CHAPTER 11

Heating and cooling in the built environment

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Abstract

In this chapter the market development and the techno-economic learning are investigated for two competing technologies to assess their relative dynamics in terms of techno-economic performance: heat pump (HP) as an exemplary technology to tap renewable energy sources and (condensing) gas boilers as the reference system.

Long-term historical data series are particularly important when using the experience curve method. Motivated by the data availability of such data The Netherlands and Switzerland are chosen to perform two case studies for which further original and secondary data was collected. Specific methodological issues related to experience curves of end use technologies are discussed.

Although the empirical basis is by far not complete, it can be affirmed that learning rates (LR) from previously studies reconfirmed by recently gathered data. The learning rate of the main cost components of HP is 12%–22% and that of the system as a whole about 20% while their utility in terms of less noise emission, system integration, and energy-efficiency improved. This is equal or higher as compared to the LR of condensing gas boiler (13%). This holds for both countries assessed, although it should be kept in mind that the time series is quite short in the Dutch case. Moreover, a LR for the coefficient of performance was found which is 5% in the case of ground source HP and 9% for air-to-water HP. Thus HP offer a high potential to improve their cost-effectiveness relative to reference systems in terms of cost of delivered heating energy which depend on both specific investment costs and on the energy efficiency.

Chapter Outline

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11.1 Introduction

Most of the technologies in the chapters focus on renewable electricity production technologies, storage of energy in the form of chemical energy (H_2, batteries), and on mobility. One other major end use sector is heat, which has been historically much harder to decarbonize than the electricity sector. Especially, the built environment with demand for low-temperature heat poses significant challenges to decarbonize.

Final energy demand for heating and cooling purposes in buildings is determined basically by the following factors:

- Thermal losses: energy-efficiency of the envelope and air exchange
- Thermal passive gains: solar gains (mainly through windows) and internal heat loads (persons, appliances)
- End use system: heating and cooling systems

Thus in technical terms, final energy demand may be managed by passive measures reducing net useful energy demand (insulation, glazing) or active systems to tap renewable energy demand (solar thermal systems, heating systems). Within the context of REFLEX, heat pump (HP) is one of the key technologies in terms of sector coupling to tap renewable energy sources (RES) (power to heat) and flexibility. Accordingly, the focus of this chapter is on HPs. For comparative reasons, condensing boilers (that might be fueled by biogas or power to gas in the future) are considered as well, also because these boilers are in many countries the current-dominant heating technologies and can be considered a reference (business as usual) technology in some countries. This chapter first describes the development and deployment of HPs and natural gas boilers in the EU and then zooms in on case studies in The Netherlands and Switzerland. From these two countries, techno-economic development and learning curves are presented.

11.2 Technology description of heat pumps

A HP is a device that transfers heat from a lower temperature level (source, typically ambient heat from air, water, or ground) to a higher temperature level (sink, typically the buildings' energy and/or hot water system) by adding mechanical energy to the system. The mechanism is described as an inverse Carnot cycle or refrigeration cycle, as shown in Fig. 11.1A (Çengel and Boles, 2015). Work ($W_{\mathrm{net,in}}$) can be added in the form of electric or thermal energy (REN21, 2017). Fig. 11.1B shows the inverse Carnot cycle for cooling (left) and heating purposes (right). HPs are able to deliver more thermal energy than mechanical energy required to operate them. In standard conditions, they can deliver three to five times more energy than consumed (REN21, 2017).

Two types of HPs are typically distinguished: air source HPs (ASHPs) and ground source HPs (GSHPs). For ASHPs the HP unit is normally fitted to the side of the building, and this type is commonly used in densely populated urban areas. There are two main types of ASHPs: air-to-air systems that directly heat the air of the rooms and can also function as air-conditioning units and air-to-water systems that are connected to the (water-based) central heating system of a house and can provide both space heating/cooling and hot water.

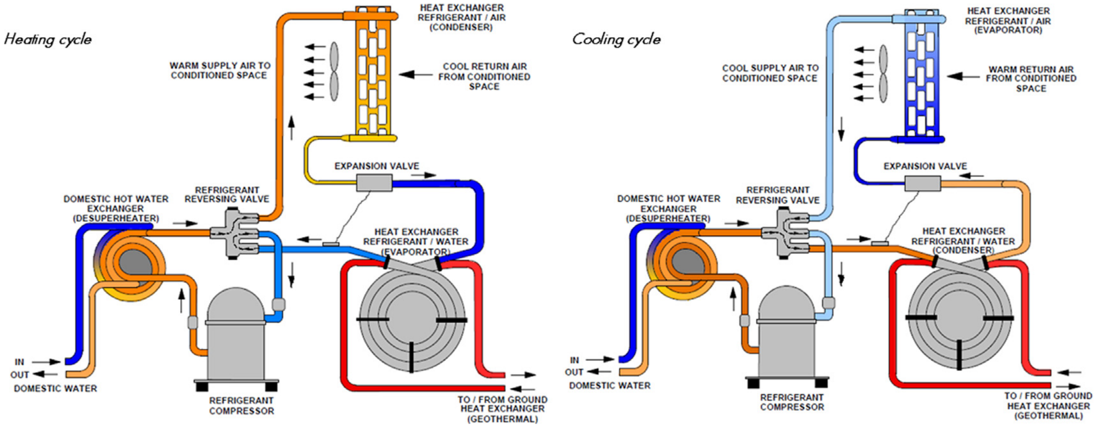

Figure 11.1

Schematic overviews of (A) the inverse Carnot cycle and (B) applications of the inverse Carnot cycle for cooling and heating. *Source: Adapted from Çengel and Boles (2015).*

For GSHPs a heat exchanger unit is installed in underground. This enables the system to reach a higher quality source of heat but also leads to higher costs (Staffell et al., 2012). Because of the stability of the underground temperature, GHSPs are very efficient all year round. ASHPs, however, have much lower efficiency when the outside air temperature is lower. In many cases, ASHPs commonly require an additional boiler (electrical or condensing gas) as backup for the winter months.

Other types of HPs include water source HPs (extracting heat from water such as groundwater layers, lakes, rivers, or the seas), systems that utilize waste heat from industrial processes, sewage water or buildings, and hybrid systems that combine different heat sources (REN21, 2017).

HPs are mainly used for space heating, cooling, and providing hot tap water in the residential buildings or commercial sectors (REN21, 2017). Also in the industrial sector, HP applications are found, to increase the temperature of industrial waste heat so it can be reused in the process. Industrial HPs are more advanced than HPs in the building sector, because they need to deliver higher temperature heat at 100°C–250°C, with a difference of up to 100°C between source and sink (Kleefkens and Spoelstra, 2014).

11.3 Technology description of condensing boilers

Conventional boilers use the sensible heat that is generated by burning fuels such as gas, oil, and wood. It can be used for space heating or heating domestic hot tap water or a combination of both (space heating + domestic hot tap water). A natural gas boiler burns the gas in the combustion chamber of the boiler to generate hot jets that move through a heat exchanger usually made of copper. The heat exchanger helps transfer heat from the gas to the water contained in the heat exchanger and heats it to around 60°C. The heated water is pushed through the system using an electric pump (Çengel and Boles, 2015). The heated water flows around a closed loop inside each radiator, entering at one side and leaving at the other. As each radiator is giving off heat, the water is cooler when it leaves a radiator than it is when it enters (Çengel and Boles, 2015). After heated water passes through all the radiators, the water has cooled down significantly and returns to the boiler to pick up more heat. Waste heat from the boiler is dispersed into the air as flue gas through a smokestack (Çengel and Boles, 2015; Weiss et al., 2008).

In condensing gas boilers the flue gases pass through a heat exchanger that warms the cold water leaving the radiators and thus heating the water and reducing the work done by the boiler (Çengel and Boles, 2015; Weiss et al., 2008). This system basically taps the latent heat of vaporization by all or part of the condensing water vapor in the exhaust gases (Weiss et al., 2009). As such condensing boilers achieve higher efficiencies (can be more than 90%) as compared to conventional boilers that do not use the latent heat.

Combi gas boilers are used to provide heat for space heating and hot tap water. They typically have two independent heat exchangers (Çengel and Boles, 2015). One exchanger is connected to the radiators for space heating and the other for hot water supply (Çengel and Boles, 2015). Combi boilers provide instant hot water, by constantly being on standby when there is no water demand. When the request for hot water is trigged by someone turning on the hot tap, this signals the boiler to start heating water inside of the system. The heat exchanger transfers the majority of the heat from the burnt gas inside the boiler to the cold water and then delivers it to the taps as required (Çengel and Boles, 2015). Inside combi boilers, the control valves operate in different directions to either allow water to flow through the central heating system or divert it to the appropriate hot water tap as required.

11.4 Market development of heating technologies in the EU

Currently, the major heating technologies in the EU are natural gas condensing/ noncondensing boilers, HPs, electric boilers, and oil jet burners (see Fig. 11.2A). Yet, the heating technology market is structured quite differently across the various European countries, see Fig. 11.2B that represents the shares of the heating technology unit sales by type per country in the EU for the year 2014. For obvious reasons the heating technology market also differs by size. Below, we describe the current market developments of gas boilers and HPs.

11.4.1 Current market developments of gas boilers

Since the beginning of this century, gas boilers have been the dominating heating technologies in Europe. This becomes apparent from Fig. 11.2A that represents the heating technology unit sales by type in the EU between 2004 and 2016 (excluding district heating). Noncondensing gas boilers were the dominant heating technology in 2004 with the share of natural gas condensing boilers being 18%. Since 2004 this share has increased to 80% in 2016, and since 2007 natural gas condensing gas boilers has overtaken noncondensing gas boilers as the dominant heating technology due to (1) its high efficiency (90%) (Kemna et al., 2019), (2) technological developments in noncondensing boiler manufacturing such as introduction of new generations of modulating burners that require more expensive closed boiler systems (historically they were open boiler systems) (Weiss et al., 2009), and (3) production and additional cost for installation and maintenance of condensing gas boilers continued to decrease compared to noncondensing boilers (Weiss et al., 2009; Kemna et al., 2019).

The most pronounced shift between condensing and noncondensing boilers occurred between 2015 and 2016 which can be attributed to the implementation of the Ecodesign and energy label regulation coupled with the end users' choice to purchase gas condensing

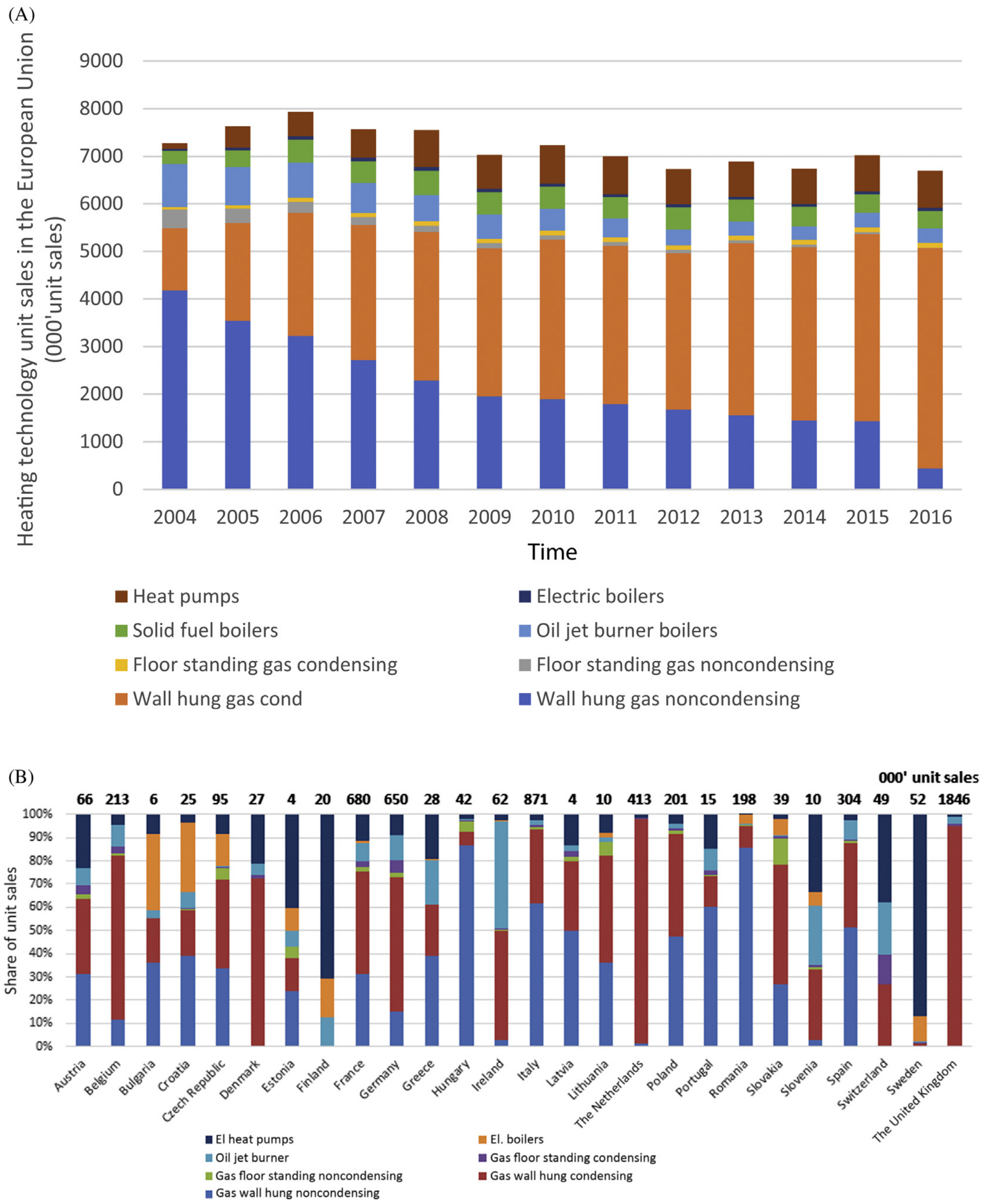

Figure 11.2

(A) Heating technology unit sales in the EU by type from 2004 to 2016 retrieved from Kemna et al. (2019), based on data from Eurostat. The figure does not include district heating. Information on the fuel type for the solid fuel boilers (e.g., wood, other biomass, and coal) was not available. (B) Share of heating technology unit sales in the EU by type and per member state in 2014. *Source: Adapted from EHPA (2016); FWS (2014); Kemna et al., (2019).*

boilers over less efficient noncondensing boilers (Kemna et al., 2019). This regulation could also be a possible reason for the increase in HP sales in 2016 as compared to 2015. Despite the implementation of the Ecodesign regulation, there still exists a share of 7% of noncondensing boilers in 2016. This could be explained by (1) the preexisting stock of noncondensing gas boilers at wholesalers and retailers that could still be sold after the implementation of the Ecodesign regulation (Kemna et al., 2019) and (2) noncondensing boilers with rated heat output ≤ 10 kW and noncondensing combination boilers with rated heat output ≤ 30 kW that can still be sold for connection to a flue shared between multiple dwellings in existing buildings (Kemna et al., 2019).

Regarding the trend in condensing gas boiler sales, an increase in share of wall hung condensing gas boilers can be seen in Fig. 11.2A when compared to standing floor gas condensing boilers. This is further highlighted for the year 2014 in Fig. 11.2B. It shows that in most EU countries, wall hung condensing gas boilers have the highest share among the types of boilers sold.

In 2014 the United Kingdom had the highest boiler sales in the EU (1.77 million units) (Kemna et al., 2019) with wall hung condensing boilers accounting for 96% of the United Kingdom's heating technology mix. These numbers could illustrate the short product lifetime of the United Kingdom boilers which leads to higher replacement rates and increased sales (Kemna et al., 2019). Italy has the second largest sales of boilers (830,000 units) (Kemna et al., 2019) in the EU in 2014 with noncondensing boilers making up 63% of the Italian heating technology mix. Though, this share has dropped and replaced with condensing gas boilers post 2014 with the Italian government's incentive by offering tax relief of 55% or 65% for upgrading efficiency of existing buildings (Italian Energy Efficiency Action Plan, 2017). Although this scheme has been in place since 2007, its effect has been negligible due to the financial crises in 2009 (Italian Energy Efficiency Action Plan, 2017). But with the Italian government making it impossible to place noncondensing gas boilers in the market from October 2015, the share of condensing gas boilers in existing buildings probably increased (Italian Energy Efficiency Action Plan, 2017). France and Germany have the third and fourth largest sales of boiler units (540,000 and 520,000, respectively) (Kemna et al., 2019) in the EU, with boiler units accounting for 80% the respective countries' heating technology mix. In both countries, wall hung condensing boilers dominates the market due to ease of installation and lower installation costs than floor standing boilers (Kemna et al., 2019). Therefore from Fig. 11.2A and B, it can concluded that natural gas condensing gas boilers are the dominant heating technology in the EU.

The share of other boiler technologies (mentioned in Fig. 11.2A and B) is relatively constant and small compared to the condensing and noncondensing gas boilers with the exception of HPs whose share increased from 2% in 2004 to 11% in 2010, followed by an increase to 12% in 2016. In the EU the total stock of HPs is estimated to have reached almost 8.5 million units in 2016, with annual sales figures reaching around 800,000 units per year. The EU market is dominated by ASHPs, representing more than 80% of the market with the largest growth is seen in air-to-water HPs since they provide heating for both space heating and sanitary hot tap water (EHPA, 2018). The increased share in HP sales (2% in 2004 to 12% in 2016) could probably be attributed to (1) countries moving away from fossil-based heating technologies to meet future climate goals, (2) government subsidies to promote the use of HPs. [e.g., Investeringssubsidie Duurzame Energie (ISDE) scheme in The Netherlands, energy efficiency action plan (EEAP) in Italy], and (3) a decrease of sales prices and an improvement of efficiencies which will be illustrated by two country case studies later.

11.4.2 Current market developments of heat pumps

The scale of the current HP market can be assessed based on the technology associations such as european heat pump association (EHPA). Annual reports give a broad overview of the current sales statistics and the market development. However, there is a lack of data and dataset inconsistency, especially in terms of technology differentiation and cost development. The first is caused by classification issues in different countries, as the main function of HPs differs per climate type: heating in cold climates or cooling in moderate climates. The latter is caused by insufficient data gathering, small- to mid-sized manufacturer structure with different market environments and subsidy schemes. Therefore availability of consistent global data for HP sales and cost development is limited (REN21, 2017).

In the EU the total stock of HPs is estimated to have reached almost 9.5 million units in 2017, with annual sales figures reaching 1 million units per year.

The EU market is dominated by ASHPs, representing more than 80% of the market. The largest growth is seen in the sanitary hot water type that combines a HP with a hot water storage tank (air-to-water system). Another trend observed by the European Heat Pump Association is that larger HPs for industrial applications are gaining popularity [+ 22% in 2017 compared to 2016 (EHPA, 2018)]. In 2017 the strongest relative growth in HP sales was seen in Austria and Lithuania, followed by Denmark and The Netherlands (EHPA, 2018). For 2017 numbers on HPs in the EU show a growth of about 13% for ASHP and GSHP. An estimated 92 GW_{th} was installed by the end of 2017. The market is led by Sweden, accounting for a total capacity of 5.6 GW_{th} (REN21, 2017). Even though the market is expanding, HPs delivered less than 1% of total final heating and cooling demand in the EU in 2015. For the residential sector, this share was a little higher but remained lower than 2% (Fleiter et al., 2017).

In relative term, HPs have a high market relevance in quite different. The highest share of HPs in their respective country's heating technology sales mix is observed in Sweden with a market share of 87% in 2004, followed by Finland (71%), Estonia (40%), Switzerland (37%), Slovenia (33%), and Austria (23%). Particularly Sweden and Switzerland have a long-term experience in introducing HPs into the heating market, see Kiss et al. (2012).

Numbers for HP markets outside of Europe are uncertain. The global amount of HPs installed in 2015 is estimated at 20 million units in buildings and 0.2 million units in the industrial sector (IRENA, 2018a). Heat consumption from HPs is estimated to have grown by 7% in 2017 compared to 2010, with the largest growth of 50% in China (OECD/IEA, 2017a). For GSHPs only the United States and China had a capacity of 16.8 and 11.8 $\mathrm{GW_{th}}$ at the end of 2014, respectively. Other important markets in Asia are Japan and the Republic of Korea (REN21, 2017). For 2017 international renewable energy agency (IRENA) reported a record increase in installed HPs globally (IRENA, 2018a).

11.5 Current market developments of gas boilers and heat pumps—a case study for The Netherlands

As outlined earlier, the natural gas condensing combi boiler is one of the most important current residential heating technologies in the EU and worldwide and accounts for 90% of the market share for heating technologies in the EU (Kemna, et al., 2019).

One front-running country is The Netherlands, which have—due to the abundance domestic natural gas—pushed the development and market deployment of these boilers since the late 1970s. The yearly sales trend of natural gas noncondensing and condensing combi gas boilers in The Netherlands for the period 1981–2017 are shown in Fig. 11.3. Condensing gas combi boiler sales in The Netherlands were around 13,000 units, while noncondensing gas boilers being the dominant technology had sales of around 167,000 units in 1981. By 1996 condensing combi boiler sales increased to 93,000 units and by 2008 reached to around 388,000, after which the sales trend seems to stabilize with the emergence of district heating and alternative heating sources such as HPs (Natuur & Milieu, 2018a; Kemna et al., 2019). Until the late 1970s noncondensing gas boilers with relatively low efficiencies of around 80% were the standard technology for space heating (Weiss et al., 2009). The increasing energy prices after the first oil crises in 1973 triggered the development of alternate sources of heating—the condensing gas combi boiler that uses the latent heat of evaporation contained in the water vapor of the flue gas. The relative low amount of sales in the 1980s can be attributed to lack of training and experience of installers with the new technology, additional requirements on household infrastructure, less reliable and more expensive than noncondensing gas boilers, and introduction of more efficient (88%) noncondensing boilers to the market (Weiss et al., 2009). From 1990 to 2004 the

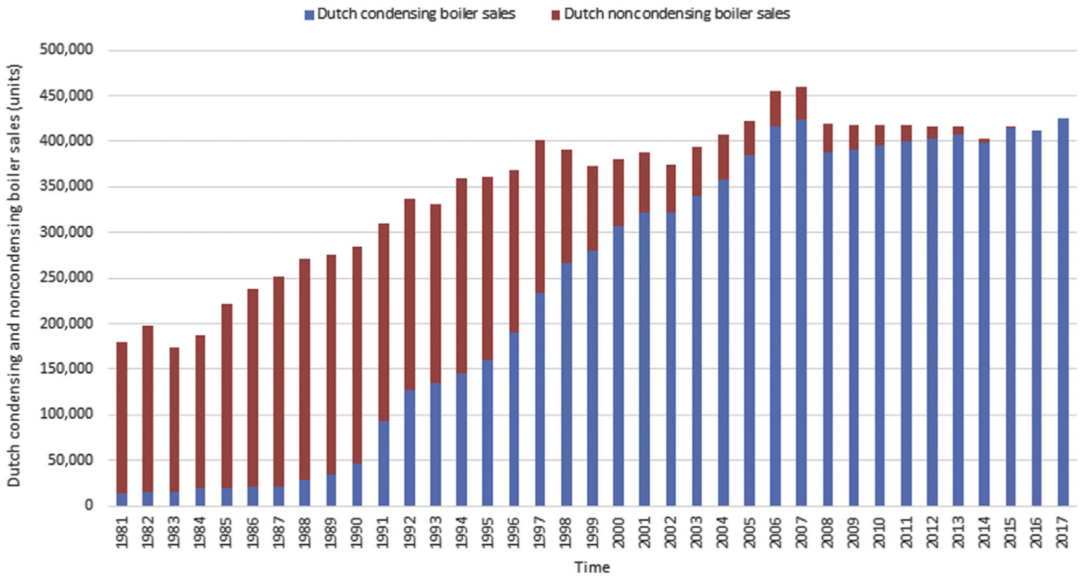

Figure 11.3

Development of natural gas noncondensing and condensing combi boiler sales in The Netherlands from 1981 to 2017. *Source: Data from Weiss et al., 2009 (original source: Weber et al., 2000; BRG Consult, 2009); Natuur & Milieu, 2018a; Kemna et al., 2019.*

condensing gas combi boiler sales were the dominant boiling technology with yearly sales increasing by around 40% compared to the previous year. This rapid market distribution can be attributed to technological developments in conventional noncondensing gas boilers that led to switch from inexpensive open to more expensive closed boiler systems, thereby making condensing gas combi boilers increasingly attractive (Weiss et al., 2009; Kemna et al., 2019).

Currently, around 90% of the 7.7 million Dutch homes have a connection to the natural gas network, while the aim is to be gas free by 2050 (Natuur & Milieu, 2018a,b). However, since 2018 the Dutch government has completely reversed its view on the deployment on natural gas. This ambition stems from the Paris Climate Agreement and the desire to reduce the risk of earthquakes in Groningen by natural gas (Natuur & Milieu, 2018a,b). Recently, the Dutch government has an ambition to “close the gas valve” for 30,000–50,000 houses every year from 2021. Therefore a transition is required in the built environment, to move away from gas sources for heating and hot tap water to electrical and more sustainable source for heating.

In order to move away from gas as a source of heating, the Dutch government introduced the ISDE scheme in 2016. This scheme provides subsidies for the purchase of solar boilers, HPs, biomass boilers, and pellet stoves for both private and business users (RVO, 2019). The available subsidy for business users and private individuals is around 100€ million in 2019. The ISDE is a multiyear plan that opened on January 1, 2016 and runs until December 31, 2020 (RVO, 2019). With the introduction of the ISDE scheme, HPs have become financially attractive and thus providing a solid boost in the market (Dutch New Energy Research, 2018). The HP sales in The Netherlands have increased from 36,000 in 2010 to 84,000 in 2017 (see Fig. 11.4). The growth was particularly high after the introduction of the ISDE scheme is 2016: +44% in 2016 as compared to 2015. In 2017 the growth rate decreased to 15% whereas sales of natural gas condensing combi boilers have been growing at a low rate of 3% per year. However, despite the introduction of the ISDE scheme, the sales of HPs are significantly lower than the sales of natural gas condensing combi boilers (84,800 HP units versus 425,000 natural gas condensing boiler units in 2017). Note that sanitary hot water is not included in the Dutch HP unit sales due to its negligible share (<1%).

The first HPs in The Netherlands were installed during the early 1980s for space heating, but the growth was affected by low sales due to factors such as low oil prices, lack of policy support, and technical problems (Weiss et al., 2008). In the early to mid-1990s, HPs began to receive attention as a result of increasing energy prices and discussions of anthropogenic climate change (Weiss et al., 2008). The introduction of new energy standards in 1995 aided in increasing the demand for HPs (Weiss et al., 2008) (67 units sold) (CBS, 2019). By 2000 the yearly number of units sold increased to 930 units, though sales figures and market growth prior to 2010 were low (16,700 units in 2009 and 4000 units in 2005) (CBS, 2019). The low sales figures could be attributed to (1) the availability

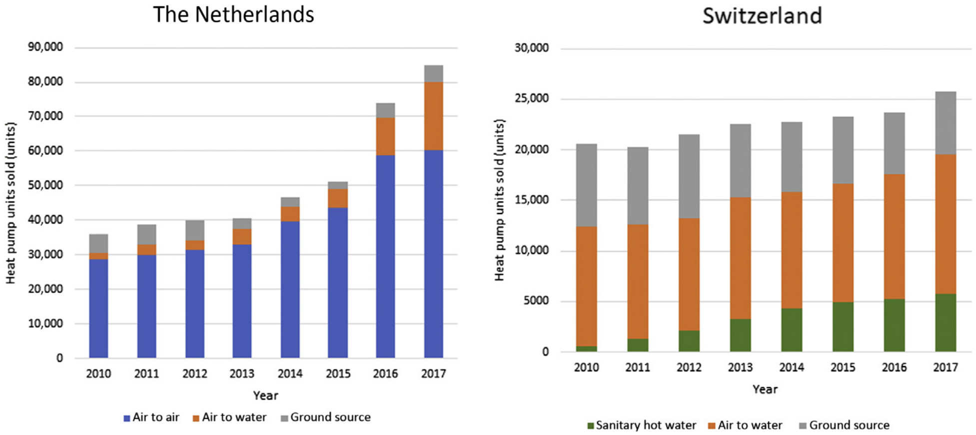

Figure 11.4

Heat pump sales by type in The Netherlands and Switzerland between the period 2010 and 2017. *Source: Data from FWS (2014); EHPA (2016); Natuur & Milieu (2018a); CBS (2019); Kemna et al. (2019).*

of highly efficient cheap natural gas boilers and cheap gas supply for heating, (2) lack of experience of installation companies in installing HPs, and (3) earlier HP systems that were suitable of newly built houses but generally not for the replacement market of the existing building stock (Weiss et al., 2008).

The CBS (Centraal Bureau voor de Statistiek) excluded air-to-air HP unit sales before 2010. According to CBS and RVOs Renewable Energy Monitoring Protocol (Protocol Monitoring Hernieuwbare Energie) (2015), air-to-air HPs sold prior to 2010 are assumed to not comply with the energy performance standards of the European Commission (2013), and therefore data on air-to-air sales was not available. From 2010 air-to-air HPs have the highest share of units sold in the observed years (81% in 2013 and 71% in 2017), while GSHPs have the lowest share (8% in 2013 and 6% in 2017) since GSHPs usually have difficulty in installing in densely populated areas (such as The Netherlands) due to a specific requirement for spacing between installations, and they are the most expensive type of HPs (Kieft et al., 2017, Dutch New Energy, 2018). Air-to-air source HP only requires a source for air and is the cheapest among the three types of HPs with an average system cost of 6800€ (Dutch New Energy, 2018). The advantage of using air-to-water HPs over air-to-air HPs is that they can provide heating for tap water (Forsén et al., 2005). The increase in share of air-to-water HPs (11% in 2013 and 23% in 2017) in The Netherlands can probably be attributed to the multifunctionality of the system to provide heat for space heating and hot tap water. The ISDE subsidy scheme introduced in 2016 does not provide subsidies for cooling technologies (RVO, 2019). Since air-to-air HPs are mostly used for air conditioning in The Netherlands, the ISDE scheme does not cover this technology and therefore could explain the 8% drop in share of air-to-air HPs and 8% rise in share of air-to-water HP units sold between 2016 and 2017.

11.6 Current market developments of fossil heating systems and heat pumps—a case study for Switzerland

In Switzerland, oil heating systems were common to be installed from the 1950s und up to the 1980s in both single and multifamily homes in new construction and retrofits. As a result, oil heating systems and oil burners (to retrofit installed systems) were dominating the heating sales market up to the end of the 1990s. Driven by concerns about security of supply the gas grid infrastructure was expanded and switched to natural gas to serve also heating purposes. As compared to other European countries, particularly The Netherlands, gas took off relatively late, also due to topographical reasons. Next to security of supply local air pollution was a further concern that impacted energy policy in Switzerland from the mid-1980s. In the case of oil and gas heating systems, technical developments toward low-emission burners and boilers were fostered by respective technical requirements. The low-NO_x and condensing technologies were first introduced for gas heating systems from the mid-1990s, followed by similar developments in the case of oil systems and later on also for wood technologies. This time lag is also explained by the technical challenge that was the lowest in the case of gas.

Referring to security of supply, diversification, clean air, and availability of nonfossil and moderately priced electricity HPs was promoted in Switzerland from the early/mid-1990s in a concerted action: the electricity industry offered special tariffs, some Cantons subsidized HP for a certain period, the Cantons' building codes and the energy-efficiency label *Minergie* were incentivizing HPs, and trust in the technology was created by building up a national HP test center (see Kiss et al., 2012 for more details). These favorable framework conditions drove a continuous increase of the HP market share, starting with the segment of new single family houses. In this market segment, HP reached a share of more than 50% from the early/mid-2000s and currently the predominating system (source: Swiss Federal Statistical Office). Further segments such as HP in building retrofits were slowly developing from the late 1990s/early 2000s and more recently also larger buildings such as multi family houses (MFHs) are equipped with HPs. As a result of these developments the technology sales gradually shifted from fossil heating systems toward HPs and since about 2008 HPs is the top ranked sales technology (see Fig. 11.5).

In the 1990s and still in 2000 the market shares of air-to-water and GSHP were quite similar, with somewhat higher shares for air-to-water HP (50%–55%, measured in terms

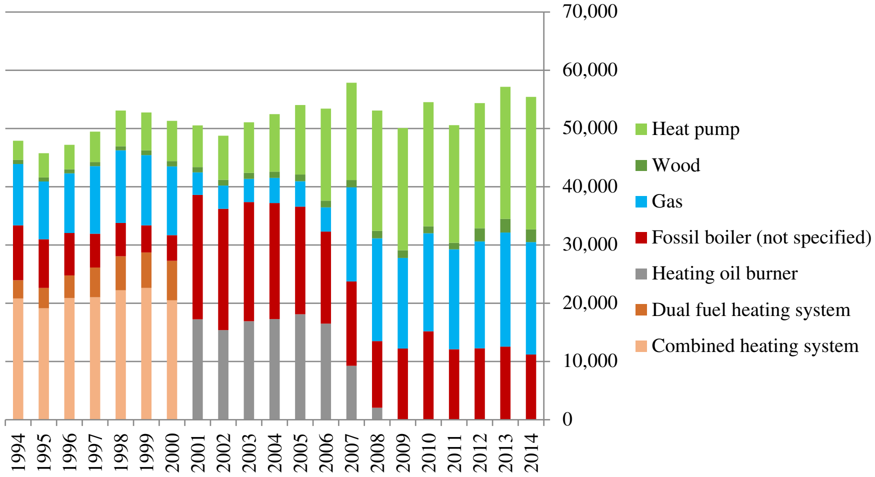

Figure 11.5

Heating technology sales by type in Switzerland between 1994 and 2014. *Source: Data from FWS (2006, 2014); TEP Energy.*

of units sold). The market share of water-to-water HP that tap groundwater was quite low, also due to legal restrictions. Water heat sources including rivers and lakes have rather been tapped with larger HP. Since the mid-2000s the relative market share of air-to-water HP (including sanitary hot water HP) gradually increased at the cost of GSHP [see Fig. 11.4 that shows the Swiss HP sales by type between 2010 and 2017; air-to-air HPs are excluded in the Swiss HP in this figure due to its negligible share (0.3% in 2010, 0.1% in 2011, 0.3% in 2013 and 0% for the remaining years)]. This shift toward air as a heat source is explained by the lower costs of these systems and the improved energy performance both in terms of coefficient of performance (COP) and seasonal energy-efficiency rating.

11.7 Methodological issues and data availability

An overview of the general data collection issues applicable to HPs is given in Table 11.1 and is discussed as follows:

- Data is not for cost but for price: This is a common issue in learning curve assessments. In the case of competitive markets price, data can be used as a proxy indicator for costs. We assume that this is a valid approach for heating technologies, albeit that in an early phase of the market introduction an extra premium is charged to tap the specific willingness-to-pay of early (demand side) adopters. This issue may be verified by

Table 11.1: General data collection issues for natural gas boilers and heat pumps.

Issue	Resolution	Applicability	
		Boilers	Heat pumps
Data is not for cost but for price	Use price data as indicator for costs	☑ Yes	☑ Yes
Data not available for desired cost unit	Data might be converted or transformed	☐	☐
Data is valid for limited geographical scope	Convert currency Combine with other datasets from various geographical scopes	☑ ☑	☑ Yes
Cumulative production figures not available	Calculate from annual figures Calculate from sales figures	☑ Yes ☑ Yes	☑ Yes ☑ Yes
Data is in incorrect currency year or currency	Correct for inflation and convert currency	☑ Yes	☑ Yes
Early cumulative production figures are not clear or available	Roughly estimate early cumulative production figures from the demand side and perform sensitivity analysis	☑ ☑ Yes	☑ Yes (NL (Netherlands))
Supply/demand affecting costs significantly	Data discarded for final recommended learning rate	☑	Yes (NL (Netherlands))
Lack of empirical (commercial scale) data	Check alternative data sources Run specific surveys		

specific expert interviews, and long-term data series might reveal such effects (in terms of particularly steep learning curves) after the termination of such phases, as outlined in Chapter 2.

- Various geographical scopes: Technologies that are composed by different production and cost elements might be produced in and traded between different countries or regions which could make it nontrivial to choose the appropriate functional unit. In such cases a geographical scope should be chosen that is predominantly determining the prices (if prices are used as a proxy). In the case of demand side and end use technologies that need to be planned and installed in buildings, the appropriate choice might be the final clients' country rather than the country of production. Indeed, learning takes place very much also at the local scale, as pointed out by Neij et al. (2017) for the case of photo voltaic (PV) installations. Thus if possible the costs are decomposed and reference units covering different geographical scopes are chosen. To aggregate the different elements a weighted index might be considered. For the case of HP the costs are decomposed (see later), but the same geographical scope is used for all elements.
- Cumulative production figures not available: This drawback might be overcome by calculating cumulative figures from annual (sales) figures. When doing so, it is important to estimate historical (sales) figures. An underestimation of the (historical) cumulative figures results in an overestimation of the learning rate (LR).
- Inflation and currency: If long-term data from count with different currencies is to be reported and compared, there is a choice on how inflation and currency conversion is performed. As end use technologies such as heating systems are usually purchased by national actors (building owners, installers) on a national market, we first deflate the data at a national scale and then to convert the real price time series using the conversion rate of the base year (e.g., the year of the most recently available data). This was done to compare price data and derived experience curves between Switzerland, The Netherlands, and other European countries: converting nominal Swiss Francs to real CHF with a common base year (e.g., 2017), using the consumer price index (CPI). Swiss Francs are then converted to Euro, using an exchange rate between CHF and EUR of that base year. With this approach, we take into account that the purchasers of HP are seeing prices in their national currency, and we avoid any deformation of the time series that would be the case if current exchange rates were used (due to the volatility of currency markets).
- Early cumulative production figures/data from the early phase are not clear or available: especially in case in which the market introduction of a technology is already a long time in the past and if the market is quite developed, early cumulative production figures should be estimated, even only roughly. Such estimates can be done from the demand side perspective if no production or (apparent) supply side data can be tapped. In case of doubt, sensitivity analysis should be performed (which is done for the Swiss

case). If the time series covers a late period only and if it is short (less than one or two doublings), one should refrain from estimating LRs and rather perform a descriptive analysis (done for the case of Dutch HP).
- Supply/demand affecting costs significantly: If such effects cannot be isolated, for example, through interviews or through long-term data series, LRs should not be estimated and used for policy recommendation.
- Lack of empirical (commercial scale) data: Alternative data sources such as statistical offices or associations that publish price indices or cost indicators. Alternatively or in addition, dedicated expert interviews or specified surveys could be performed. This approach was chosen for the case of Swiss HP.

Additional methodological issues that are specific for building related end use technologies in general and for HP or condensing gas boilers in particular are discussed in the following sections.

11.7.1 Methodological issues for heat pumps

Ideally learning and experience curves assessments cover the considered systems as a whole as energy performance, and costs very much depend on system configuration and building integration. Due to data availability and data gathering costs, such assessments can possibly be decomposed in different elements. In the case of HP systems, cost components that occur for building owners can be summarized in three groups which might of comparable cost relevance (which also implies that the HP device as such might only amount to half or even less of the total system cost):

- HP device
- Tapping the energy source [e.g., air—water, water—water, or borehole heat exchangers (BHEs)]
- Ancillary systems (e.g., controls, technical storage, heating, and hot water mixer), installation (to install and connect HP device, source tapping device, and heating distribution system), and other up-front costs (grid connection, structural adjustments, planning, etc.)
- Energy costs to operate the HP system

Such cost categories are differentiated analogously for gas heating systems which in addition to the boiler need components such as a grid connection and exhaust air installation. Referring to these cost components, learning and experience curve effects in the case of HP heating systems (thus including tapping the RES) can be attributed to the following effects:

1. Decreasing costs (price) per unit (at a given technical performance)
2. Improved energy efficiency and technical peak performance at constant (real) prices
3. General technical improvements or additional features not directly linked to energy-efficiency

In the ideal case, these effects are considered at ones in an integrated approach. Effects 1 and 2 can be integrated by adopting a life cycle-cost approach with an appropriate functional unit such as costs of delivered heat per unit of heat floor area (similarly to the cost-of-saved energy concept presented in Jakob and Madlener, 2004).

Nonenergy aspects could be integrated by adopting a multivariate learning curve approach [as proposed for instance by Badiru (1991, 1992)] to attribute costs to different utility components (similarly to hedonic price functions that elicit the economic value of such attributes).

If experience curve assessments are done for different cost elements changing boundary condition and interaction between these elements and between the different learning attributes need to be taken into account. Concretely this relates to as follows:

- A higher degree of integration: HP systems in the 1990s or the early 2000s are characterized by quite some components that needed to be integrated in the planning and installation processes, for example, MSC (metering, sensors, and controls), connectors, and heat source exchangers. Much of these devices and functionalities are now integrated the HP device as such, which means that the utility of the device has been increased (which might compensate part of the cost reduction from learning, if only the device is considered).
- Noise mitigation: particularly ASHPs have been facing noise issues, either internally of the building (compact HP) or against neighboring buildings (split configurations). As such issues often hindered the HP option against other heating systems, the HP industry improved the design of their products to reduce noise emissions.
- Generally, the quality of the HP systems including the planning and installation process (to which costs and efficiency of HP systems are particularly vulnerable) has been improved over the past years, particularly related to integrated controls including remote and self-auditing.

11.7.1.1 Data availability and data collection

Data availability long-term techno-economic data series of end use systems such as HP or gas heating systems are generally scarce. For these reasons, we focused on two cases for which historical data was available and could be extended within the framework of the REFLEX project. To do so, original data was collected from industry stakeholders and experts in Switzerland and in The Netherlands.

11.7.1.2 Data collection for heat pumps

Prices and technical data were collected by approaching key market players both in Switzerland and in The Netherlands. This included both the HP suppliers (representatives from large European manufacturers) as well as borehole companies and planers. In addition, data from the cost element indicator database of the Swiss Federal Office of Statistics was collected and used (BFS, 2019). Data collection included of a selection of implemented projects, generic cost indicators, and price catalogs from which also technical data was considered (energy-efficiency, rated power, noise emissions. etc.). In addition, data from the Swiss HP center is used to characterize the development of the energy-efficiency of the HPs. Stiebel Eltron provided price data for The Netherlands for different HP capacities from the year 2011 to 2016. The capacities of these residential HPs range from 3 to 30 kW. This price data needed to be harmonized with the 7.5 kW HP capacity selected for the Swiss HP learning curve by Weiss et al. (2008). For each year (2011–16), price data was plotted against their respective capacity and a power curve was fitted to the graph. The equation of the power curve was then used to calculate the price per kW for a 7.6 kW HP. The equation of the power curve provides an indication of the economies of scale for HP capacity for the years 2011–16. The economy of scale is quite pronounced: with a doubling of unit capacity, the price of a HP unit on average drops by 27%.

11.7.2 Methodological issues and data collection for gas boilers

Price and sales data of Natural Gas Combi boilers from the year 1981 till 2007 were gathered from Weiss et al. (2009). Weiss et al. acquired the price data from Consumentenbond (1981–2006) and Warmteservice (2007) and acquired sales data for The Netherlands from Aproot and Meijnen (1993). They uniformly used market prices and Dutch market sales data as proxies for actual production costs and actual natural gas combi boiler production. Using prices as proxies for production cost assumes a competitive market where prices closely follow production costs (BCG, 1972) which is also the case for Natural Gas Combi boilers (Weiss et al, 2009). The result of this research is a continuation/updating of the experience curve generated by Weiss et al. (2009).

To maintain consistency, prices and Dutch sales were used as proxies for production costs and actual boiler production respectively also for the research presented hereafter. For the updated experience curve, natural gas combi boiler price data was gathered from Consumentenbond (2015–18), and Dutch sales data was acquired from Natuur & Milieu (2018a). Boiler price and sales data between 2007 and 2013 were not readily available. Therefore sales data prior to 2013 was interpolated using the average yearly change in sales between 2013 and 2018. This was done in order to calculate the cumulative boiler sales from 2007 till 2013. The price of natural gas combi boilers excludes VAT. Weiss et al. reported the price of natural gas combi boilers in $€_{2006}$/kW. This was converted to $€_{2017}$/kW using the EU CPI from Eurostat (2019). Based on the price data, for each year, the average prices were calculated and used to generate the experience curve. In their analysis, Weiss et al. (2009) only included natural gas combi boilers with a capacity less than or equal to 30 kW_{th} because these boilers are typically used for central heating and hot water production in residential buildings (CBS, 2019; Weiss et al., 2009). Therefore to maintain consistency with Weiss et al. (2009) analysis, only boilers within the same range (≤ 30 kW$_{th}$) were considered.

11.8 Techno-economic progress and experience curves

Techno-economic progress and experience curves for the case of HP are illustrated along the following dimensions:

- Decreasing costs (price) per unit (at a given technical performance)
- Improved energy efficiency
- General technical improvements or additional features not directly linked to energy-efficiency

11.8.1 Decreasing costs (prices) per unit for the case of heat pumps

The investment costs for HPs with BHEs continuously decreased in Switzerland since 1890 (Fig. 11.6), both for the case of single family houses (data available up to 2008) and for multifamily houses (data available from 2012). For comparability reasons, data was transferred into specific costs per m^2 using a standard design approach (about 40 W/m^2). The cost level of HP for the case of The Netherlands is considerably lower (40–50€/m^2) as

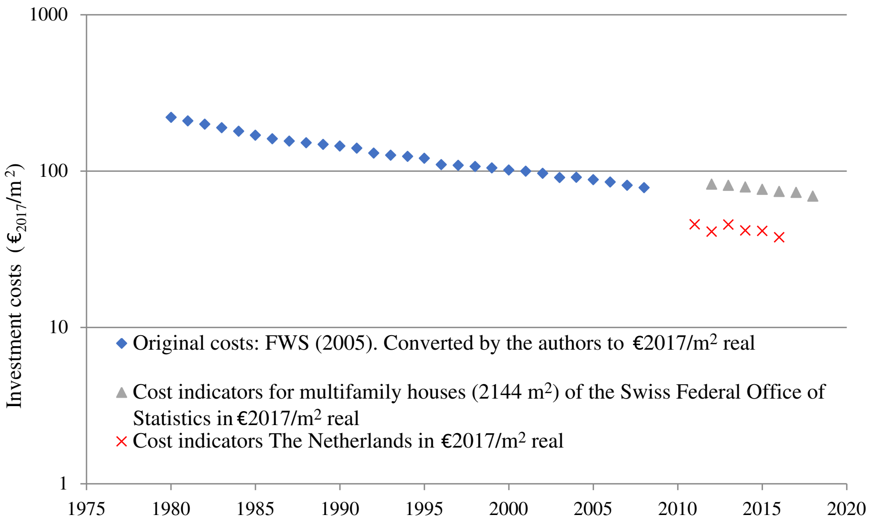

Figure 11.6
A specific investment for complete heat pumps systems with borehole heat exchangers for multifamily buildings in Switzerland (*gray triangle*) and for air-to-water residential heat pumps in The Netherlands (*red cross*).

compared to the Swiss one (in 2017 about 65€/m^2). There are several reasons for this: which is explained by the different types of HP and scope that in the case of the NL only includes the HP module and inverter and not a BHE. The borehole covers about 50%–70% of the cost. Second, the Swiss data includes installation and piping (another 20%). Last but not the least, price levels of all consumer goods, labor, etc. are more expensive in Switzerland than in the EU, including homogenous products such as household appliances and heating systems.

Fig. 11.7 shows two experience curves for a 7.6 kW residential HP sold in Switzerland and The Netherlands. The country's specific selling prices were plotted against cumulative HP sales of each of the respective countries and costs were converted as per m^2 of heated floor area using a standard conversion factor of 40 W/m^2. The experience curve for the Swiss HPs is derived from the dataset of FWS (2006), and Kiss et al. (2012) show a LR of 18% for a time series of 28 years (1980–2008). Weiss et al. (2008) estimated a LR of 26% for the period 1980–2004, but probably carried out inflation correction twice. The LR for the case of Swiss MFH HP of the same type (see BFS, 2019 for details) for the period of 2012–18 is considerably higher (27%) which is mainly explained by the learning effects for BHEs (see Fig. 11.8), which supports this result by independent data. Combining the

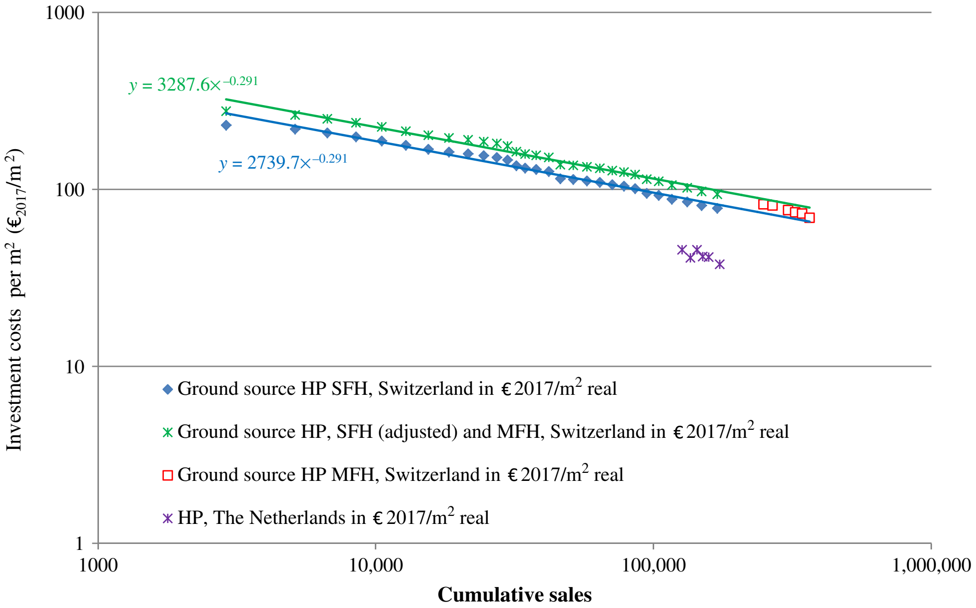

Figure 11.7

Experience curves for heat pumps. Blue data points stem from FWS (2006) and Kiss et al. (2012), green data points are level-adjusted of the latter, red data points are for MFH (source SFOS), violet data points were gathered for this report, and were scaled to costs for heat pump with a thermal capacity of 7.6 kW and converted into €/m^2 using 40 W/m^2.

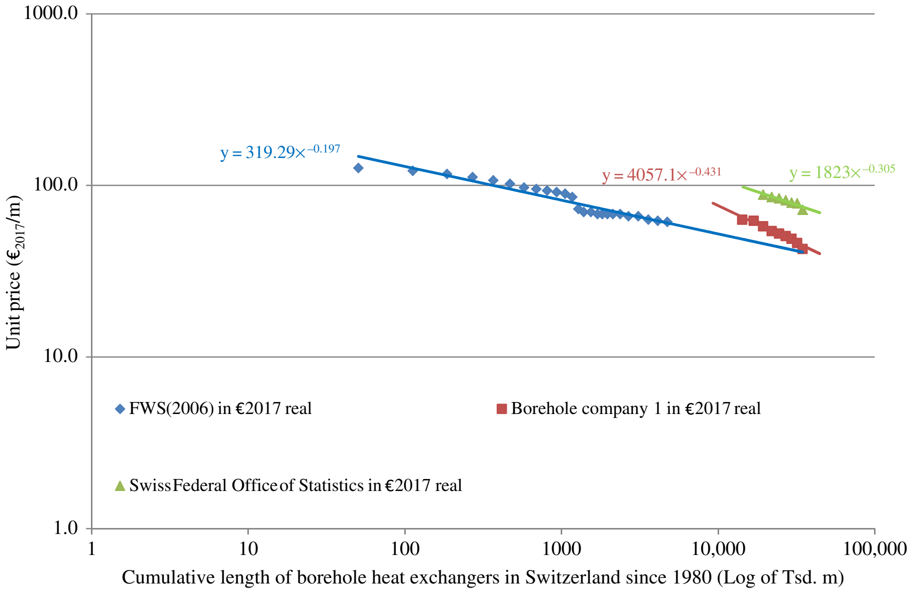

Figure 11.8

Experience curves for borehole heat exchangers for heat pump with a thermal capacity of 7.6 kW (case of new single-family houses in Switzerland). Blue diamonds were taken from FWS (2006), orange squares were gathered by TEP Energy for this report.

two series (level adjusted) yields a long-term LR of 19%. A sensitivity analysis was performed in terms of cumulative sales of the period before 1980 (assuming 3000 units) which almost did not affect the LR result. The LR of the Dutch data for the period 2011–17 is estimated to 19%. Although this result is similar to the one of the Swiss case, it should be kept in mind that the data series are quite short and covers less than one doubling of the sales, and the R^2 is very poor.

The observed cost reductions can be attributed to technological learning in the manufacturing and installation of both HPs and related system components (Weiss et al., 2008). In the past decades, heat exchangers became both smaller and cheaper. The main components of a HP (e.g., the vapor compression cycle and heat exchangers) are used in the cooling industry, and therefore the major driver for cost reductions in HPs can be attributed to technological learning in HP assembling and system integration. Note that compressors are imported with increasing shares from Asia, and production in Europe is decreasing. Cost reductions were also achieved by economies of scale, including manufacturing costs, purchasing costs, sales costs, and possibly other cost items (Weiss et al., 2008). Further learning potential could be expected from other optimizations in the design and production processes when HPs are produced in larger numbers above 100,000 units sold per manufacturer.

A second experience curve for Dutch HP prices is also shown in Fig. 11.7, based on own data collection. The curve for the Dutch HPs shows a LR of 18% for a time series of 5 years (2011–16). We used price lists for different HP capacities from the year 2011 to 2016. This price data was harmonized with the 7.6 kW HP capacity selected for the Swiss HP learning curve by Weiss et al. For all years together (2011–16), price data was plotted against their respective capacity on a linear axis. For each year the average price was taken and plotted above. From this dataset the data for the year 2012 was omitted since it was determined to be an outlier.

11.8.2 Decreasing costs (prices) per unit for the case of heat pump borehole heat exchangers and heat pump modules

HPs have a long-term tradition in Switzerland which was part of the first phase of the development of the technology. To foster energy-efficiency, to diversify the energy supply mix, and sales of domestic electricity production HP were strongly promoted from the mid-1990s (see Kiss et al., 2012 for an overview). HPs with vertical BHE to tap geothermal energy had relatively high market shares, especially in the steep market development phase, mainly due to energy-efficiency reasons. Later on, although air–water HPs have been working more efficiently in recent years (Fig. 11.9), some saturation of the installed amount

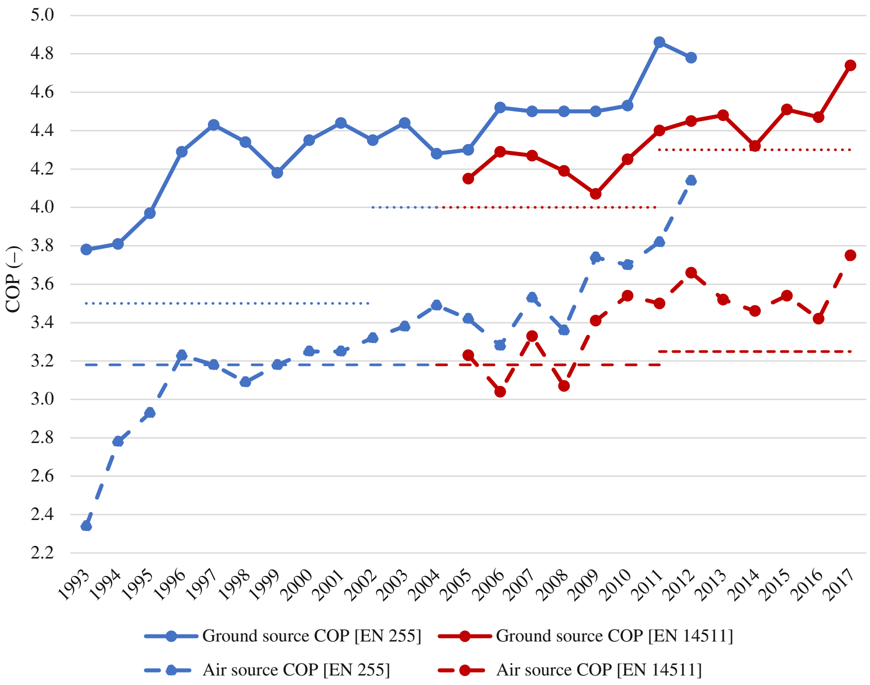

Figure 11.9

Development of COP of HP with borehole heat exchangers and for air source HP in Switzerland (Eschmann, 2017). *COP*, Coefficients of performances; *HP*, heat pump.

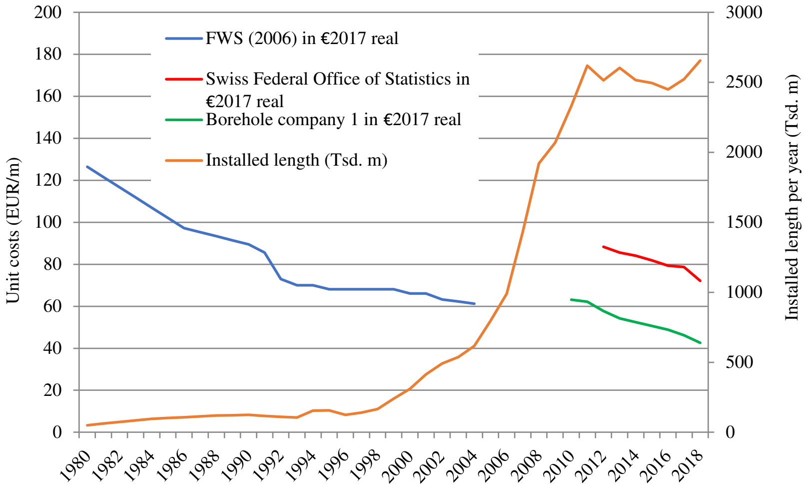

Figure 11.10

Unit costs and installed length per year (in thousand m) for borehole heat exchangers (based on a case of HP with a thermal capacity of 7.6 kW for new single family houses in Switzerland). Unit costs up to 2004 were real prices (base year 2004) and were taken from FWS (2006), those from 2010 were gathered by TEP Energy for this report (*green*) and by the Federal Office of Statistics (*red*). All price data in CHF is first deflated to real CHF (base year 2017) and then converted to EUR (exchange rate 2017: 1€ = 1.11 CHF). *Source: Data from (FWS, 2000, 2006, 2018).*

is observed (Fig. 11.10). Alongside with gaining experience and higher demand for BHE, specific costs dropped continuously over the past years (Fig. 11.10). Note that unit cost data is missing from the years 2005 to 2009, and that unit costs stem from three different sources which might explain the different level.

Cost respectively price reductions are related to the cumulative installed borehole length, as shown in Fig. 11.8 that also displays the estimated learning curve in a log–log representation. LRs are about 12% for the first data source (FWS, 2006), about 26% (Borehole company 1) and 19% (Swiss Federal Office of Statistics). The reasons for the price decrease since 2010 are attributed to the following reasons:

- Economy of scale (larger drilling machines with greater power).
- Higher utilization rate of borehole equipment entailing lower unit costs.
- Equipment (drilling machines) is mostly paid off and thus prices are related to variable costs, which hampers drilling companies to reinvest.
- Increased competition though overcapacity caused by new market players who focus on low prices (as the overall demand has been quite constant during the last few years, see Fig. 11.8).
- Increased competition against other types of HP, particularly air-to-water HP, due to technical improvements (higher COP) and low(er) prices.

The LRs may not be extrapolated for longer time scales as some of these factors are specific to the recent and current market situation.

Similarly, LRs were estimated separately for HP modules (the HP appliance as sold by the manufacturers and suppliers) and for installation and piping. Independent data from FWS (2006) covering a long-term period and from the Swiss Federal Office of Statistics covering some recent years BFS (2019) was used. The LR of HP appliances was estimated to 22% for piping and to 14% for installation.

11.8.2.1 Improved energy efficiency in the case of heat pumps

In Switzerland (new), HP models are tested by an independent test center. Since 2005 the first year the COP was measured according to EN 14511, the COP increased on average by 0.8% per year (Eschmann, 2017). Before 2005 also the COP increased considerably (see Fig. 11.9). A considerable increase of the COP was achieved with the introduction of the HP quality certificate in 2011. In order to receive this certificate, a COP of 4.4 needed to be achieved from 2011.

The learning and experience curve concept may also be applied to the technical development. To apply the usual experience curve concept, the (log of the) cumulative sales (e.g., in terms of sold units) are related to the (log of the) inverse of the COP. A LR of 5% is estimated for the transformed variable 1/COP. This means that the COP increased with 5% with each doubling of the sales (Fig. 11.11).

11.8.3 Decreasing costs (price) per unit in the case of gas boilers

The experience curve for natural gas condensing combi boilers from the period 1981 to 2018 shows a curve with an R^2 of 0.8645 and a LR of 13.1% (see Fig. 11.12). This is 1% less than the LR reported by Weiss et al. (14%) from the period 1981 to 2007 but still lies

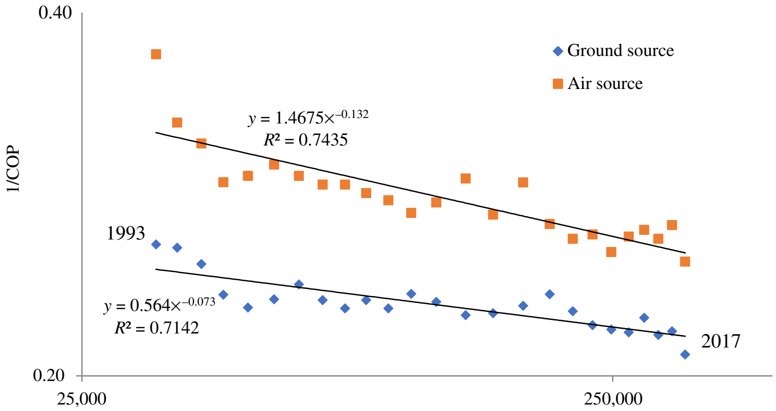

Figure 11.11
COP of ground source and air source HP as a function of cumulative sales of HP in Switzerland. *COP*, Coefficients of performances; *HP*, heat pump.

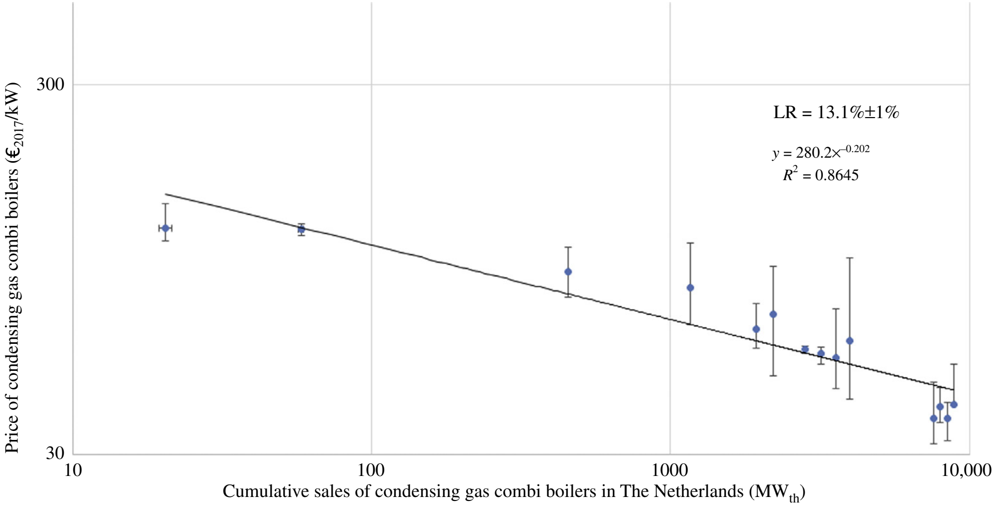

Figure 11.12

Experience curve for natural gas condensing combi boilers in The Netherlands between 1981 and 2017.

within the reported range of ± 1%. Prices of natural gas condensing combi boilers reduced from 122€$_{2017}$/kW in the 1980s to around 40€$_{2017}$/kW in 2018. Between the years 1981 and 2007, Weiss et al. (2009) identified (1) economies of scale (2) increased specialization and automation of production process, and (3) outsourcing of production to low-wage regions as the main drivers for price reduction. They reported that the major changes related to individual components refer specially to heat exchangers and control electronics. The share of cost of heat exchangers has drastically reduced from 30% in the past 25 years. Currently, control electronics are the most important cost component (Weiss et al 2009). They conducted a cost−benefit analysis on natural gas condensing combi boilers for the period 1981−2007. The analysis showed that these boilers were not profitable for consumers several years after market introduction. It required more than 10 years to break through the market. Their analysis further showed the increased cost effectiveness in saving nonrenewable energy resources and CO_2 emissions after 1999. The high natural gas prices between 1999 and 2006 aided in the improved cost effectiveness of condensing combi boilers. The price reduction from 55€$_{2017}$/kW in 2007 to 40€$_{2017}$/kW in 2018 can be attributed to similar drivers (Natuur & Milieu, 2018a,b; Navigant, 2018) as mentioned by Weiss et al. (2009).

11.9 Future market trends of heat pumps in The Netherlands and Switzerland

Currently, investment costs for GSHPs are still significantly higher than natural gas boilers in countries, such as The Netherlands, Italy, the United Kingdom, Germany, which could be attributed to the maturity of the natural gas boiler market in these countries and high installation costs of GSHPs (Kemna et al., 2019). With low power prices, GSHPs could become a cost-effective option at higher levels of space heating because of the relatively low operation costs. In terms of costs for delivered thermal energy, ASHPs are already competitive with condensing gas boilers in some European countries (EHPA, 2018; Iten et al., 2017). Its further diffusion is hampered by the fact that they are recommended for very well-insulated buildings only and require backup in colder climates, among other issues. For low-temperature industry heat, it is expected that costs of HPs will be similar to costs of natural gas boilers around 2040. This expectation is driven by increasing operational costs of gas boiler costs due to increasing CO_2 taxes and fuel costs, and maintaining similar costs for HPs due to higher electricity costs opposing technological learning (OECD/IEA, 2016b).

The future market size of HPs remains uncertain, but HPs play a critical role as source of renewable heat in scenarios of both the international energy agency (IEA) and IRENA for keeping global temperature rise under two degrees. The IEA scenario shows an increasing trend of HP units installed toward approximately 25% of heating (space and water) equipment in buildings by 2060 (OECD/IEA, 2017a). The IRENA scenario expects the stock of HPs to increase to 253 million units in buildings, accounting for a share of 27% of the heat demand, and 80 million units in the industrial sector by 2050 (IRENA, 2018a). With the current growth rate, HP technology is not on track of meeting the two degrees scenario (OECD/IEA, 2017a).

In The Netherlands the current Dutch subsidy support scheme ISDE has aided the (near) doubling of sales in The Netherlands between 2013 and 2017. This trend is expected to continue at least until 2020. Also, it is likely that the HP is the dominant technology in the new building with a market share of at least 60%. Under these circumstances, it is expected that the growth of HPs in new housing will grow within a few years to 30,000 pumps per year (Dutch New Energy, 2018). But with current sales of over 20,000 HPs annually versus nearly 400,000 natural gas condensing combi boilers (mainly for replacement in existing homes), the current market penetration is still only around 5%. Installing HPs in existing buildings is more limited than in the new building because of infrastructural issues and the need to first take adequate insulation measures installation (Dutch New Energy, 2018; Bettgenhauser et al., 2013). A possible transition solution could involve hybrid concepts with an HP as a basic facility in conjunction with a gas or biomass (pellet) boiler as peak supply and providing hot water (Dutch New Energy, 2018; Natuur & Milieu, 2018a,b; Bettgenhauser et al., 2013). These techniques require less or no major changes to the building shell and can dramatically save on gas. The Dutch government's ambition to revamp the entire housing stock as sustainable by 2050 means that in the short term 200,000 homes per year will have to be sustainable (near zero energy) (Dutch New Energy, 2018; Bettgenhauser et al., 2013).

We refrain from using this expected growth rate to extrapolate the Dutch HP experience curve due to the uncertainty surrounding the experience curve data. The experience curve covers a short time series (2011–16) with a poor R^2 which renders the LR to be highly uncertain. However, even though price data for the Dutch HPs relate to air-to-water HPs and the price data encompasses the price of the HP and inverter and the Swiss data relates to GSHPs, we can use the Swiss LR of the HP device (w/o borehole heat exchanger) to extrapolate the Dutch HP experience curve till the projected cumulative sales in 2030. Using the Swiss LR of 19% and an expected yearly installations of Dutch HPs of 30,000 units till 2030, the learning curve for the Dutch case is extrapolated over the Dutch cumulative HP sales. It is estimated that the price of air-to-water HPs in The Netherlands drops to around $28€_{2017}/m^2$ by 2030. It is important to note that using the Swiss LR as proxy to extrapolate the learning curve for the Dutch case leads to high uncertainty due to (1) different types of HP s, (2) different time series, and (3) heterogeneity of cost components included in the price/m^2, so these findings should be considered indicative at best.

In Switzerland, it is currently explored at several levels how carbon emissions from buildings could be cut significantly or even to zero by 2050 (or even shorter). The Federal Office of Environment for instance considered a subsidiary ban of fossil heating systems if other policy instruments would not be sufficient to achieve the targets of the Swiss government (− 50% by 2027/28). Common to all these initiatives is the prominent role that is attributed to HP. Up to 2030 the cumulative sales of small HP for single family house (SFH) could be doubled (from about 370,000 to about 730,000). If medium and large HPs were included cumulative sales (weighted by its thermal power to account for their size), the cumulative sales up to 2030 could be tripled. Thus prices for HP could drop by 20% to more than 30% while their energy-efficiency could increase by 7%–12% or even more if targeted research and development is launched (note that the physical and technical limits are not reached by far), especially in terms of system integration.

11.10 Summary and conclusions

Altering the European building stock and switching from fossil-based heating systems to technologies that rely on RES is the key if ambitious climate change mitigation goals should be achieved. A competitive techno-economic performance would decisively support a significant diffusion of such technologies. Yet, as in other cases, RES technologies are newer and initially more costly as compared to fossil systems that are long term deployed to the market place. In the previous sections, we have investigated the market development and the techno-economic learning for two competing technologies to assess their relative dynamics in terms of techno-economic performance: HP as an exemplary technology to tap RES and (condensing) gas boilers as the reference system to be substituted (or to be fueled by renewable gas).

Table 11.2: Summary of estimated learning rates (LRs) for natural gas boilers and heat pumps.

	Gas condensing boilers		Heat pumps	
	NL (%)	CH	NL (%)	CH (%)
Specific investment costs				
Appliance (boiler or HP module)	13	NA	18	22
Heat source tapping	—	—		12—20
Balance of system	NA	NA		14
Total system	NA	NA		20
Technical performance				
Air-to-water HP				9
Ground source HP				5
Total system (specific cost of generated energy)				20—25

HP, Heat pump; *NL,* The Netherlands; *CH,* Switzerland.

Although the empirical basis is by far not complete, it can be affirmed that LRs from previously gathered historical data are confirmed by more recent data gathered in the context of the REFLEX project. As compared to the condensing gas boiler generally, the LR is equal or higher for all specific cost components of HP (see Table 11.2). This holds for both countries assessed, although it should be kept in mind that the time series is quite short in the Dutch case.

Overall, the relatively high LRs for HPs compared to natural gas imply that HPs have the potential to become increasingly competitive in the coming years. Indeed, given the historical production and sales of the two systems, the cost reduction of HP will be more dynamic as the cumulative production (or sales) will double faster, particularly in a climate mitigation scenario. Moreover, for HP, there is still a considerable technical potential to improve peak performance and energy-efficiency (as opposed to gas condensing boilers where the technical potential is basically tapped). Therefore competitiveness particularly will be improved from a life cycle-cost perspective, and from this perspective HP are competitive already for different use cases in many countries, also depending on the framework conditions. Indeed, as also pointed out in Chapter 14, diffusion will also depend on other factors, such as electricity and natural gas prices, effective policy instruments (e.g., CO_2-tax, differentiated energy taxes, ban of fossil energies), the rate of replacement of heating systems in existing buildings, and other soft factors (such as consumer preferences: installers' and planners' acceptance and skills).

To conclude, decreasing costs could contribute to the deployment of HP and thus to climate change mitigation and reversely stringent climate change mitigation policy instruments could foster the diffusion of HP which entails a cost decrease that supports climate change mitigation (self-enforcing feedback loop).

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