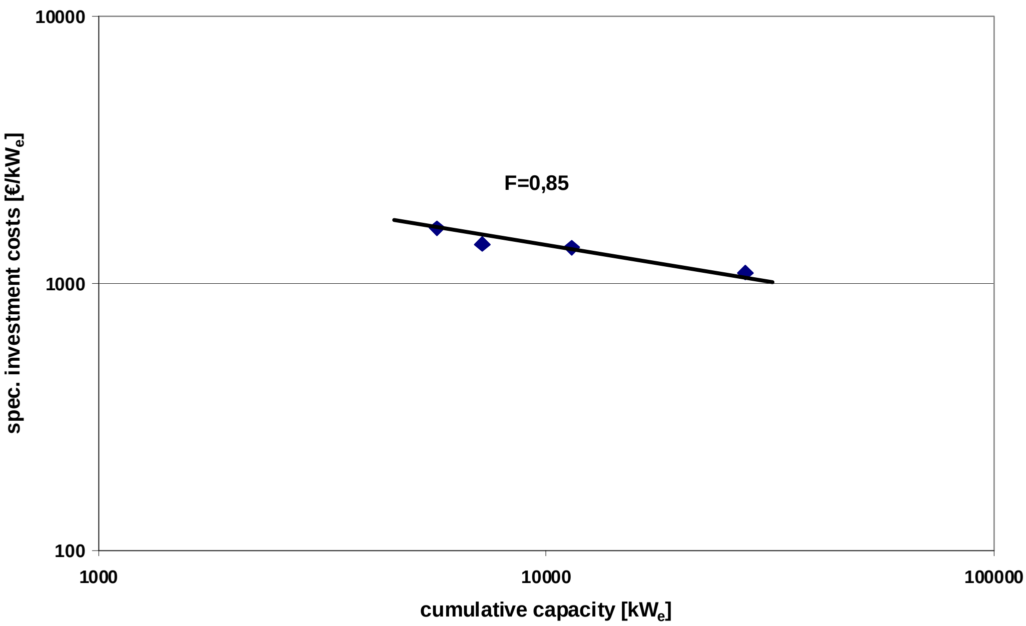

Figure 6.3 *Learning curve for ORC modules (European market)*

The learning factor for ORC modules is currently 0,85, which is quite typical for this stage of the technology, as there´s no serial production of ORC modules so far. For the calculation of the overall investment costs it is important to know that the ORC module is just one part of the entire plant, as there are a lot of other components required, depending on the plant´s purpose (e. g. district heating supply) and its energy source (for instance geothermia or combustion of different kinds of waste materials or fuels) utilized. Some of the other components that are vital to the operation of an ORC plant have already been produced in serial production (e. g. the boilers, pumps, heat exchangers), some have to be manufactured in single production without a chance for serial production (buildings, fuel preparation). For these parts neither a general or an essential cost reduction should be expected even for an increased cumulative capacity.

6.4 Current R&D issues

R&D activities in ORC technology are focussing on the quest for new organic working fluids and new energy sources, especially from different kinds of industrial processes. In the geothermal area the number of plants projected is steadily increasing. Besides, the manufacturers of ORC modules are eager to develop and install serial production facilities in order to raise the output and cut down production costs.

7. Capture and sequestration of carbon dioxide

Carbon dioxide capture and sequestration (CCS) has gained a lot of interest lately, not only in the context of climate change, where it may be used to mitigate the effects of CO_2 emissions, but also from industry, as it provides a motive for extension of lifetime of coal power plants in the USA. While it is regarded as a new technology in the context of energy systems, in the chemical industry CO_2 separation already occurs for process purposes. However, as industry and material flows fall outside the scope of this study, the industrial use of CO_2 separation will not be treated, and hence the focus will be on energy related CO_2 capture. Furthermore, the use of natural occurring CO_2 for enhanced oil recovery and the single example where it is used for enhanced coalbed methane recovery will not be considered here.

7.1 Current status of CCS

The development of CCS is mostly in the research and development phase, with only three demonstration projects in progress. Presently, only tree sites are actually capturing and storing the captured CO_2. In Norway, CO_2 is captured from gas mined at the Sleipner oil field, and sequestrated instead of vented to the atmosphere. At the Weyburn facility in Canada CO_2 from a coal gasification plant in the USA is used in enhanced oil recovery. Further projects with CO_2 capture from energy processes are announced but are only on the drawing board at this time, such as capture and storage at LNG facility in Australia.

7.2 Technologies

The IEA GHG R&D programme has collected an extensive number of reports containing thorough descriptions of technologies, with all possibilities and parameters. For detailed technology analysis and comparison these are very valuable, but for large energy system analysis tools, they prove to be too detailed. For this study, two technology options for capture will be retained. They cover the bulk of the capture possibilities and have a wide area of application that is favourable for technology spill over effects.

7.2.1 Post combustion separation and capture of CO_2

A variety of techniques is available for post-combustion separation of CO_2 from the flue gas. The main one in use today is scrubbing the gas stream using an amine solution. After leaving the scrubber, the amine is heated to release high purity CO_2 and the CO_2-free amine is then reused. This option can also be used for separation of CO_2 from other gas streams. As an example of the process, Figure 7.1 shows the capture from a natural gas turbine.

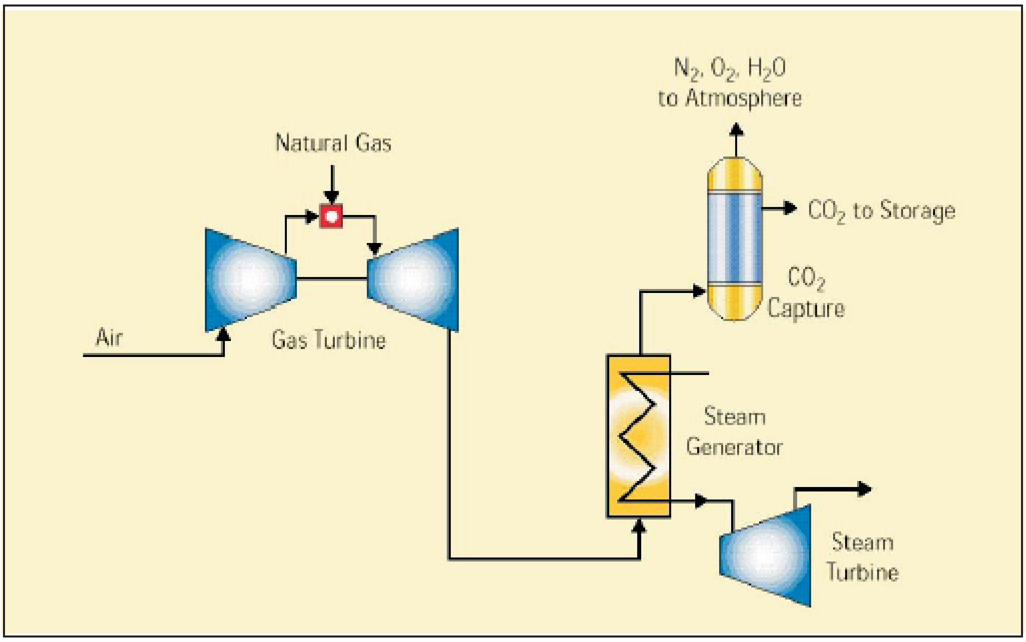

Figure 7.1 *Post-combustion capture of CO_2, here shown for capture from a gas turbine*

In many respects, post-combustion capture of CO_2 is analogous to flue gas desulphurisation (FGD), which is widely used on coal- and oil-fired power stations to reduce emissions of SO_2. The flue gas has low concentrations of CO_2, ranging from 14% in pulverised coal (PC) power plants, through 9% for integrated gasification combined cycle (IGCC) power plants, to as low as 4% in natural gas combined cycle (NGCC) power plants. This leads to large volumes of gas that have to be handled, resulting in large and expensive equipment. A further disadvantage of the low CO_2 concentration is that powerful solvents have to be used to capture CO_2. Consequently the regeneration of these solvents in order to release the CO_2 requires a large amount of energy. The CO_2 capture rate presently is about 85%, and is expected to increase to 90% in 2010, i.e. 85% of the carbon contained in the flue gases (and hence in the fuel) is separated and ready for storage, the remaining 15% is vented in the air.

The CO_2-concentration can be increased greatly by using concentrated oxygen instead of air for combustion, either in a boiler or a gas turbine. If fuel is burnt in pure oxygen, the flame temperature is excessively high, so some CO_2-rich flue gas would be recycled to the combustor to make the flame temperature similar to that in a normal combustor. The advantage of oxygen-blown combustion is that the flue gas typically has a CO_2 concentration of over 90%, so only simple CO_2 purification is required. The disadvantage is that production of oxygen is expensive, both in terms of capital cost and energy consumption. This option is actually not considered due to lack of information about dedicated oxygen technologies (turbines, combustion chambers) for power technologies.

The post combustion option is considered to be suitable for CO_2 capture from all flue gas flows from power plants (and large industrial boilers). As mentioned above, it is even suitable for other processes involving the separation of CO_2 from gas streams; e.g. the Sleipner project uses the same technology with amine scrubbers to remove excess CO_2 form the extracted natural gas.

7.2.2 Pre-combustion capture of CO_2

An alternative way to increase the CO_2 concentration and partial pressure is to use pre-combustion capture. This involves reacting the fuel with oxygen and/or steam to give mainly carbon monoxide and hydrogen. Carbon monoxide (CO) is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. The CO_2 is then separated, e.g.

using Selexol as solvent and with depressurisation to release the CO_2. The hydrogen (H_2) is used as fuel in a gas turbine combined cycle plant. In principle, the process is the same for coal, oil or natural gas. In Figure 7.2 a simplified diagram of a coal-fired (IGCC) power plant with pre-combustion capture of CO_2.

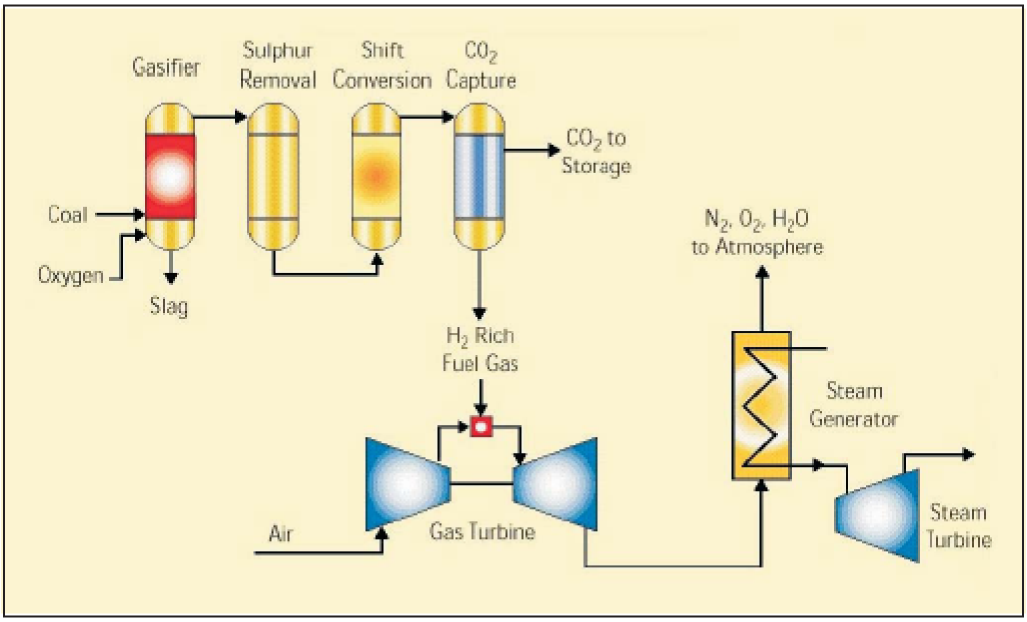

Figure 7.2 *Pre-combustion of CO_2, here shown for an integrated gasification combined cycle process*

Although pre-combustion capture involves a more radical change to the design of the power plant, most of the technology is already well proven in ammonia production and other industrial processes. One of the novel aspects is that the fuel gas is essentially hydrogen. Although it is expected that it will be possible to burn hydrogen in an existing gas turbine with little modification, this is not a commercially proven technology. Nevertheless, at least two gas turbine manufacturers are known to have undertaken tests on combustion of hydrogen-rich fuels.

The hydrogen produced in pre-combustion capture processes could, alternatively, be used to generate electricity in a fuel cell. The technology of capture and storage is therefore expected to be suitable for future as well as current power generation technologies, and may even prove to be useful in a transition towards an energy system without fossil fuels.

Pre-combustion capture can be considered suitable for all fuel treatment processes in which hydrocarbons are shifted to H_2 and CO_2. Thus it can play a role in fossil fuel gasification for electricity generation as well as in H_2 production from the (partial) oxidation of natural gas, oil or solid fuels (coal and biomass). The capture rate presently lies above 90%, and is can reach 97% for H_2 production facilities. The Weyburn facility uses CO_2 from a synthetic fuel plant and hence is an example of a pre-combustion separation and capture process.

7.3 Characteristics of CO_2 capture technologies

7.3.1 Costs of CO_2 capture

The costs of carbon capture are usually expressed as additional costs, rather than in terms of absolute costs. For post-combustion CO_2 capture, these additional costs are expected to decrease roughly one third between now and 2012 (Herzog, 1999, 2003; David, 2003).

For the long term, an assumption on the floor costs can be made, which will still depend on the type process used as well as on the fuel used. The actual costs for the various technologies are summarized in Table 7.1, which however does not include the option of retrofitting existing coal-fired plants. It is expected that retrofitting can be done at additional cost of 710 $\$/kW_{electric}$.

Table 7.1 *Additional cost of CO_2 capture for pre- and post combustion capture*

Process	2000 [$\$/kW_e$]	2003 [$\$/kW_e$]	2012 [$\$/kW_e$]	floor cost [$\$/kW_e$]
Pre combustion capture		451-504	314	180
Post combustion coal	920	890	623	400
Post combustion gas	470	370	314	200

Source: Herzog, 1999, 2003

7.3.2 Energy penalty of CO_2 capture

The capture of CO_2 from an electricity producing process will result in a loss of efficiency, which is called the energy penalty. Thus, the energy penalty of CO_2 capture is the difference in efficiency between similar power plants without and with CO_2 capture. It is largest for post-combustion processes, where it currently lays around ten percent for coal fired power plants, and slightly less for gas fired power plants. These energy penalties are expected to decrease due to further optimization of the components in the CO_2 capture process, to six percent by 2010. For pre-combustion capture the energy penalty is expected to decrease from its present level of a little over six percent to some four percent in 2012. All in all, one might say that the energy penalty is expected to be rather small as compared to the power plant efficiencies. A summary of the numerical values is given in Table 7.2.

Table 7.2 *Energy penalty of CO_2 capture*

Process	2000 [%]	2012 [%]
Pre combustion capture	6.1	4.3
Post combustion coal	10.2	6.0
Post combustion gas	7.2	6.0

7.3.3 Additional costs of CO_2 capture from H_2 production

Another technological option in which capture of CO_2 may occur is in the production of H_2 by means of partial coal oxidation processes. For such processes, additional costs for CO_2 capture ranges from 2.2 to 2.9 $\$_{2000}/(GJ\ H_2)$.

7.4 Storage options

Capturing of CO_2 is not sufficient to remove it from the atmosphere; a safe and permanent storage is also required. To store CO_2 again different options are recognized. The most important ones are to be found in geological storage. Storage in mineral products or for example use in food products (gasified drinks), or other more ‘exotic’ forms of sequestration are not expected to contribute significantly to climate mitigation. Particularly because it is hard to imagine how such options could be comparable in scale with respect to the quantities of CO_2 captured from energy technologies. Sequestration in biological sinks, such as forest and soils, is not considered here because these options capture the CO_2 directly from the atmosphere and do not need a separate capture technology or process.

There are various options that can be used for geological storage of CO_2. Here, the following are considered:

- Depleted oil and gas fields: the CO_2 is injected into fields that have been taken out of production,
- Enhanced oil and gas recuperation (EOR and EGR): the CO_2 is used as a mean to pressurize a production field, thus combining the advantage of CO_2 storage with the benefits of continued mining,
- Unminable coal seams, combined with the recovery of methane (generally referred to as enhanced coal bed methane, ECBM). Like in the previous option, this storage option has a side benefit, in that the storage results in the recovery of methane
- Saline aquifers: storage in underground saline water reservoirs.

The option to store the CO_2 in oceans is expressively not included. At present, its impact on the environmental is unclear, making it highly unsure whether this particular option is acceptable in the long run. Such misgivings do not (to the same extend) exist for the other options.

7.4.1 Potentials of storage options

The various options each come with their own global potential. These are summarized in Table 7.3, where the potentials according to two different sources are given. The potential as given by (IEA, 2001) is expressed in terms of the cumulative storage capacity up until 2050, whereas (Edmonds, 2000) provides an estimate for the total cumulative capacity. The table clearly illustrated that the most important option is the storage in saline aquifers, as this is the most abundant resource.

Table 7.3 *Potentials for CO_2 storage*

	Gton CO_2 2050[1]	Gton CO_2[2]
Depleted oil fields	126-400	150-700
Depleted gas fields	800	500-1100
Enhanced oil recovery	61-65	
Unminable coal seams	>15	>73
Saline aquifers	400-10,000	320-10,000

[1]Source: (IEA GHG, 2001)
[2]Source: (Edmonds, 2000)

There are some studies reporting on regional distributions for some of the options. These are included in the Annex. One of these studies also provides estimates for technical and economical parameters. Furthermore, it gives an overview of the operations currently taking place. These are mainly concentrated in the USA, where the oldest project in the world is running, in which 33 Mton CO_2 per year from natural resources has been stored in enhanced oil recovery since 1972. Since 2000, use of CO_2 sequestration in enhanced oil recovery at the Weyburn field resulted in an annual storage of 1 Mton CO_2. A further 30 kton per year from natural sources has been stored in the USA in enhanced coal bed methane mining. Presently, the only long-running project outside the USA is the injection of removed CO_2 into saline aquifers at the Sleipnir field, in the Norwegian part of the North Sea.

7.4.2 Costs of storage options

It is clear that the range in the estimates of potentials is considerable. Therefore, it should come as no surprise that the cost estimates are far from uniform. Moreover, in many cost estimates for storage in combination with enhanced recovery, the price of oil or gas is included in storage cost estimates.

The uncertainty, and in some cases model-dependence of these prices, make it hard to directly use the cost estimates, while at the same time the present price range make a de-convolution far from trivial. When the fuel costs are included, quite often negative storage costs per ton CO_2 are quoted, taking into account the benefits from the energy recovered (oil, gas or coal bed methane).

Nevertheless, some order-of-magnitude estimate for the costs of storage can be obtained from the literature. The estimates are given in Table 7.4, together with some technological characteristics, such as the amount of electricity needed per ton of CO_2. For those options where the CO_2 is applied in the extraction of fossils, also the energy recovered per ton CO_2 is given.

Table 7.4 *Economical and technical parameters for various storage options*

		Depleted fields	EOR/EGR	ECBM	Aquifers
Investment cost	[$/ton CO_2]	5-11	5-11	12.5-17.5	1-11
Transport cost	[$/ton CO_2/300km]	2.5	2.5	2.5	2.5
Fixed O&M cost	[$/ton CO_2]	0.25-0.35	0.17	0.25-0.50	0.375
Variable O&M cost	[$/ton CO_2]	1.35	0.90	12.5	0.30
Electricity requirement	[MWh/ton CO_2]	0.08-0.11	0.14	0.08-0.21	0.11
Energy recovery	[GJ/ton CO_2]	-	1.80-2.22	5.5-9.0	-

Source: (Smekens, 2003; IEA, 2004).

7.5 Cumulative capacity for capture and storage

In Table 7.5 the cumulative capacity of CO_2 capture and storage is given, including the capture from natural resources, but with the exception of the 33 Mton CO_2 per year in EOR in the USA.

In the USA there is experience over a couple of decades already about CO_2 storage in enhanced oil recovery (EOR), but this is not driven from a climate point of view but purely business driven in order to increase oil production. This actually has consequences for the storage time - it is uncertain in many cases whether CO_2 storage is actually taking place. In this context it is justified to rather use 'CO_2 injection' instead of 'CO_2 storage' for the present the USA EOR activities.

In addition, leakage and accounting play now no role in the existing CO_2 storage in EOR in the USA. About retention times and leakage rates to the atmosphere, some studies are available, but they are not supported by empirical data. There is also no risk assessment methodology and the EOR projects usually take place in sparsely populated areas, so no problem with public resistance.

Furthermore, most EOR projects use CO_2 from natural sources (the purchase of which contributes on average to 68% of the storage costs) and therefore do not mitigate climate change (Johns et al , 2002).

Table 7.5 *Cumulative capacity for CO_2 capture and storage*

[Mton CO_2/yr]	1995	1996	1997	1998	1999	2000	2001	2002	2003
Captured	-	0.2	1.2	2.2	3.2	4.2	6.2	8.2	10.2
Stored[1)]	-	0.2	1.2	2.23	3.26	4.29	6.32	8.35	10.38

[1]Excluding 33 Mton per year from enhanced oil recovery in the USA

In the Sleipner project, CO_2 is captured in the exploitation of a gas field. The CO_2 is separated from natural gas through scrubbing, and as was explained in paragraph 7.2.1, this process may well be compared to post-combustion capture of CO_2 in a power plant. The resulting CO_2 from the Sleipner field is stored in a saline aquifer. The process is active since 1996 at a rate of 1 Mton CO_2 per year, with a smaller amount in the year of start-up. As can be seen from the table, the other contribution to the cumulative capacity in carbon capture starts up in 2000, as the Weyburn facilities starts to contribute another 1 Mton CO_2 per year. Here, the capture is done in a shift reactor (i.e. in a gasification plant), and the CO_2 is used in EOR. Two smaller contributions, to storage only, are the 30 kton per year since 1998 from the Allison unit in the USA, and a further 2.2 kton stored in aquifers in Japan from 2003 onwards. It is clear that there is only very limited experience with an integrated system involving capture of CO_2 and its storage. Strickly speaking, there is only one project in which CO_2 is actually captured in a power plant, namely at the Weyburn facility. However, because of the similarities between separating and capturing CO_2 from natural gas, the data from the Sleipner project can be included under post combustion capture. Thus, the capacities associated to the Weyburn and Sleipner projects can be estimated using the captured amount of CO_2, in combination with an estimated efficiency and operation conditions. The resulting numbers are given in Table 7.6.

Table 7.6 *Cumulative capture capacities for key technologies in the power sector*

[MW_e]	Region	1995	1996	1997	1998	1999	2000	2001	2002	2003
Post combustion gas	Western Europe	0	70	350	350	350	350	350	350	350
Pre combustion	USA						0	210	210	210

7.6 R&D expenditures

Various sources are available from which estimates of R&D expenditures can be constructed. As the major part of the interest in CCS technologies stems from the previous decade, and the interest is furthermore concentrated in a few projects, data on the major projects seems to suffice for such an estimate. An overview is provided in Table 7.7. In case a project concerns both capture and storage, it is assumed the expenditures are shared equally between these two technologies.

Table 7.7 *Estimated cumulative R&D expenditures in $M€_{2000}$*

Year		Capture		Storage
	Pre comb.	Post comb., coal	Post comb., gas	
1990	0	0	0	0
1991	0	0	0	0
1992	0	0	0	0
1993	0	0	0	0.8
1994	0	0	0	1.7
1995	0	0	0	2.5
1996	0	0	0	2.5
1997	0	0	0	13.9
1998	2.5	2.5	2.5	32.7
1999	6.5	6.5	18.8	167.5
2000	13.5	13.5	37.8	309.2
2001	22	22.1	58.2	453.9
2002	35.3	36.5	82.8	620.6
2003	44.1	46.5	91.7	660.7

Note: Comb. Stands for combustion

A graphical representation is provided in Figure 7.3, showing clearly that energy related R&D for CO_2 capture and storage has only gained interest the last decade. Furthermore, storage is currently clearly the main field of interest from the point of view of R&D.

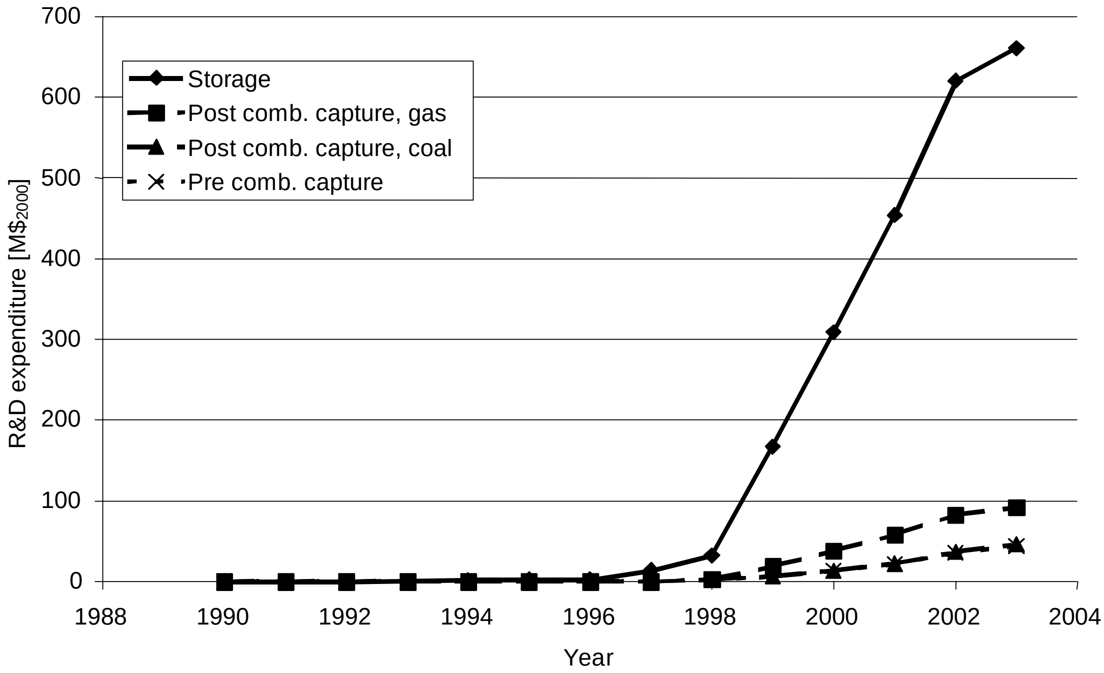

Figure 7.3 *Estimate for energy related R&D expenditures on capture and storage of CO_2*

8. Electrolysis

8.1 Technology description

In this report only electrolysis as mean for hydrogen production is considered. The main feed-stock is water which is converted to H_2 and O_2 by means of electricity.

Electrolysis accounts for 4% of the global hydrogen production (Duwe, 2003) (Table 2.1).

Table 8.1 *Current global hydrogen production*

Origin	Amount of hydrogen [bln Nm^3/yr]	Fraction [%]
Natural gas	240	48
Oil	150	30
Coal	90	18
Electrolysis	20	4
Total	500	100

Note: Mainly industrial use for ammonia-based fertilisers and oil refining.

The following industries supply electrolysers (Internet source 6):
- GL&V Hydrogen Technologies, Montreal
- Hydrogen Systems N.V., Belgium
- Norsk Hydro, Norway
- Proton Energy Systems, Inc
- Stuart Energy Systems, US
- Tathacus Resources Ltd.
- Teledyne Energy Systems
- Waterflame, Thailand.

8.2 Cost development

Basically, there are three types of electrolysis technology for hydrogen production, viz.:
- Alkaline electrolysis technology,
- Solid oxide electrolysis technology,
- PEM electrolysis technology.

Alkaline is the nearer term technology for larger systems, whereas solid oxide electrolysis is in early development. The PEM technology seems to be more apt for small-scale applications (Kaufmann, 2003). Solid oxide electrolysis is a high-temperature electrolysis process. High-temperature steam electrolysis makes use of a high-temperature heat source (Herring, 2003).

Table 8.2 gives an overview of the current state-of-the-art and the expectations of electrolyser technology.

Table 8.2 *Characteristics of electrolyser technology*

Company	Type of electrolyser	Energy consumption [kWh/Nm³]	H_2 production [Nm³/hour]	Input Power Rating [kW]	Pressure [bar]	Efficiency [% LHV]
Norsk Hydro	Alkaline	4.1-4.3	Up to 485	50-300	0.5-1	61-72
	PEM	4.8	Up to 60		~15	70-73
Teledyne		5.3-6.1	Up to 42	-	4-8	67-72
Energy Systems		5.6-6.4	Up to 150		8-15	66-71
Stuart Energy	Alkaline	5.9	>50	-	1-25	68-72
	PEM	4-4.2	10-60	60-360	~25	73-75

The specific investment cost of electrolysers is expected to come down from the current level of \$ 1000-2500/kW for state-of-the-art alkaline electrolysers to – in the long term – \$ 300-500/kW for advanced electrolyser technology (Liu, 2003). According to (Wurster, 1994) the specific investment cost of electrolysers could come down to € 700/kW in 2050 (550 ECU/kW_e in 1994).

With regard to the experience with electrolysers until this date, Appendix gives an overview of worldwide hydrogen fuelling stations (Internet Source 7; The Clean Fuels and Electric Vehicles Report, 2003b). This overview of hydrogen fuelling stations in the world gives the following result with regard to the sourcing of H_2 (Table 8.3).

Table 8.3 *Sourcing of H_2 for hydrogen fuelling stations based on data from Table 2.2*

	Delivered LH_2	Delivered compressed H_2	Central electrolysis	On-site electrolysis	H_2 from crude oil, natural gas, or methanol	Total
Number of stations	18	5	1	19	8	51

Therefore, it may be concluded that delivered LH_2 and on-site electrolysis are the most widely applied ways to fuel hydrogen fuelling stations at this stage.

8.3 R&D development

Like for the automotive applications, the number of patents is used as proxy fro the R&D expenditures.

Table 8.4 gives the overview of public and business R&D over the last decade. The 1990 value is estimated based on the number of pre-1990 patents compared to the post-1990 number of patents. Private or business R&D is supposed to be 63% of the total R&D, a fraction based on a global average for a number of technologies, not specifically for electrolysers.

Table 8.4 *Cumulative R&D expenditure for electrolysers*

Million [$€_{2000}$]	Cumulative public R&D	Cumulative private R&D
1990	44	102
1991	46	104
1992	55	120
1993	67	139
1994	81	162
1995	97	189
1996	116	221
1997	128	241
1998	140	260
1999	147	272
2000	156	285
2001	158	289
2002	172	312

9. Liquefaction of natural gas (lng)

Liquefaction is the process where through cooling a gaseous matter is converted to a liquid. At present, the technique is primarily used in transportation of natural gas. On a smaller scale, liquefaction is also used in handling of hydrogen. It may be expected that particularly the latter application may become the major process in the future, but spillovers between the two types of liquefaction is likely.

9.1 Cumulative capacity

The use of liquefaction for natural gas has had an extensive history. The first commercial liquefaction plant became operational in 1941 in the USA. International trade commenced from 1964 onwards, as the United Kingdom started to import LNG from Algeria. Since then, the number of large-scale facilities for liquefaction has gradually increased, as is shown in the figure below.

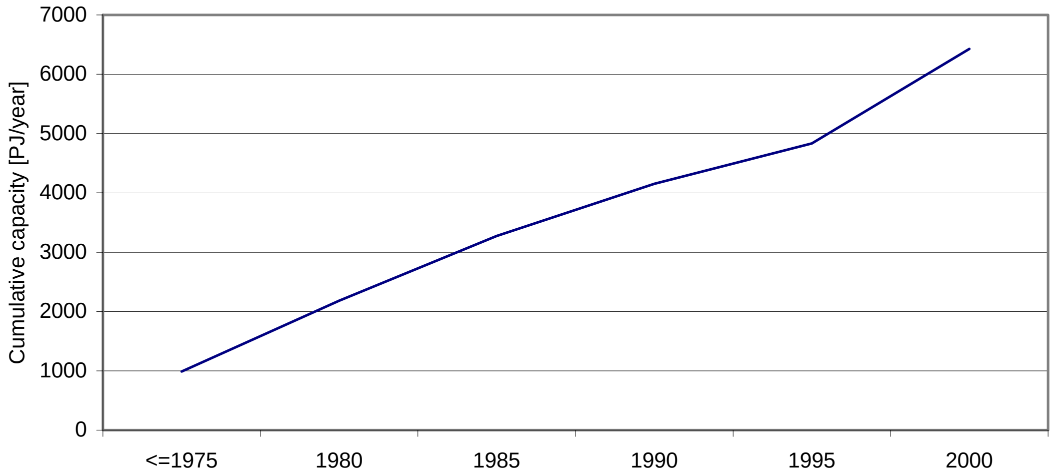

Figure 9.1 *Cumulative capacity of Liquefaction plants for LNG*

9.2 Specific costs of LNG

Specific costs for liquefaction have shown a gradual decline. However, this decline is partially due to expansion of existing production facilities, rather than the construction of greenfield plants (Shepherd, 1999). Moreover, as various concepts for liquefaction are implemented, large variances in specific costs may be found. On the one hand, this should be kept in mind when examining the relation between cost data and capacities. On the other hand, one might argue that such effects are part of the technological development, and should be reflected in an overall learning of liquefaction. The sparsely available data is given below.

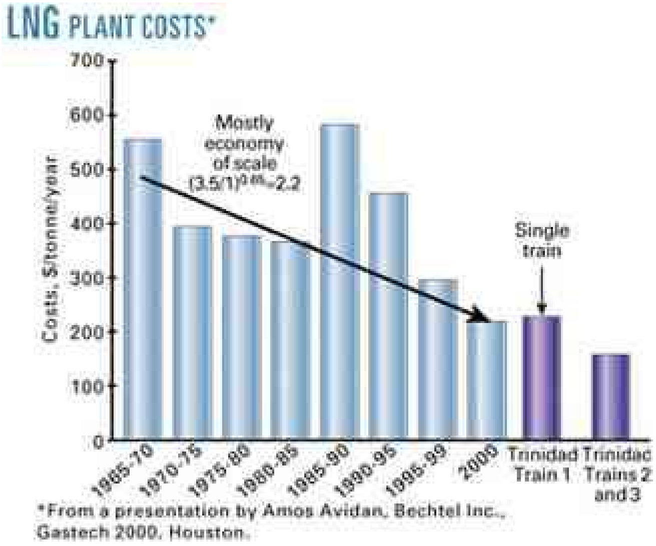

Figure 9.2 *LNG plant cost development according to Bechtel Inc.*

Aside from the possible spill-over with hydrogen on the long term, the importance of LNG on the shorter term will be to globalise the gas market. Where gas markets are generally local at present, as a result of pipeline limitation, continued growth of liquefaction capacity will clearly facilitate international trade in gas.

9.3 Research and development on LNG

There exist various types of liquefaction plants. In recent years these competing technologies have led to lower prices, but from the perspective of data gathering, this competition has one major drawback: data on business R&D expenditure is of strategic value, and hence hard to come by. Furthermore, on the side of governments the focus is on safety aspects, as becomes clear from the classification in the IEA R&D-database (IEA, 2004).

Because of the scarcity of data, combined with the focus on non-power technologies, it was decided not to include LNG technologies in the project.

10. Methodology for development of an R&D Database for selected non-power technologies

The development of a database containing data of non-power technologies is an essential part of the SAPIENTIA project. The characterization should be such that both a direct implementation of the technology is feasible, as well as an implementation in which the technology is described as a (part of a cluster of a) learning technology. What is more, the description of technologies in terms of two-factor learning curves (TFLC) as developed in the preceding project, SAPIENT (Kouvaritakis *et al.*, 2005), is to be deployed to the new technologies as well. This requires that not only present day data and (expert guesses of) future developments are gathered, but also historical data is presented from which the parameters of the two-learning mechanism can be deduced. To a large extend, the methodology used for data analysis is based on previous work on power sector technologies. In particular, the use of patent data leans strongly on the methods as developed by Criqui *et al.* and described in Chapter 1 of the SAPIENT report. In this chapter we will discuss which technologies have been chosen, and what data has been collected for these technologies. In the Annexes, data sheets for the different technologies are included.

10.1 Choice of technologies

In the SAPIENT project a description of technologies using a two-factor learning mechanism was developed. The technologies in the models used were mainly power-technologies. One of the aims of the present project is to extend the description in terms of a TFLC to a selected set of non-power technologies. The selection should on the one hand be sufficiently broad to show that the idea of learning technologies may be applied to many different sectors. However, on the other hand the selection should be such that reliable data can be gathered, or that an alternative description may be developed in which proxies may be used to estimate the relevant parameters for the two-factor learning curve.

In the kick-of meeting of the project a preliminary set of technologies was discussed. The list was finalized during the second meeting. It now consists of the technologies given in the table below. To show that indeed a broad range of sectors is to be included in the analysis, the table also shows the sectors in which the technologies are applied.

Table 10.1 *Choice of technologies for the SAPIENTIA project*

Technology	Power related	Power and heat	Industry	Commercial	Domestic	Transport
Fuel cells		×	×	×	×	×
Condensing boilers		×	×	×	×	
Conventional boiler		×	×	×	×	
Heat pump		×	×	×	×	
ORC		×	×			
Liquefaction	×	×				×
Compression	×					×
Electrolysis H_2	×					×
Gas steam reforming H_2	×					
Coal partial oxidation H_2	×					
Biomass pyrolysis H_2	×					
Solar thermal HTS electrolysis H_2	×					
Heat insulation			×	×	×	
ICE, Otto						×
ICE, Diesel						×
Electric engine			×			×
Capture of CO_2	×					
Storage of CO_2	×					

From the table it is clear that we have chosen to include some technologies that are also used in the power sector. The main reason for choosing these is that they are applied in other sectors. The choice is in line with the objective of the project also to study spill over effects.

10.2 Data gathered for the selected technologies

It is clear that the data gathering is essential in order to reach some of the objectives of the SAPIENTIA project. In particular, the extension of the models to include non-power technologies can only be commenced if and when sufficient data is gathered to enable some form of estimation for the two-factor learning curves. In Table 10.2 an overview of data gathered for the selected technologies is given.

Table 10.2 *Status of data*

Technology	Present data		Future guesses		Historic data	
	Price	Technical	Price	Technical	Price, Capacity	R&D
Fuel cells	yes	yes	yes	yes	short history	SAPIENT
Condensing boilers	yes	yes	yes	yes	figures	estimate
Conventional boiler	yes	yes	yes	yes	no	no
Heat pump	yes	yes	no	no	no	no
ORC	yes	yes	no	no	no	no
Liquefaction	yes	yes	yes	yes	yes	yes
Compression	no	no	no	no	no	no
Electrolysis H_2	yes	yes	yes	yes	short history	aggregate
Gas steam reforming H_2	yes	yes	yes	yes	short history	aggregate
Coal partial oxidation H_2	yes	yes	yes	yes	short history	aggregate
Biomass pyrolysis H_2	yes	yes	yes	yes	short history	aggregate
Solar thermal HTS electrolysis H_2	yes	yes	yes	yes	short history	aggregate
Heat insulation	yes	yes	yes	yes	windows	no
ICE, Otto	yes	yes	yes	yes	yes	yes
ICE, Diesel	yes	yes	yes	yes	yes	yes
Electric engine	yes	yes	yes	yes	yes	yes
Capture of CO_2	yes	yes	yes	yes	no	no
Storage of CO_2	yes	yes	yes	yes	no	no

As a first note to the table, it can be remarked that current data on selected technologies is available for all but one technology (compression of gasses, such as H_2), both on price levels as well as on key technological data such as efficiencies. The situation is almost as favourable for the (expert guesses of) future technological characteristics for the selected technologies, where only ORC in addition to compression shows a lack of data.

The real problem in the data turns out to be reliable historical data on technologies, both for data on (cumulative) installed capacities as well as on specific costs. The situation is even worse for R&D-spending, most particularly that of business. It can be seen that for many technologies, hardly any data on the R&D expenditures has been gathered. It is furthermore noteworthy that for those technologies for which R&D expenditures have been found, in many cases the data is on an aggregate level, *i.e.* does not give information about specific technologies. Given the problems encountered so far, it is unrealistic to assume that one may use a more detailed level of technologies.
From the efforts in the SAPIENTIA project, we can conclude that for non-power technologies the knowledge on key statistics needed for a dynamical description of technologies using learning is quite unfavourable. There are several reasons for the somewhat diverging situation for non-power technologies as compared to the SAPIENT technologies:

1. A database similar to the (public) R&D expenditure database of the IEA is currently lacking for the selected technologies,
2. Many of the technologies are in a very early stage of development, so that
    a. In many cases, there is no data on installed capacities, a key statistic even for the relatively simple framework of learning-by-doing,
    b. Existing data is of strategic value and hence not readily surrendered for public use,
    c. Firms involved in developing the selected technologies are starters, and may prove hard to identify, rendering the collection of business R&D extremely difficult.
3. Even for established technologies, R&D data on specific technologies may prove hard to get due to strategic value of such data; an example is provided by the automotive industry. Here, a methodology for disaggregating data using proxies can be developed.

One might be tempted to use generic values, but for the present project such generic values would be useless, since we are interested in the *specific behaviour of the technologies under consideration.*

The unfavourable situation due to the limited data availability poses some challenging questions to the project team. A major possible solution to the problem is to use the description developed by Criqui et al. as described in the SAPIENT report (Kouvaritakis *et al*., 2005), where one uses patent data to decompose some general spending over specific technologies. Some other possible solutions are described below. Furthermore, during the SAPIENTIA project, considerable effort has been put into developing a method for estimating two-factor learning curves for technologies with limited data availability (to appear in the final SAPIENTIA report).

10.3 R&D showcase: the automotive industry

As noted in the previous paragraph, data on R&D is hard to obtain, particularly when considering specific technological options. For some of the technologies selected in the project the data may be harder to come by than for other technologies, particularly for individual technologies. In such cases, when data on aggregated technologies *is* available, auxiliary data (or proxies) may be used to decompose the R&D spending to the level of individual technologies. To show the most likely approach to yield data, we have selected a relatively easy set of technologies as a showcase: the automotive technologies.

The main advantages of these technologies are:
- A small number of companies that dominate the market.
- A strong pressure on companies to show their efforts to improve the (environmental) performance of the technologies.
- Easy access to (recent) company data.
- Spearhead development area for governmental research.

To gather data on the expenditures on research and development, both from companies and through government, we have used the following scheme:
- Identify the major companies involved in R&D.
- Gather annual reports from these companies, if these contain explicit figures on R&D.
- Build a data set containing as much data on R&D spending as possible.
- Gather auxiliary data: patents and sales numbers of specific technologies.
- Combine the above to estimate the R&D expenditure through companies.

The result is a complex set of data. This complex set should be reduced to a simple set that contains technology, sales, capacity, business R&D, and government R&D. It may be interesting to provide sales and capacities on a regional level, since these may be data directly relevant to the models used in SAPIENTIA.

So far, we have been able to find data on a global scale, which is not surprising given the fact that automobile companies are mainly international corporations. The number of independent producers is quite limited, as the result of substantial mergers in the past. This concentration appears to continue until this very day, but the focus has shifted from full-blown mergers to enhanced cooperation. As to the data collection efforts, the effects of these recent concentration activities for now can be ignored, but the full-blown mergers are likely to have a profound effect on the data available. As we extract data on sales and particularly on business R&D from the annual reports, it is important to know to what extent merging companies are included in the historical figures of the new company.

For the automotive industry, there appear to be twelve major companies. It should be noted that these companies in many cases are the results of mergers in the recent or more distant past. This results in a limited history of the companies, and a limited availability of annual reports. Furthermore, in some cases mergers have occurred in the very recent past. This also limits the applicability of data in the annual reports.

For the twelve major companies, a varying historical record is available in the annual reports. The variation may be either in the number of years for which data can be found, or in the amount of information provided on the R&D expenditures, or even both. Thus, we obtain a data set on sales and business R&D expenditures containing several 'holes'. These holes can be filled when additional assumptions are made on the behaviour of companies. For example, if we assume equal behaviour for all companies, an average value may be inserted (imputed) for a missing value. Other options are to assume linear investment trends within a company, or investment trends within a year, or even a combination of the two.

Using the data mentioned in the previous paragraphs, we have constructed a data set for twelve companies spanning twelve years. None of the companies provide data for the full set. Nevertheless, from the data that is available, some striking features can be found. First of all, when expressing the R&D budget as percentage of sales, the various companies spend between 2.1% up to 6.5%, averaged over the years for which data is available. From the data gathered, it is clear that firm size in terms of sales, or geographical origin cannot serve as an auxiliary variable for estimation of the R&D budget. All one can do is estimating the budget for a specific firm on the basis of data available for that particular firm. Thus the sector-average of the R&D spending as percentage of sales budget can be estimated on the basis of available data.

From this we find a sector average of 4.6%. On the basis of the data, no reliable estimate can be given for the time-dependence of the percentage.

From the previous paragraph it should be clear that at present R&D dynamics can not be established on the basis of business R&D data alone. Furthermore, in many cases government R&D expenditures are linked to business R&D, e.g. in the case of spending by the federal government in the United States. As a result, the government spending is also not very practical as a variable introducing R&D dynamics. The only remaining possible data mentioned in the beginning of the section would be to use patent data, or sales numbers of specific technological options. As the latter are a proxy for learning by doing (see below), we opt for patent data.

Gathering the patent data involves the use of the major companies identified in the first step of the data collection. Using the patent database of the European Patent Office (available at http://ep.espacenet.com) we first search for all patents posted by the selected companies. Next, we look for specific patents, either dealing with internal combustion engines, electric vehicles or fuel cell vehicles. The result is a data set containing both the absolute and the relative amount of patents. It should be noted that the data set of the European Patent Office contains both national and international data. Therefore, one technological innovation may be posted in several countries as separate patents, causing double counting. As we ignore this double counting, we assume that an innovation posted as several patents is perceived to be more successful, which in turn is assumed to be an indication for the amount of funds invested in the development of the technology.

Using the previous steps, we end up with a database containing business R&D spending on automotive options. This gives us only half of the story on R&D spending, since in general for every two dollars spent by business, there is (roughly) one spent by government. For the automotive industry, the contribution from government to the overall R&D budget is relatively small. Furthermore, as there is a limited number of countries contributing to the development of automotive technologies, and the efforts of the countries leading in automobile industry are concentrated in research programs since the early nineties of the previous century, the data collection is relatively easy.

The result of the database build-up is a number of data sheets with information on car companies (sales, R&D expenditures), patent data and government R&D expenditures. The latter two contain details on the class of vehicles the money is invested in. These classes are Internal Combustion Engine (ICE), Electric Vehicle (EV, also including hybrid vehicles), and Fuel Cell cars (FC). This information is consequently summarized in three sheets, each covering a specific technological option. The information contained in these sheets is the information needed for the SAPIENTIA project, i.e. the sheets are filled according to a pre-defined template. One of these templates is included as an appendix to this document.

10.4 Data on other technologies

As has been shown in the previous section, it is relatively easy to find data on automobiles. At the same time it was noted that the automotive sector provides a rather exceptional showcase, when compared to the situation for other technologies selected in the project, as there it seems less favourable. Nevertheless, in many cases some numbers on public R&D expenditures can be found. In particular, for CCS technologies, an extensive number of projects were undertaken in previous years, and some clear assumptions on the mix of government and private participation can be made. From this, the combined R&D estimate can be estimates, and in turn a decomposition into public and private financing is possible.

For hydrogen technologies, mostly aggregated data on public expenditures is available.

Here, we have assumed patent data where available to disaggregate the expenditures over the various technologies. The patents in this case are used both for the estimate of the fraction of the total hydrogen budget, as well as to establish the total cumulative expenditures prior to the statistical information. For the four hydrogen production technologies considered in the project, the assumption on the allocation of the public expenditure *r*(*y*) in year *y* to each of the technologies *i* can formally be written as

$$r_i(y) = r(y) \cdot \frac{p_i(y)}{\sum_{i=1,4} p_i(y)} \tag{1}$$

where r_i is the budget allocated to technology *i* and $p_i(y)$ are the patents awarded for he technology in the specific year. The estimate for the cumulative expenditures *R* on a particular technology is based on the same statistics, according to

$$R_i(y) = (1-d) \cdot \sum_{x=y_0}^{y} r_i(x) \cdot \frac{\sum_{x=y_0}^{y} p_i(x)}{\sum_{x<y_0} p_i(x)} \tag{2}$$

the factor *d* being a depreciation rate. It is introduced to account for the fact that some of the cumulative knowledge stock will get lost, and should somehow be related to the 'scraping rate' used to depreciate the cumulative R&D investments in the usual framework (Criqui, P. in Kouvaritakis *et al.*, 2005). Here, we choose d=0.05, only a little higher than the 'scraping rate' which is 0.03 because we assume that the bulk of the investments are rather recent. We justify this assumption with the observation that the hydrogen technologies show a steep increase in the attention for them.

To determine the contribution from business to R&D expenditures for hydrogen technologies, we assume that this can be approximated by the global, technology-averaged fraction of business-to-public spending, found in the literature (0.63). Since it is unlikely that the average indeed applies to all technologies alike, the impact of this assumption should be subjected to sensitivity analysis. It may be quite determining for the impact of R&D policies, as the fraction directly influences the estimate for the R&D elasticity in the two-factor learning curve (Kouvaritakis *et al.*, 2005).

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Appendix A CO_2 regional storage capacities

Table A.1 *Regional storage capacities according to (GHGT-7 proceedings); in the table, depleted fields refer to either oil or gas fields*

	Depleted fields [Gton CO_2]	Depleted fields [Gton CO_2]	ECBM [Gton CO_2]
FSU	177		19
Middle east	197		
USA	47	13-98	35
Canada	17	0.283 (oil) + 2.8 (gas)	12
Western Europe	17	6 (oil) + 30 (gas)	4
Australia			30
China			13
Other Asia			29
Africa			7
Global	455		148

Table A.2 *Regional storage capacities*

	Depleted fields [Gton CO_2]	EOR/EGR [Gton CO_2]	ECBM [Gton CO_2]	Aquifers [Gton CO_2]
Africa	3-6	3-23	5	1000
Australia	0-1	0-9	50	550
Canada	1-6	6-35	50	1050
China	0-1	0-1	100	550
Eastern Europe	1-2	1-2	20	250
Former Soviet Union	15-30	35-244	100	1000
India	0	0	10	500
Japan	0	0	0	10
Latin America	9-20	20-61	0	1255
Middle East	25-85	20-300	0	505
Other Asia	6-12	11-52	50	1040
USA	10-20	15-30	80	1050
Western Europe	3-5	16-46	30	300
Global	72-187	125-801	495	9060

Source: (IEA, 2004)

Appendix B Hydrogen fuelling stations

Table B.1 *Worldwide hydrogen fuelling stations*

Location	Fuel	Project	In operation since	H_2 production technology	Specifics/ Comments
Davis, California	Compressed H_2	University of California, Davis	In operation	Air Products delivered LH_2	n/a
Riverside, California	Compressed H_2	University of California, Riverside	1992	PV + Stuart Energy electrolyser	Electrolytic hydrogen generation
El Segundo, California	Compressed H_2	Xerox Corp et al	1995	PV + Stuart Energy electrolyser	Electrolytic hydrogen generation
Thousand Palms, California	Compressed H_2	SunLine Transit Agency et al	April 2000	Stuart Energy hydrogen fuelling station	Electrolytic hydrogen generation
Sacramento, California	Liquid to compressed H_2	California Fuel Cell Partnership	November 2000	Air Products and Praxair	LH_2 and compressed H_2
Torrance, California	Compressed H_2	American Honda Motors Co.	July 2001	n/a	PV-electrolysis + grid backup
Torrance, California	Compressed H_2	Toyota Motor Sales USA	2003	Stuart Energy and Air Products	Electrolysis, 24 kg H_2/day (renewables)
Oxnard, California	Liquid H_2	BMW North America	July 2001	Air Products delivered LH_2	LH_2 fuelling station
Chula Vista, California	Compressed H_2	City of Chula Vista	2003	Stuart Energy hydrogen fuelling station	60 kg H_2/day
Thousand Palms, California	Compressed H_2	Schatz Hydrogen Generation Center	1994	PV + Teledyne Energy electrolyser	Electrolysis powered by PV
Richmond, California	Compressed H_2	AC Transit facility	October 2002	Stuart Energy hydrogen fuelling station	Electrolytic hydrogen generation
San Jose, California	To be determined	VTA, San Mateo Transportation District et al	Target 2004	Air Products delivered LH_2	Current fuelling station will be enhanced
Chicago, Illinois	Liquid to compressed H_2	Chicago Transit Authority et al	March 1998 (February 2000)	Air Products delivered LH_2	n/a
Dearborn, Michigan	LH_2 and liquid to compressed H_2	Ford Vehicle Refuelling Station	1999	Air Products delivered LH_2	n/a
Ann Arbor, Michigan	Liquid to compressed H_2	EPA's NVFEL et al	2003	Air Products	Storage up to 1,500 gallons of LH_2
Arizona (mobile station)	Compressed H_2	Ford Motor Company	2001	Stuart Energy hydrogen fuelling station	Electrolysis (24 kg H_2/day)
Phoenix, California	Compressed H_2	Arizona Public Service	2001	Proton Energy Systems electrolyser	DOE/private sector H_2 station
Northern Nevada	Compressed H_2	Nevada Test Site Development	November 2002	Air Products	Using 50 kW PEMFC
Washington DC	LH_2 and compressed H_2	General Motors Corp. et al	October 2003 – 2005	Shell Hydrogen	H_2 pump at Shell retail gas station
Penn State, Pennsylvania	Compressed H_2	APCI et al	Fall 2004	N/A	On-site natural gas steam reforming
Munich, Germany	Liquid H_2	Refuelling Station BMW	1989	Linde AG	n/a
Hamburg, Germany	Compressed H_2	W.E.I.T. hydrogen project	1999	Delivered compressed H_2	n/a
Hamburg, Germany	Compressed H_2	CUTE Bus Demo	Target 2003	Hamburgische Electrizitäts-werke AG	Electrolysis powered by renewables
Nabern, Germany	LH_2 and liquid to compressed H_2	Daimler Chrysler Refuelling Station	1998	LH_2 delivered by Linde AG	Linde AG H_2 refuelling technology

Location	Fuel	Project	In operation since	H_2 production technology	Specifics/ Comments
Munich, Germany	LH_2 and (liquid to) compressed H_2	Munich Airport Vehicle Project	1999	LH_2 and compressed H_2 delivered by Linde AG	Linde AG H_2 refuelling technology
Wolfsburg, Germany	Liquid H_2	Fuelling of VW hydrogen vehicles	n/a	LH_2 delivered by Linde AG	Linde AG H_2 refuelling technology
Russelsheim, Germany	LH_2 and compressed H_2	Fuelling of GM hydrogen vehicles	n/a	Linde AG supplied LH_2 and compressed H_2	Linde AG technology
Sindelfingen, Germany	LH_2 and compressed H_2	Daimler Chrysler	Planned	H_2 delivered by Linde AG	Linde AG H_2 refuelling technology
Berlin, Germany	LH_2 and compressed H_2	Aral Refuelling Station	Target 2003	H_2 delivered by Linde AG	Linde AG LH_2 refuelling technology
Berlin, Germany	LH_2 and compressed H_2	TotalFinaElf et al	October 2003	Linde AG supplied LH_2, Proton Energy Systems electrolyser	Linde AG LH_2 refuelling technology
Copenhagen, Denmark	Mobile LH_2	Framework: EU fuel cell bus program	Target 2003	LH_2 delivered by Linde AG	Linde AG mobile LH_2 filling station
Lisbon, Portugal	Mobile LH_2	Framework: EU fuel cell bus program	Target 2003	LH_2 delivered by Airliquido	Linde AG mobile LH_2 filling station
Erlangen, Germany	Mobile LH_2	MAN, Linde AG	December 1996 – 2001	LH_2 delivered by Linde AG	n/a
Oberstdorf Spa, Germany	Compressed H_2	CUTE Bus Demo	Target 2003	BP affiliated	On-site natural gas steam reforming
Stockholm, Sweden	Compressed H_2	CUTE Bus Demo	Target 2003	Stuart Energy hydrogen fuelling station	Central hydro powered electrolysis
London, UK	Compressed H_2	CUTE Bus Demo	Target 2003	BP affiliated	Centralised production via excess H_2 from crude oil
Amsterdam, The Netherlands	Compressed H_2	CUTE Bus Demo	Target 2003	Hydrogen System's IMET® electrolyser	On-site electrolyser
City of Luxembourg	Compressed H_2	CUTE Bus Demo	Target 2003	N/A	On-site methanol steam reforming
Oporto, Portugal	Compressed H_2	CUTE Bus Demo	Target 2003	BP affiliated	Centralised production via excess H_2 from crude oil
Madrid, Spain	Compressed H_2	CUTE Bus Demo	April 2003	N/A	On-site natural gas steam reforming
Barcelona, Spain	Compressed H_2	CUTE Bus Demo	Target 2003	BP & Stuart Energy, IMET® electrolyser	On-site electrolyser powered by renewables
Reykjavik, Iceland	Compressed H_2	ECTOS Bus Demo	April 2003	Shell Hydrogen/ Iceland	Geothermal and hydro powered electrolyser
Perth, Australia	Compressed H_2	Daimler Chrysler et al	Target 2004	Centrally produced H_2 at BP refinery	BOC refuelling technology
Victoria, Australia	Compressed H_2	H_2 fuelling station	To be determined	To be determined	Reviewing electrolysis and reforming of natural gas
Beijing, China	To be determined	GEF and UNDP; demonstration of fuel cell buses	Target 2003	n/a	n/a
Shanghai, China	To be determined	GEF and UNDP	Target 2003	n/a	n/a

Location	Fuel	Project	In operation since	H_2 production technology	Specifics/ Comments
Cairo, Egypt	To be determined	GEF and UNDP	Target 2003	n/a	n/a
Mexico City, Mexico	To be determined	GEF and UNDP	Target 2003	n/a	n/a
New Delhi, India	To be determined	GEF and UNDP	Target 2003	n/a	n/a
Sao Paulo, Brazil	To be determined	GEF and UNDP	Target 2003	n/a	n/a
Osaka, Japan	Compressed H_2	PEMFC Vehicle Demo	Fall 2001 – end of 2003	n/a	On-site natural gas steam reforming
Takamatsu, Japan	Compressed H_2	PEMFC Vehicle Demo	Fall 2001 – end of 2003	n/a	PEM electrolyser
Tsurumi, Japan	Compressed H_2	PEMFC Vehicle Demo	August 2002	n/a	n/a
Yokohama, Japan	Compressed H_2	Cosmo Oil JHFC	FY 2002	n/a	Hydrogen and Fuel Cell Demonstration Project
Yokohama, Japan	Compressed H_2	Nippon Oil JHFC	FY 2002	n/a	Hydrogen and Fuel Cell Demonstration Project
Japan	Compressed H_2	Honda Company Filling Stations	2001	n/a	n/a
Japan	Compressed H_2	Toyota Company Filling Station	2001	n/a	n/a
Tokai, Japan	Compressed H_2	Toho Gas Co.	October 2002	n/a	n/a
Tokyo, Japan	LH_2 and compressed H_2	Iwatani International Corporation et al	Target April 2003 – April 2005	LH_2 from Iwatani and compressed H_2 from Linde AG Cryo-Compressor	Hydrogen and Fuel Cell Demonstration Project
Kawasaki City, Japan	Compressed H_2	Air Liquide Japan JHFC	N/A	Senju	Hydrogen and Fuel Cell Demonstration Project
Vancouver, Canada	CompressedH_2 and H_2/natural gas blend	British Columbia Hydro	2001	Stuart Energy hydrogen fuelling station; electrolyser	Supplies H_2 and H_2/natural gas blend to a variety of vehicles
Montreal, Canada	Compressed H_2	Montreal Urban Transit Authority	1994 (closed in 1994)	Stuart Energy hydrogen fuelling station; electrolyser	n/a
Surrey, Canada	Compressed H_2	BC HydroGen	Fall 2001	n/a	Electrolyser powered by renewables
Torino, Italy	Compressed H_2	PEMFC City Bus Demo	Target 2002/2003	n/a	Hydro powered electrolysis
Bi-cocca, Italy	LH_2 and compressed H_2	Hydrogen and fuel cell demonstration project	2002	AEM, SOL et al	Hydrogen liquefier and vehicle refuelling
Oostmalle, Belgium	Liquid H_2	Belgian Bus Demo	1994	Messer Griesheim GmbH	LH_2 storage
Leuven, Belgium	Compressed H_2	NexBen Fueling	2003	NexBen Fueling	LNG and hydrogen fuelling station
South Korea	Compressed H_2	Hyundai Motor Company	2001	Pressure Products Industries, Inc. (PPI) & Doojin Corporation	PPI two-stage compressor
Singapore	Compressed H_2	Part of BP joint venture	2004	Air Products	20 kg of compressed H_2 per day
Submarine-mobile infrastructure		Class 212 submarine driven by H_2 fuel cells	2002	Air Products (USA)	

Appendix C Specific description of data

In the Chapter 10, no specific description of the desired data was given. The minimal data set needed to include a technology in the models is given in the upper part of the template in Appendix D. The main data is denoted as ‘Basics’ in the table, and appears in the upper part of the appendix. This data is already available for all (relevant) technologies. However, to apply a one-factor learning curve description for a technology, also the development of the specific cost of the technology, and it cumulative capacity over the years has to be known.

To be able to apply a 2-factor learning curve approach for a technology, even more data is needed. If available, one should have the cumulative research expenditures, both by government and by business. In many cases, this information will not be available for the technology itself. In such cases, overall spending figures should be provided, plus auxiliary variables from which the share the technology gets from the total can be deduced. Generally, patent data serves as the preferred data for this. A use of patent data as in the case of the automobile is preferred, i.e. the share of expenditures of a technology is proportional to the relative number of patents, implying also the total amount of patents should be known. If the use of data other than patents is proposed, one should give an indication of how to do so.

In the table below the data needed for inclusion of a technology in the models involved in the SAPIENTIA project[3] is given. Aside from the parameter name., its default value (if any), and the description of the parameter, a column is included to indicate the complexity class of the parameter. This characteristic indicates the maximal complexity of the model that can be used if only the parameters in the complexity class are given. Here, ‘B’ stands for ‘Basic’, ‘S’ for single factor learning curve, ‘T’ for 2-factor learning curve, and ‘A’ for 2-factor learning curve with auxiliary variable. For example, if only values for parameters from classes ‘B’ and ‘S’ for specific technology are known, the modelling of this technology can either be as a non-learning technology, or as a single-factor learning technology.

[3] As a matter of fact, it contains only the variables proposed by ECN. The other partners gave no reaction to the proposal, implying but not affirming that the proposal covers all models.

Table C.1 *Data requirement for inclusion of a technology in the model(s). The column 'Class' indicates the complexity class of the parameter (see text for further explanation)*

Parameter	Default Value	Description	Class
Capacity	GW	Unit of capacity	B
Activity	PJ	Unit of annual activity	B
Life		Life (economical) in years	B
Start	1990	First year of availability	B
Output		Output(s) of the technolgoy, e.g. electricity	B
Input		Input(s) of the technology, for a conversion technology this includes the fraction needed for one unit of output	B
Growth	Infinite	Maximum annual growth as decimal fraction, e.g. 1.5 implies a maximal annual growth of 50%	B
Availability	1	Annual availability, or 1 minus fraction outage resulting repairs, etc.	B
Efficiency	1	Efficiency of the process. Note: efficiencies for conversion technologies are generally given as numerical value in the specification of the input.	B
Investment cost		Specific investment cost in million € per unit of capacity	B
Fixed O&M cost		Costs connected to the annual operation and management in million € per unit of capacity, not depending on actual the output	B
Variable O&M cost		Costs connected to the annual operation and management in million € per unit of activity, depending on the actual output	B
Specific costs		Historical evolution of the investment costs in the same time period for which data on the cumulative capacity id known	S
Cumulative capacity		Historical evolution of the capacity in the same time period for which data on the specific costs are known	S
Government R&D spending		Historical evolution of the spending by government on R&D into the specific technology under consideration, or on an aggregate containing this technology (in which case an auxiliary variable is also needed)	T
Business R&D spending		Historical evolution of the spending by business on R&D into the specific technology under consideration, or on an aggregate containing this technology (in which case an auxiliary variable is also needed)	T
Auxiliary variable	number of patents	(Optional) Historical evolution of the auxiliary variable used for disaggregation of the R&D spending by government and business	A

Appendix D Template containing the desired information on technologies

Explicit model data														
Parameter	**Const**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CAPACITY	[1e+6]													
ACTIVITY	1e+9 person.kilometer													
LIFE	15													
START	1990													
OUTPUT		1	1	1	1	1	1	1	1	1	1	1	1	1
INPUT		0.272	0.266	0.243	0.227	0.214	0.205	0.195	0.189	0.179	0.173	0.166	0.16	0.157
GROWTH														
AVAILABILTY	0.99													
PEAKCONTRIB														
EFFICIENCY														
COUPLING_CETL														
CC0_CETL														
CCMAX_CETL														
SC0_CETL														
PR_CETL														
INVCOST		23000												
FIXOM		1176												
VAROM		22.5												

Implicit model data (for determination of the learning curve)														
Parameter	**Start**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CAP_HIST	430	440	450	460	470	480	490	501	512	523				
SC_HIST		17277	17921	19483	19983	20935	20273	21220	21759	23013				
GRD_HIST														
BRD_HIST		36	36	36	36	36	34	34	35	39	39	37	38	
SALES_HIST		577	600	626	668	705	720	762	757	855	911	868	869	
SPECPAT_HIST		2476	2778	3070	3021	2872	2926	2971	3259	3654	3631	3900	4374	
TOTPAT_HIST		17430	18285	19139	19994	20849	21704	22559	23413	24268	25123	25978	26833	
MAJORCOMP														

Example of data for a private car

CAP_HIST	Historical development of the total installed capacity
SC_HIST	Historical development of the specific price, i.e. the price per unit capacity
GRD_HIST	Historical governmental expenditures on R&D
BRD_HIST	Historical business expenditures on R&D
SALES_HIST	Historical sales (may either be number or monetary value, specify which)
SPECPAT_HIST	Historical numbers of patents specifically for the technology, applied for by the major companies involved in the development of the technology
TOTPAT_HIST	Historical totals of patents, applied for by the major companies involved in the development of the technology
MAJORCOMP	The major companies involved in the development of the technology