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# Understanding Green Energy Technology

## Learning Processes in the Development of the Ground Source Heat Pump

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# Abstract

## Understanding Green Energy Technology: Learning Processes in the Development of the Ground Source Heat Pump

*Amanda Gidén Hember*

The aim of this thesis is to increase the understanding of small-scale green energy technology development. In the transition towards a fossil free energy system, heat pumps are a low emission heating alternative. Contrary to other types of new small-scale green energy technology such as solar cells and electric vehicles, heat pumps are established on the Swedish market, with more than half the share of single family buildings. This makes it possible to study an example of a mature technology, and that knowledge could be used in the development and deployment of other technologies with similar small-scale green characteristics. The type of heat pump technology studied is ground source heat pumps, and their development is explored from an economic and performance perspective, using the concept of learning. Learning tracks how a product develops for each doubling of units produced.

The results show that the efficiency has increased by a learning rate of 2.8 %. When the effects of a low-temperature heating system is included, the learning rate is even higher, 5.8 %. The efficiency improvement is mainly due to new and more expensive components, which has resulted in a price increase. Even if the price slightly decreased until 2008, it has increased with 29 % since. Nevertheless, the ground source heat pump is profitable compared to several other heating technologies. The most important factors underpinning the development are regulations, competition among manufacturers and research.

Keywords: ground source heat pumps, small-scale technology, energy efficiency, learning, experience curve, gridless technology

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# Sammanfattning

Den energi som används för att driva det moderna samhället har länge producerats av teknik vars bränsle, som olja och naturgas, ger utsläpp av växthusgaser. För att minska samhällets påverkan på klimatet sker en omställning mot mer förnybar energi. I samband med det har ny energiteknik börjat användas, som exempelvis solceller, vindkraftverk, elbilar och batterier. Studier har visat att många av dessa nya innovationer delar vissa egenskaper som de traditionella energiteknikerna saknar.

Traditionell energiproduktion domineras typiskt av stora anläggningar som kärnkraft, fjärrvärme och vattenkraft. Den typen av storskalig teknik är beroende av en omfattande infrastruktur som nationella elnät och lokala fjärrvärmenät. Storskaligheten krävs i många fall för att dessa tekniker ska vara lönsamma och effektiva. Som kontrast utmärks den nya energitekniken av småskalighet och oberoende av infrastruktur. Den småskaliga tekniken kan tillverkas i moduler och användas i små energisystem, som exempelvis i en byggnad som är självförsörjande på energi. I ett sådant mini-energisystem kan solceller användas för att producera el, som i sin tur kan ladda en elbil och driva en värmepump för uppvärmning. I ett scenario där detta dras till sin spets kan en byggnad vara helt bortkopplad från alla former av infrastruktur.

Syftet med den här studien är att öka förståelsen för hur den småskaliga och förnybara energitekniken utvecklas. Det görs genom att studera en teknik som redan är väletablerad i Sverige, nämligen bergvärmepumpar. En ökad förståelse för hur utvecklingen hos en mogen teknik har gått till kan ge kunskap som kan användas när nya tekniker ska utvecklas. I Sverige finns värmepumpar i mer än hälften av alla småhus och Sverige är en av de ledande marknaderna för bergvärmepumpar. Bergvärmepumpar tar värmeenergi från berggrunden och höjer temperaturen till ca 35–55 °C, och den värmen går sedan ut till byggnadens värmesystem (tex element eller golvvärme).

För att förstå olika produkters utveckling används ofta en teori som kallas *learning*. Learning beskriver hur en produkt utvecklas i takt med att den sammanlagda produktionen av produkten ökar. Oftast tillämpas teorin på prisutveckling för att förutse framtida priser, men den kan även användas för att analysera en produkts prestanda. I denna studie används learning för att analysera utvecklingen av ekonomi och prestanda hos svenska bergvärmepumpar. Ekonomin undersöks genom att studera bergvärmepumpens pris och lönsamhet. De kostnader som är analyserade är framförallt själva pumpen och driftskostnader. Men även den totala kostnaden, inklusive borrhålet ned till berggrunden och installation, studeras. Kostnaden jämförs med andra uppvärmningsalternativ för att analysera hur konkurrenskraftig bergvärmepumpen är. Prestandan mäts genom att undersöka bergvärmepumpens verkningsgrad, som är ett mått på effektivitet och bestäms av den mängd el som krävs för att driva bergvärmepumpen, samt den mängd värme som den ger till byggnaden. För att

analysera vad som ligger bakom utvecklingen utförs intervjuer med värmepumpstillverkare, kompletterat med en litteraturstudie.

Resultaten visar en ökning av bergvärmepumpens verkningsgrad från i genomsnitt 2,35 till 3,7 mellan år 1991 till 2020, vilket är 2 % per år. Det betyder att för en viss mängd värme som levereras till byggnaden av värmepumpen, så krävs en allt mindre mängd el. En mindre mängd använd el ger en lägre driftkostnad och minskade utsläpp. Värmepumpens verkningsgrad är beroende av temperaturen på elementen, i energieffektiva hus används därför element eller golvvärme med låg temperatur. När effekten av en lägre temperatur inkluderas i beräkningarna blir ökningen av verkningsgraden ännu större, 7,5 % per år. Bergvärmepumpens effektivitet beror alltså både på hur den ser ut inuti och hur byggnadens element är utformade. Det som ligger bakom ökningen av effektiviteten inuti bergvärmepumpen är att bättre komponenter har tagits fram. Detta har dock, tillsammans med allt mer avancerade funktioner och ett större fokus på design, lett till en tydlig prisökning de senaste ca tio åren. Resultaten visar att priset steg med 29 % mellan 2008 och 2020.

Förutom priset på värmepumpen är kostnaden för en kund även driftskostnaden, som är beroende av elpriset och verkningsgraden. Elpriset har stadigt ökat under 2000-talet, men eftersom mängden använd el samtidigt har minskat, har driftskostnaden legat på en jämn nivå. I jämförelse med andra uppvärmningstekniker visar resultaten att även fast kostnaden på värmepumpsenheten har ökat, så är bergvärmepumpar oftast det mest lönsamma alternativet när totalkostnaden för hela bergvärmepumpens livstid beaktas. Exempelvis så ligger medelpriset för totalkostnaden under medelpriset för fjärrvärme.

Bergvärmepumparnas utveckling har drivits fram av regelverk, forskning och konkurrens. Det är ovisst hur effektiviteten kommer fortsätta utvecklas, det som är aktuellt nu är istället nya sätt att använda bergvärmepumpen på. Möjligheten att styra värmepumpen genom trådlös kommunikation gör att den kan användas på ett dynamiskt sätt tillsammans med det omgivande energisystemet. En större andel elproduktion som inte går att planera, som solceller, kan i framtiden leda till mer fluktuerande elpriser. Detta kan utnyttjas i värmepumpen genom att den körs på högre effekt när elpriset är lågt, och kanske slår av helt vid högt elpris. Det är ett exempel på flera nya användningsområden som tillverkarna och litteraturen lyfter fram. På det sättet förändras värmepumpens roll i takt med att energisystemet i stort förändras.

Att värmepumpar är lönsamma jämfört med andra alternativ har bland annat att göra med ett förhållandevis lågt elpris. Det finns även andra gynnsamma förutsättningar, specifika för Sverige, som har möjliggjort en kraftig expansion av värmepumpar. Resultaten från studien talar för att bergvärmepumpen är en utpräglat svensk produkt. Den svenska industrin har en lång tradition och är ledande på bergvärmepumpar. Dessutom finns starka nätverk mellan tillverkare, återförsäljare och installatörer. Så trots att bergvärmepumpen är en småskalig teknik som inte är direkt beroende av infrastruktur, så finns det andra strukturer och förutsättningar kring den, och detta är avgörande för att förstå hur den har utvecklats.

# Preface

This master thesis is the final examination of the Master's Programme in Sociotechnical Systems Engineering at Uppsala University. It was written in collaboration with Stockholm Environment Institute, as part of their *gridless initiative*. I would like to give special thanks to my supervisor Björn Nykvist at Stockholm Environment Institute for excellent guidance and support through the process. I would also like to thank my academic supervisor David Lingfors at Uppsala University who gave great feedback, and Olle Olsson at Stockholm Environment Institute who contributed with valuable input.

Finally, I want to thank my partner Martin Westlund for being by my side, in both senses of the phrase, through the unexpected challenges that comes with writing a thesis during a pandemic.

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*Uppsala, May 2020*

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# 1. Introduction

The way society produce and use energy is undergoing transformation. With the climate change challenge as the driving force, measures are taken to lower the greenhouse gas emissions from sectors such as electricity production, transportation and heating. A consequence of this development is an emergence of new, more environmentally friendly, energy technology.

Characteristics shared by several of the new technological innovations are scale and modularity. They are often small in scale and possible to mass produce, in comparison to many of the traditional techniques that are big in scale and dependent on large and complex infrastructures (Wilson et al., 2020). Examples of these more recent technological advancements are photovoltaics (solar cells), lithium-ion batteries and heat pumps, while nuclear power and district heating can be considered the large scale counterparts. The different characteristics of green technologies, and how scale influences their development, are investigated in several studies (Neij et al., 2017; Trancik, 2006; Wilson et al., 2020). The studies find advantages in small-scale technologies that the large scale technologies lack.

Unit size and unit cost are central factors that can be used to categorize the different technologies. Wilson et al. (2020) make a systematic analysis of development factors for a range of energy technologies. A strong correlation between unit size and unit cost is found; cost is reduced more quickly for small-scale technologies than for large-scale technologies. Wilson et al. (2020) find additional properties of small-scale low-carbon technologies that make them advantageous, such as low investment cost, variable size, simple installation and few components involved. Extensive planning is not required, and this makes the process of implementing a technology faster, enabling a more rapid deployment of small-scale technology. Large scale technology, on the other hand, may have a high technological complexity and be surrounded by process inertia and risks (Wilson et al., 2020).

The modularity of the small-scale technologies enables a flexibility in their application, they can for example be used both in the national energy system and in smaller energy systems on the local level. One potential application is in off-grid solutions or increased self-efficiency in buildings. Buildings becomes less dependent on central infrastructures such as the power grid when it is possible to generate one’s own electricity by solar panels, possibly in combination with some form of energy storage (Battaglia et al., 2017). In the most ambitious scenario, a building could be completely disconnected from all grids, becoming gridless.

In a building using gridless technology, there may for example be photovoltaics, electric vehicles, heat pumps and a smart software enabling those to interact. Out of these three, photovoltaics and electric vehicles have small shares of their respective markets in

Sweden. Solar power from photovoltaics constitutes 0.6 % of total electricity production in Sweden in 2019 (Swedenergy, 2020), and electric vehicles and plug-in hybrids compose 2 % of the Swedish car fleet in 2019 (Trafikanalys, 2020). Consequently, they have a potential to grow. Heat pumps, on the other hand, are used in half of all single-family houses in Sweden (Johansson, 2017). The heat pump is therefore an example of a small scale green energy technology that already is established on the market, and if other technologies follow a similar development path, the ones which are in an early phase could learn from more mature examples.

This thesis examines how heat pumps have developed in Sweden. An improved understanding of factors behind this development may be a tool in supporting other technologies, and in expanding the market share of heat pumps globally. On an international level, heat pumps are not as common (Swedish Energy Agency, 2015a). The most common types of heat pump in Sweden are ground source and air source heat pumps (Johansson, 2017). Sweden is one of the largest markets of ground source heat pumps (GSHP), and has a tradition of domestic production. Air source heat pump production is more global, and would require a broader international scope beyond the limitations of this thesis. Therefore, the GSHP has been chosen as the object of this case study. Sweden also has an extensive district heating system making comparisons between these two small scale and large scale technologies possible.

Two of the factors central to product deployment are price and performance. In this thesis these two factors are studied by a quantitative analysis of historical price and efficiency data of GSHPs, and a qualitative analysis of the historical and present developments using interviews and literature studies. The analysis is based on the theoretical concept of *learning*, which describes the experience that is gained in developing a product, and the related price decline and/or efficiency improvement. The *learning rate* shows how fast the product develops, often regarding price, compared to the cumulative units produced or sold. This can be depicted using an *experience curve* that has logarithmic axes with price or performance on the y-axis and cumulative units produced or sold on the x-axis. Several recent studies describe learning of electricity generating technologies (Junginger and Louwen, 2019; Samadi, 2018). A technology whose development follows the typical experience curve shape of a linear declining curve is photovoltaics (PV). The learning rate of PV is 23.5 % (VDMA, 2020), meaning that for every doubling of cumulative units produced, the price of the PV decrease with 23.5 %.

Junginger and Louwen (2019) present an experience curve of GSHPs in Switzerland and the Netherlands in 2019, and Martinus et al. (2005) for Germany and Switzerland in 2005. Kiss et al. (2012) analyze the Swedish development of GSHPs with an experience curve that covers the years 1994–2008, showing small price reductions during that time period. It is not clear if that trend has remained, and this fact motivates an updated learning analysis of GSHP in Sweden. Regarding performance, Karlsson et al. (2013)

made an analysis of the efficiency in 2013. In this thesis the analysis of the efficiency is extended to 2020 and include system aspects.

## 1.1 Aim

The aim of this study is to improve the understanding of the development of small scale green energy technology. The knowledge obtained by studying a mature and established technology could be used in implementation and deployment of new technologies. The development is investigated by a learning analysis of two central factors, economy and performance. The technology chosen as a case study is ground source heat pumps.

The research questions are:

1) How has the technology of ground source heat pumps developed with respect to performance and economy in 1982–2020?

2) What factors have caused this development?

## 1.2 Limitations and delimitations

Since learning analysis requires data of the cumulative production development, this study is limited by the available statistics. Heat pump production existed in the 70's, but reliable data from that time has proven difficult to obtain. The production of GSHPs starts to become visible in statistics in 1982. Therefore, the studied time period is from 1982 until 2020. Since the price development in 1994–2008 is analyzed in the study by Kiss et al. (2012), the focus of the qualitative price analysis is on the time period after 2008.

A delimitation made in this study concerns the studied type of customer, which affects the size of the heat pump and the heat demand of the building. GSHPs are increasingly being used in bigger buildings such as multifamily houses and commercial facilities (Johansson, 2017). However, this study is limited to GSHPs in single family buildings, since this is still the typical heat pump customer in Sweden (Swedish Energy Agency, 2019).

Another delimitation is the complexity of the technological description. Section 2.2 introduces the basics of heat pumps. The physics behind the heat pump and its components is not described in detail, since that is not necessary for the analysis. When analyzing the efficiency improvements, the exact physical conditions inside the heat pump are not studied, but rather the reasons behind the changed physics.

Finally, it should be mentioned that the focus of the analysis is the heat pump unit. Installation and drilling of borehole are only briefly studied.

## 1.3 Outline

This report contains seven chapters. The introduction is followed by a background chapter that first outlines the Swedish heat market and electricity supply system: the types of heating solutions available, environmental goals and legislation, as well as trends in the power system. The background also gives an introduction to heat pump technology, historical growth in Sweden, environmental impact and legislation concerning heat pumps. After that, there is a brief review of the development of other energy technologies, to enable a comparison in the discussion section. Chapter 3 explains the theoretical concepts of *learning* and *coefficient of performance*. Chapter 4 introduces the methodology and data used to answer the research questions. The results of the study are presented in chapter 5, by illustrating the development of efficiency and price with figures with corresponding analyses. The results are discussed in chapter 6, and the conclusions are summarized in chapter 7.

# 2. Background

This section consists of an overview of the Swedish energy system, and especially the heat sector, in section 2.1. Section 2.2 gives a brief description of the heat pump technology, and 2.3 presents examples of development of other energy technologies.

## 2.1 The Swedish energy system

There are almost five million residential units in Sweden, of which about two millions are single family buildings (SCB, 2020a). In the Swedish building stock, several different heating technologies are used. The different types are suitable for different kinds of applications. Apart from heat pumps, heating solutions on the Swedish heat market are district heating, electric resistance heating and bio fuels such as pellet and firewood. While heat pumps dominate in single family buildings, district heating covers 71 % of the total heat demand in residential and commercial buildings (Swedish Energy Agency, 2020a). District heating is most common in densely populated areas, although the other heating solutions are present in those areas as well. When looking at matters such as the available bedrock heat in relation to the heat demand density in urban areas, GSHPs are able to compete with district heating in parts of the areas (Åberg et al., 2020). The density of boreholes is however already high in some suburban areas (Johansson, 2017).

In 2010, an EU directive on energy performance in buildings was launched (2010/31/EU, 2010). The directive defines the framework of a *nearly zero-energy building,* including a low energy consumption and that the energy used to a high extent should be renewable. The directive requires that all new buildings meet this standard from 2020 onwards. Heat pumps are driven by electricity, which means that the environmental impacts of heat pumps to a large extent are dependent on the electricity mix. In the power system, about 80 % of the Swedish electricity is produced by hydro power and nuclear power, and wind power stands for about 10 % (Swedish Energy Agency, 2020a).

The amount of available electricity over time is seldom a problem and Sweden is a net exporter of electricity (Swedish Energy Agency, 2020a). In 2018, the Swedish power grid had a reliability of 99.978 % (Wallnerström et al., 2019). The more complicated factor is the power, which is described as an increasing issue (Swedish Energy Agency, 2020a). To maintain the power balance in the power grid, the electricity consumed must always equal the electricity produced. Electricity demand is expected to increase because of increasing electrification in sectors such as transportation and industry (Svenska Kraftnät, 2019a). According to the Swedish transmission system operator Svenska Kraftnät, the electricity consumption is expected to increase from 140 TWh in 2020 to 165 TWh in 2040. At the same time, an increasing share of electricity production is impossible to steer and schedule, as a consequence of more intermittent power such as solar and wind power, and closed nuclear power plants (Swedish Energy

Agency, 2020a). The production of wind power increased from 2.5 TWh in 2009 to 19.5 in 2019 (Swedenergy, 2020).

The price of electricity varies according to several parameters. It fluctuates every hour and between different geographical locations. Looking at yearly average, it also varies between years. In 2004, the price (including trade price, grid fee and energy tax) for a single family building was about SEK 1 per kWh, and in 2019 it was about SEK 1.5 per kWh (Swedish Energy Agency, 2020b). If the share of wind power continues to grow, it may lead to a lowered price of electricity since wind power has no operating expenses (Svenska Kraftnät, 2019b). According to the Swedish Energy Agency (2020a), an extensive expansion of wind power is necessary to reach the goal of 100 % renewable electricity production by 2040, set by the Swedish government.

The Swedish Energy Agency (2020a) describe some of the most important policies, on the current electricity market, that meet the challenges of a larger share of intermittent power. Among other things, policy measures are taken in favor for energy storage and *demand flexibility* (Swedish Energy Agency, 2020a). Demand flexibility means that electricity consumers get paid for adjusting their consumption depending on the instantaneous available power in the grid.

## 2.2 Heat pumps

A heat pump transfers heat from a source outside a building envelope to the heating system inside the envelope. The heat source can be the outside air, exhaust air or the ground. Ground source is either vertical boreholes that reaches and extend into the bedrock, horizontal pipes or a lake. Borehole is most common in Sweden since lake and horizontal pipes require a suitable watershed and large areas of land (Johansson, 2017). The heat pumps that are called "ground source heat pumps" can be used on vertical, horizontal and lake sources (Karlsson et al., 2013).

Figure 1 shows the schematic configuration of a house with a ground source heat pump and borehole. The picture is not made to scale. The heat pump unit is typically about 180×60×60 cm (CTC, 2019; Nibe, 2019; Thermia, n.d.) and is located inside the house. The borehole, or multiple boreholes which is sometimes the case, is much deeper than Figure 1 shows, about 100-250 m (Björk et al., 2013). The heat in the bedrock is extracted by a collector, which consists of plastic pipes filled with a brine. The brine is circulating in a closed cycle between heat pump and borehole. When the heat is transferred from the heat pump to the indoor air, different types of heat emitters are used, such as radiators, underfloor heating, towel drying racks etc. (Björk et al., 2013).

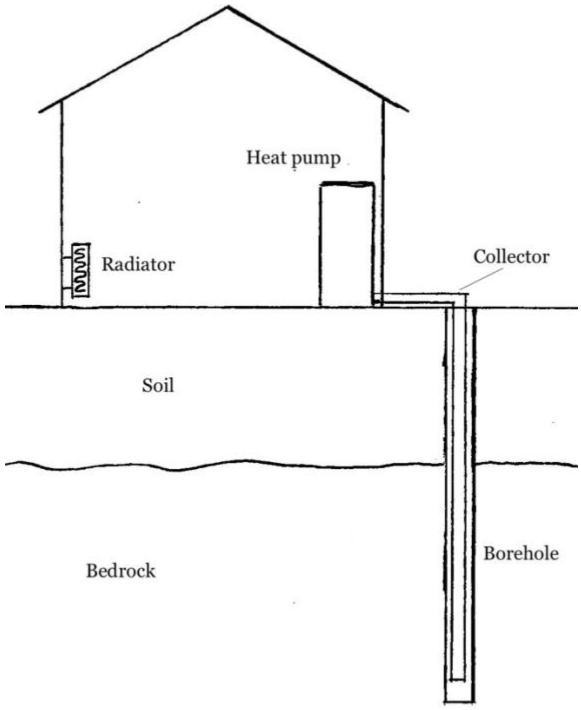


*Figure 1. Schematic drawing of a house with a ground source heat pump.*

Regardless of heat source, the working process in the heat pump is performed as a Carnot cycle (Johansson, 2017). In short, the process starts by absorption of energy from the heat source (brine in the case of GSHP) by a refrigerant. This happens through a heat exchanger. After that, the refrigerant becomes pressurized in a compressor. The temperature of the refrigerant increase during the compression, and the heat radiation transfers through a heat exchanger to the heating system of the building and to the tap water (Björk et al., 2013). The refrigerant is then expanded in an expansion valve, and the cycle starts over again.

The heat pump is an old invention but has been used to a larger extent in the last 40 years. The technology originates from inventions in the 19th century (Johansson, 2017). Early production and sales of the modern heat pump in Sweden occurred in the 1970's (Johansson, 2017). In 1982, 2530 GSHPs had been sold (Swedish Refrigeration and Heat Pump Association, n.d.). At that time, there were over 100 heat pump brands in Sweden (Johansson, 2017). In 2017, there were four big heat pump manufacturers, together with a number of smaller brands that have specialized in niche products (Johansson, 2017). Figure 2 shows the yearly sales of three types of heat pumps: ground source, air-water and exhaust air. The largest growth in numbers of GSHP occurred around year 2000. The peak in 2006 is explained by a governmental subsidy addressing single family houses, giving 30 % of the cost for converting from electric resistance heating or oil heating to a heat pump (Johansson, 2017).

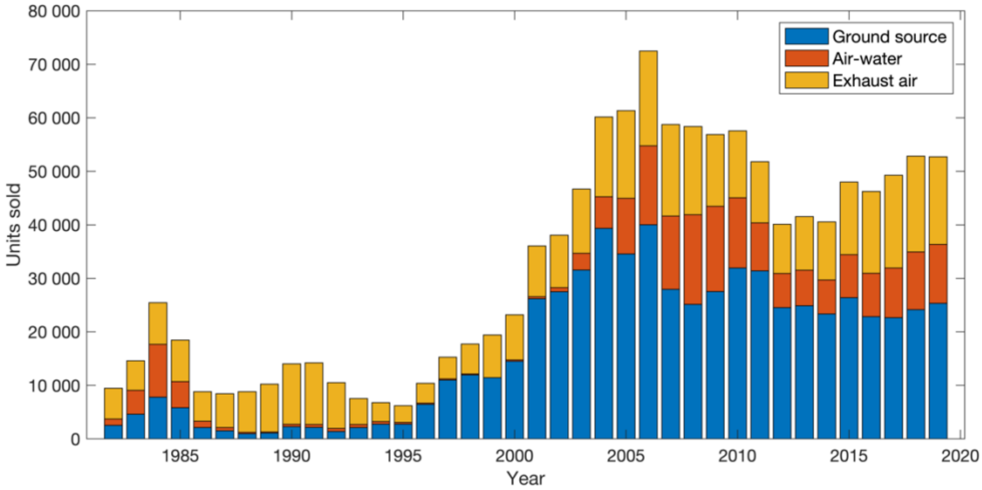


*Figure 2. Yearly sales of ground source, air-water and exhaust air heat pumps from 1982 to 2019. Data of air-to-air heat pumps are uncertain and therefore not presented (Swedish Refrigeration and Heat Pump Association, n.d.)*

In 2018, there were 1.2 million one- or two family-buildings using a heat pump in Sweden (Swedish Energy Agency, 2019). 36 % of them were GSHP and 32 % air-to-air heat pumps. Heat pumps are first and foremost a heating solution for single family buildings, although applications in multi-family buildings and non-residential premises are increasing (Karlsson et al., 2013; Swedish Energy Agency, 2019, 2015b, 2011). Large types of heat pumps can be found in some district heating grids (Karlsson et al., 2013). Sweden is at the forefront of heat pump technology, and the Swedish market of GSHPs is one of the largest in the world. Presence of GSHPs is in most other countries small (Swedish Energy Agency, 2015a). Heat pumps have a share of 7 % of the heating market in Europe (Johansson, 2017).

In the EU, heat pumps are seen as an important technology in the transition to an energy efficient society (Johansson, 2017). The main environmental impact of heat pumps emanate from the electricity used to drive the heat pump. The amount of electricity needed and the power source determine the final impact (Swedish Energy Agency, 2015a). Electricity generated by coal leads to higher emissions, compared to, for example, wind-generated electricity that has no emissions during operation. Heat pumps are covered by EU legislation such as the Ecodesign Directive (2009/125/EC), Energy Labelling Directive (2010/30/EU) and indirectly by the Energy Efficiency Directive (2012/27/EU) (Johansson, 2017), all of which were launched in 2009–2012. In the EU Renewable Energy Directive (2009/28/EC), the output heat energy from the heat pump is considered renewable if it by far exceeds the amount of primary input energy. Most of Swedish heat pumps meet this criteria (Swedish Energy Agency, 2015a). In a study of GSHPs in 2012, all models fulfilled by far the minimum requirements in the Ecodesign Directive (Karlsson et al., 2013). Among energy labels of GSHPs sold in 2020, most of the models are classified with A+++ or A++, which are the two highest grades on the scale (CTC, 2019; IVT Värmepumpar, 2020; Nibe, n.d.). Previous estimates of the efficiency improvement of GSHP have shown rates of 2 % (Karlsson et al., 2013;

Swedish Energy Agency, 2015a) and 1.5 % (Johansson, 2017) improvement of COP per year (see section 3.2 for a definition of COP).

Another environmental concern is the refrigerants, which often have a high Global Warming Potential (Björk et al., 2013). If there is a leakage, which seldom happens, the refrigerant may reach the atmosphere. In the end, the environmental gain by using a heat pump largely depends on what the alternative would have been (Johansson, 2017).

## 2.3 Development of other energy technologies

The price and efficiency development patterns vary between different renewable energy technologies. As mentioned in the introduction, the learning rate of the price of crystalline silicon PV, which is the most common type of PV, was 23.5 %, for 1976-2019 (VDMA, 2020). If the time range is narrowed to 2006–2019, the learning rate is higher, 40 % (VDMA, 2020). From 2006 onwards mass production of PV started in China, and this could partly explain the steeper price decline (VDMA, 2020). *Levelized Cost of Energy* (LCOE) is a metric describing the price of energy generating technologies in relation to the amount of energy they can produce (IRENA, 2019). The global weighted average LCOE of photovoltaics in 2018 was USD 0.085 per kWh. The learning rate of onshore wind power is almost half that of the PV, 12 % for LCOE in 1983–2014 (IRENA, 2017).

In wind power design, there is a trade-off between bigger plants with a higher efficiency, and smaller cheaper plants with lower efficiency (IRENA, 2019). Over time, however, the price has declined and the efficiency improved. The price levels are different between onshore and offshore wind. Onshore wind had a LCOE of USD 0.06 per kWh in 2018, while offshore wind had a LCOE of USD 0.13 per kWh (IRENA, 2019). The onshore solution is thus favorable from an economic perspective. The opposite is true when it comes to efficiency. The efficiency of wind power is measured by the capacity factor, which among other parameters depends on the size of the wind power plant. The capacity factor of onshore wind in 2018 was 34 % (an increase from 27 % in 2010), and 43 % for offshore wind (IRENA, 2019).

# 3. Theory

## 3.1 Learning

The concept of learning is a means to describe technological development. The origin is a theory for describing the cognitive learning that comes with repetition, for example remembering a sequence of digits (Ebbinghaus, 1885). The probability of remembering the exact sequence increase with number of repetitions, at an exponential rate called the *learning rate* (Ebbinghaus, 1885). The exponential nature means a fast learning in the beginning, while the effort it takes to learn thereafter increases. This theory was applied on the traditional industry to predict how fast workers would learn a certain task (Wright, 1936). A skilled worker can work in an efficient way and produce more units per time unit, which decreases the production cost. In this context, the learning rate show how much the cost of a product decreases for every doubling of cumulative production.

The modern interpretation of learning is broader. Learning can take place within a company or in a whole industry (Boston Consulting Group, 1970). It can also occur in different parts of technological development, not exclusively at the factory floor but in research for example (Boston Consulting Group, 1970). It may be difficult to distinguish a specific factor when many factors contributes to learning. Therefore system boundaries, that define what is included in the analysis, are important.

The system boundary can be extended to the context in which the technology is eventually installed. Neij et al. (2017) argue that, after a product is produced, learning often takes place at the local site. Deployment of new energy technology is even dependent on learning at the local scale. By looking at photovoltaics (PV), Neij et al. show that PV, which are developed and produced internationally, in the installations requires a certain knowledge among installers. This knowledge differs geographically since solar irradiation and building conditions differ. Parts of the knowledge are difficult for outside actors to access, because the experience that is gained by the local installers becomes tacit knowledge (Neij et al., 2017). Apart from the importance of knowledge flows, aspects such as interactivity and relations between local firms and customers are described as important to the customers trust and confidence in investing in the technology (Neij et al., 2017).

When additional factors are included in the learning analysis, a more accurate term is *experience*. When learning is presented in a graph showing improvement as cumulative installed/produced volume growth it is called an *experience curve*. In modelling economic improvements as an experience curve, production *costs* may be difficult to get hold of, which motivates the use of market *prices* instead (Junginger and Louwen, 2019). When doing this, economic mechanisms not present in the production cost are added. Market price include the company’s margin and strategy. According to Boston Consulting Group (1970), the strategy varies in different development stages. In the beginning of selling a new product, the strategy may be to set a low market price, lower than the production cost. When that phase is over and there is a demand for the product, the price may be risen. Competition from other companies may push down the price again, and after that a stabilized market price follows. In the final stabilized phase, the ratio of the cost and price is constant (Boston Consulting Group, 1970). A consequence of the approximation of price instead of cost in learning analysis, is that data points in early stages may vary substantially and it may be a bad reflection of the actual learning rate (Junginger and Louwen, 2019).

The experience curve can be expressed as

$$C_Q = C_1 \cdot Q^b, \tag{1}$$

where $C_Q$ is the cost at the cumulative production Q, $C_1$ is the cost of the first product and b is the experience parameter (Junginger and Louwen, 2019). The learning rate (LR) is dependent on the experience parameter as

$$LR = 1 - 2^b. \tag{2}$$

Junginger and Louwen (2019) applies the learning concept on the energy technology context. Here, upfront price of installation may be insufficient and not capture the full development. Instead price per energy unit, the *Levelized Cost of Energy* (LCOE), is more relevant. LCOE usually describes the cost of producing electricity. In the case of heat pumps, it can be used as a metric for cost of heat produced.

The concept of learning can be applied on other metrics than cost. Junginger and Louwen (2019) use it to describe heat pump efficiency development of Swiss heat pumps.

## 3.2 Coefficient of performance

The efficiency of heat pumps is measured by the coefficient of performance (COP). COP is determined by energy input and output according to:

$$COP = \frac{Q}{W}, \tag{3}$$

where Q [J] is the heat output and W [J] is the amount of electricity used by the heat pump (Björk et al., 2013). Using the theory behind the Carnot cycle, Q can be replaced by $T_H$ and W by $T_H - T_C$, giving the maximum theoretical COP:

$$COP_{max} = \frac{T_H}{T_H - T_C}, \tag{4}$$

where $T_H$ is the supply temperature on the hot side to the heat emitters and $T_C$ the collector temperature on the cold side from the heat source (Björk et al., 2013). The heat source is in a heat pump context the outside air or ground. Equation (4) shows that a narrower temperature difference gives a higher maximum COP. In the case of ground source heat pumps in Sweden, the bedrock temperature $T_C$ hovers around 2–10 °C (Björk et al., 2013). The second variable in the equation, however, can vary more. The supply temperature $T_H$ is determined by the temperature demand on the heat emitter, which varies depending on the size of the heat emitter. Smaller emitters need higher temperatures for the same amount of thermal convection as a large emitter with lower temperature (Björk et al., 2013) A typical supply temperature in radiators is 45 °C. Underfloor heating on the other hand, is larger in size and use a supply temperature of maximum 40 °C (Björk et al., 2013). If the supply temperature is lowered, the maximum COP becomes higher. In Figure 3, the theoretical maximum of varying $T_H$ and $T_C$ is displayed.

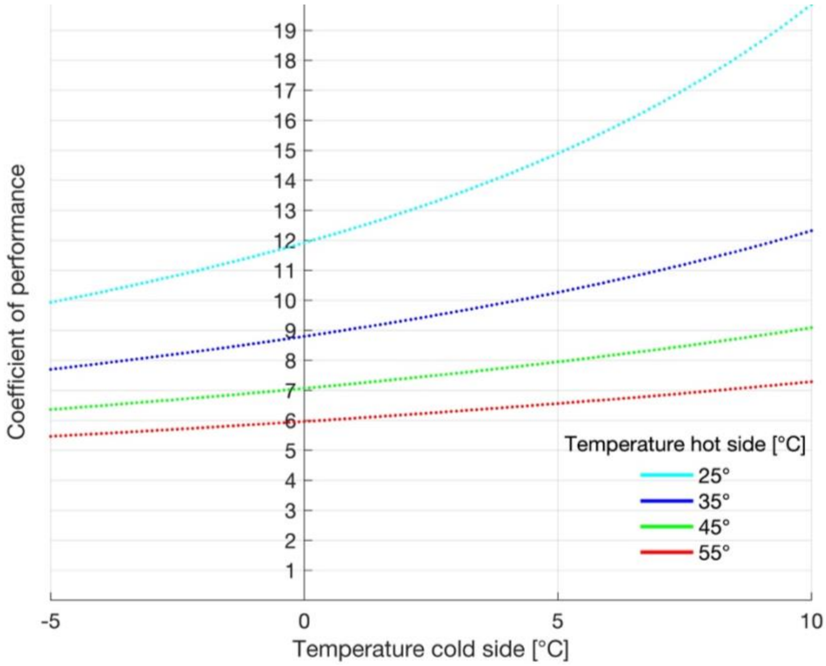


*Figure 3. Theoretical maximum of coefficient of performance.*

During heat pump testing, COP is measured at several temperature intervals. A drawback of COP is that is does not take seasonal temperature variations into account. To include this, there is the seasonal coefficient of performance, SCOP, which is the average COP over a year (Johansson, 2017).

To enable comparison between heat pumps there are testing standards, set by the European Committee for Standardization. The standards used are EN 14511 for COP and EN 14825 for SCOP. COP is measured at a few different temperature intervals, such as $T_C$ = 0 °C/$T_H$ = 45 °C and $T_C$ = 0 °C/$T_H$ = 35 °C (Swedish Standards Institute, 2018), while SCOP is measured in three climate zones: Athens (warmer), Strasbourg (average) and Helsinki (colder) (Rasmussen, 2011). In 2020, both COP and SCOP are presented in product sheets (CTC, 2019; Nibe, 2019; Thermia, n.d.).

# 4. Methods and data

The development of ground source heat pumps is quantitatively studied by a price and efficiency data collection. The learning concept is applied on both price and efficiency. To compare the profitability to district heating, price data of district heating are also gathered. These data are together used to show the historical development from different perspectives, answering the first research question. The second research question, concerning factors behind the heat pump development, is investigated through interviews with manufacturers and a literature study.

The methodology is described in sections 4.1–4.5 below. First, the system boundaries are defined in section 4.1. Section 4.2 covers a description of how the price is calculated and presented. The price and efficiency data are presented in section 4.3. Section 4.4 and 4.5 describes the methodology of the interviews and the literature study.

## 4.1 System boundaries of efficiency analysis

In this thesis, the heat pump unit is isolated as starting point of the efficiency investigation. The explored COP is measured at a fixed supply temperature of 45 °C only, to show the efficiency improvement of the heat pump unit itself. This system boundary is marked by the red dotted line in Figure 4, and will henceforth be referred to as the *heat pump system*.

As Figure 3 shows, the efficiency of the heat pump is highly dependent on the hot side supply temperature. The supply temperature can be lowered in a low temperature heating system. To investigate the impact of lower temperature heating, an efficiency analysis is made with a supply temperature decreasing with 10 °C, from 45 °C to 35 °C. This is referred to as the *extended system* and is marked by the blue square in Figure 4.

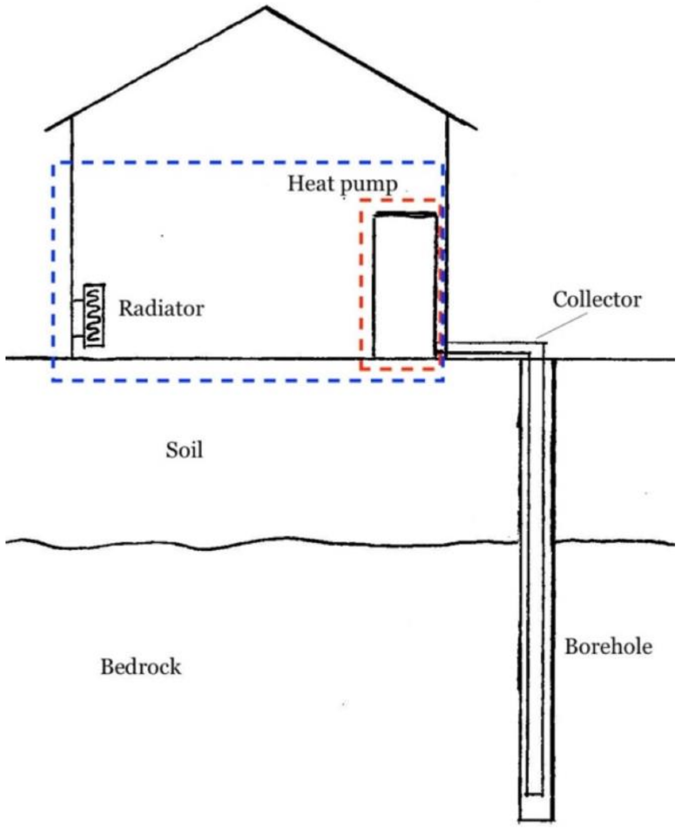


*Figure 4. Schematic drawing of a GSHP installation, with the two system boundaries marked. The red square is the heat pump system and the blue one is the extended system.*

## 4.2 Presentation of price development

The price data are presented from several perspectives, showing different aspects of the development:

- **Price distribution** – The price distribution of heat pump unit only, showing all models each year.
- **Average price** – The average price of 6–10 kW heat pump units, in SEK per kilowatt installed, is used in the learning analysis and presented with cumulative sales per year on the x-axis. In data of heat pump model prices for different years, the same heat pump model is present in several different years. For example, a model launched in 2014 may be on the market in the following years but for an adjusted price. The price for each year is thus a snapshot on available alternatives for the customer on the market that specific year. Data collected in February and March 2020 are approximated as values of 2019 in the average price calculation.
- **Sensitivity to price of electricity** – Shows the total GSHP solution price (see section 4.2.1) with varying price of electricity.

- **Total yearly price compared to district heating** – The total price of the GSHP solution, see section 4.2.1, and price of district heating.
- **Operating costs** – The operating expense is compared to the price of electric resistance heating.

### 4.2.1 Total price for a GSHP solution

To show the total price of a GSHP, the price from a lifetime approach of twenty years is calculated. This is the levelized cost of energy multiplied with the heat demand.

The price of a GSHP installation can be divided into capital expenditures (CAPEX) and operating expenses (OPEX):

- CAPEX – the turnkey purchase price, including heat pump unit, installation and drilling of borehole
- OPEX - the price for operating the heat pump, which depend on the price of electricity and the amount of electricity used

The parameters used in the calculation of CAPEX and OPEX are:

- $C_{hp}$ – Purchase price of heat pump turnkey solution [SEK]
- COP
- $C_{el}$ – Price of electricity [SEK/kWh]
- l – Lifetime [years]
- $E_{in}$ – Input energy [$kWh_{in}$], the electricity that is used to operate the heat pump
- $E_{out}$ – Output energy [$kWh_{out}$], the yearly heat demand

Equations (5) – (7) are used to calculate the total price, CAPEX + OPEX, in SEK per year.

$$E_{in} = \frac{E_{out}}{COP} \qquad [kWh_{in}] \qquad (5)$$

$$OPEX = C_{el} \cdot E_{in} \qquad [SEK/year] \qquad (6)$$

$$CAPEX = \frac{C_{hp}}{l} \qquad [SEK/year] \qquad (7)$$

## 4.3 Data

This section presents the price, efficiency, heat demand and sales data, and how these data are processed. The price is presented for heat pump unit, whole GSHP solution, electricity and district heating.

### 4.3.1 Price of the ground source heat pump

The investment cost of a GSHP turnkey installation consists mainly of three parts; heat pump unit, borehole and installation. When an installation is made for the first time there are also steps such as digging down pipes connecting the borehole to the heat pump and possibly removing an old heating solution (Björk et al., 2013). During operation, the costs are the electricity needed and maintenance of the system. Data for the heat pump unit only, as well as for the whole turnkey solution, are used in this study. Like Junginger and Louwen (2019) suggest, manufacturer price is chosen instead of production cost.

The data of heat pump unit prices are collected from several sources. In a couple of years around 2000, the Swedish Energy Agency performed tests on heat pumps regularly (e.g. Energimyndigheten, 2002). The test results, containing price information, are available, so are also test results from the Swedish test magazine Råd & Rön, published by the Swedish Consumer Agency (e.g. Lagergren, 1995), and a collection of publications on residential house heating also by the Swedish Consumer Agency (e.g. Konsumentverket, 1986). These sources cover the years from 1985 to 2006, and 2012. Prices listed in those sources are given by manufacturers. For some years, no data are found, especially between 1986 and 1994. An explanation may be the abrupt slowdown in sales from 1986 to 1995, see Figure 2 (Swedish Refrigeration and Heat Pump Association, n.d.).

After 2012, no official tests have been published. Instead, manufacturer's suggested retail price, published on their websites, is used. The website Internet Archive provides snap shots of historical websites (Internet Archive, n.d.). Data from 2007 to 2020 are collected from this web archive (e.g. (Nibe, 2008)). The manufacturer's suggested retail price should be seen as the upper limit of what a customer would pay. Reseller prices, which also are available on the Internet Archive, are lower. The manufacturer price is however chosen, to get conformity with the data from the 80's, 90's and 00's.

There is a variation in the features of GSHPs. To be able to compare models from different years, two delimitations are made. First, a limitation in the power size of the heat pump is made. Heat pumps designed for single family buildings are typically in a power range of ca 3–18 kW. The size depends on the heat demand. In a household with a heat demand of 20 000 kWh per year, which is chosen as heat demand in section 4.3.5, the maximum power demand is ca 8 kW (Swedish Consumer Agency, 1998; Swedish Refrigeration and Heat Pump Association, n.d.). To get a larger dataset, heat pumps with 8 kW larger and 8 kW smaller sizes than 8 kW are chosen. Thus, the data set consists of heat pumps with a power of up to 16 kW. GSHPs with inverter compressors have a variable power. A typical power range among the inverter models in the data is 3–12 kW. In calculations, the average power is used. When the average price is calculated, only heat pumps with a power of 6–10 kW are included.

Secondly, only heat pumps containing a water heater are included. Information on whether the heat pump contain a water heater is usually attached to data sets. In the data from 1995, this is not the case. The price list contains models between SEK 20 000 and SEK 75 000. Dimensions of the units (height, depth and width) are presented, and those vary in relation to the price. In this thesis, it is estimated that models with both small dimensions and low price do not contain a water heater, and therefore not included in the calculations of 1995.

To fully understand the market price, some other aspects of the price are briefly examined, such as manufacturer price versus reseller price and prices of Swedish based manufacturers versus international manufacturers.

Regarding the CAPEX part of the total price, the price of drilling of borehole varies considerably depending on the circumstances at the geographical site (Swedish Energy Agency, 2004). The Swedish Refrigeration and Heat Pump Association publish an annual survey on heat pump consumer price, estimated by resellers and installers (Swedish Refrigeration and Heat Pump Association, n.d.). The estimate considers a turnkey solution for a house in the respondent's vicinity with a heat demand of 20 000 kWh per year. These data are used to calculate the total price. The survey covers 2010–2019, therefore the total price is only presented for that time period.

All price data are inflation-adjusted to 2019, using consumer price index (SCB, 2020b).

### 4.3.2 Price of electricity

The price of electricity consists of trade price, electricity tax and grid fee. The data are collected from statistics published by the Swedish Energy Agency (Swedish Energy Agency, 2020b). A variable trade price from the statistics category "buildings without electric heating" is used. The yearly average of the three data sets is used in the calculations.

### 4.3.3 Price of district heating

The price calculation of district heating is limited to the variable price. The investment cost of connecting to the district heating grid is not included, since a new district heating connection is rarely an option for single family buildings.

The span of yearly district heating price is usually between SEK 8 000 and 20 000 (Svenska Kyl & Värmepumpföreningen, n.d.). Therefore, outliners are ignored, such as yearly price of SEK 17 or SEK 50 000 or above. These extreme values are not considered probable or representative, which is confirmed by the publisher, the Swedish Consumer Energy Markets Bureau, in an e-mail conversation.

The district heating price is affected by local conditions (Swedish Energy Agency, 2020a). For example, in municipalities with a lot of industry waste heat the price can be kept low. Because of the variations, the maximum and minimum price of district heating are presented together with the average.

### 4.3.4 Efficiency

The same sources that provide the price data are also used to collect data of COP and SCOP, but several years lacks data, for example in 1985 and 1986. No other sources, except for one in 1991, was found that could cover the missing years. In the data lists, which spans 1994–2020, COP is given for every heat pump model. To include an even earlier data point, a separate source from 1991 is used (Swedish Consumer Agency, 1991). This source does not specify COP for different models, but for an average.

As explained in section 3.2, COP and SCOP are measured for certain temperature intervals. In data from 1994–2006 and 2012, COP is specified for a cold side collector temperature of 0 °C and a hot side supply temperature of 45 °C (except for 2005 when the interval is 0 °C/50 °C). In collecting COP from 2007–2020, the same temperature interval is chosen to get conformity. This is used to show the efficiency development of the *heat pump system*. To present the development of heat pumps working with a low temperature heating system in the *extended system*, SCOP measured at 0 °C/35 °C in Helsinki climate zone, in 2014–2020 is used. SCOP is used because it gives a more appropriate estimate on the seasonal variations in temperature. The change in supply temperature starting in 2014 reflects the EU directive on energy efficiency buildings that that was introduced in the 2010's.

The heat pumps studied in this thesis have built-in heat water boilers. A part of the input power goes to tap water heating. This is however not included in COP, but presented as a separate efficiency metric in product sheets (CTC, 2019; Nibe, 2019; Thermia, n.d.).

Two metrics describing efficiency development are presented; the overall COP increase between the first and the last data point in percentage as a yearly development rate, and the learning rate which describes the efficiency development in relation to the cumulative production. The learning rate is calculated (equation (1) (2)) from the absolute lowest and highest values from the data. A regression analysis of the learning curve is made.

### 4.3.5 Heat demand

The yearly heat demand of a single family building varies with the size and insulation of the house. A heat demand of 20 000 kWh/year is chosen, since the turnkey price is based on that (Swedish Refrigeration and Heat Pump Association, n.d.).

### 4.3.6 Lifetime

The lifetime of a GSHP installation is different for different components. The heat pump unit has a lifetime of about twenty years (Johansson, 2017), and the collector and borehole at least 50 years (Björk et al., 2013). A total lifetime of twenty years is used in the calculations, thus the longer borehole lifetime is not taken into account.

#### 4.3.7 Number of heat pump sales

The cumulative number of GSHPs sold in 1982–2019 is provided by the Swedish Refrigeration and Heat Pump Association, see Figure 2 showing yearly sales. These data do not include the number of exports to other markets.

### 4.4 Interviews

Interviews are used as a method to analyze the second research question; factors behind the price and efficiency trends. Manufacturers are chosen as interviewees, because they develop the product and set the recommended price. There are mainly four big heat pump manufacturers in Sweden; Nibe, IVT, CTC and Thermia (Johansson, 2017). Three of those are interviewed, representing a 75 % coverage of Swedish manufacturing. The interviewees are CEOs and/or technical experts, or have other key positions in their respective companies.

The interview methodology is qualitative semi-structure, which means that open-ended questions are asked and the respondent is invited to answer freely (Dalen, 2015). The the focus of the questions were:

- The price development in the last ten years, and possible future development.
- The efficiency development since the production of GSHP began, and possible future development.
- The production process.
- Why GSHP has grown to become one of the most common heating solutions in Sweden.

The focus were the heat pump unit, and not the borehole or installation aspects. A list of the questions asked can be found in Appendix A. On a general level, all three interviewees got the same questions. But the questions were adjusted after the first and second interview, to focus on the most important parts and to not repeat superfluous questions. In addition to the broad questions, detailed questions concerning the technology and data were asked to understand those parts better. Two of the manufacturers answered some questions spontaneously without having been prompted.

The interviews were held remotely, because of practical reasons and as a precaution during the Corona pandemic. Online video or telephone meeting call was suggested to the interviewees. Two of the interviewees chose telephone and one video call. Supplementing questions by email was answered by two interviewees.

The interviews were done without giving the interviewees the result from the quantitative study on price and efficiency. The reason was to see whether the manufacturers views are in line with the actual development.

The interviewees are anonymous and referred to as Manufacturer A, B and C.

## 4.5 Literature study

The interviews are complemented with a literature study, to add and confirm information from the interviews. The literature study consists of a review of recent (2010–2020) studies where Swedish heat pump development is analyzed. Information that contribute to answer the research questions is collected. The method of the literature search is *chain search* and *systematic search* (Rienecker and Stray Jorgensen, 2014). In chain search one study leads to another by the references. One important paper studied in this thesis is a dissertation thesis covering the history of Swedish heat pumps (Johansson, 2017). That thesis refers to several other studies used in this thesis. Systematic literature search has also been used, by the online Uppsala University library search engine.

# 5. Results

This section is divided into two parts; performance and economy. The first part, section 5.1, presents the results of the performance of the heat pump system (section 5.1.1) and the extended system (section 5.1.2). The economy section, 5.2, first presents the price development of the GSHP unit, showing the quantitative results and analysis of it in section 5.2.1–5.2.3. The impact of the price of electricity on the total price of the GSHP solution is presented in section 5.2.4. That is followed by an analysis of the operating expense in comparison to electric resistance heating, as well as the profitability of the total GSHP solution in comparison to district heating in section 5.2.5. Lastly, results on future improvements are presented in section 5.2.6.

## 5.1 Performance

### 5.1.1 Efficiency development of the heat pump system

The data of GSHP efficiency spans from 1991 to 2020, but some years lack data. The result of yearly COP, measured at a collector temperature of 0 °C and a supply temperature of 45 °C, is presented in Figure 5. The average value in 1991 was 2.35 (Swedish Consumer Agency, 1991), and the average on manufacturers websites in 2020 was 3.7. That means a total efficiency improvement of 58 % in 29 years, which is 2 % per year on average. The theoretical maximum of COP measured at 0 °C/45 °C is 7.06 (equation (4)). The calculated learning rate is 2.8 %.

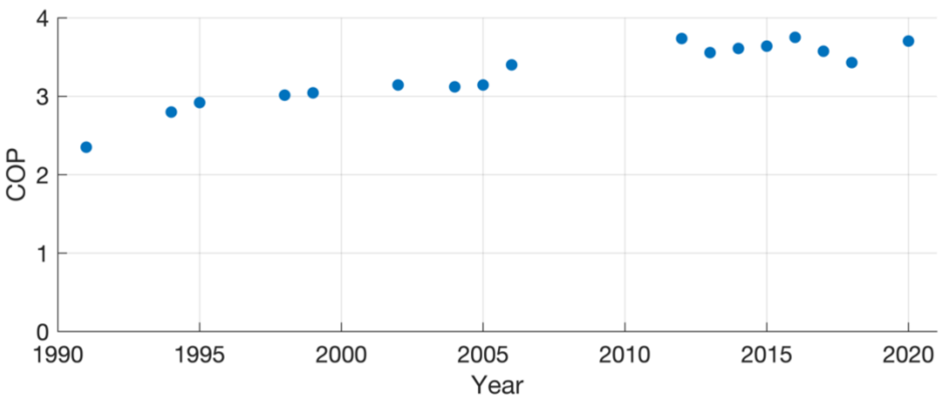


*Figure 5. Heat pump efficiency, with COP measured at 0 °C/45 °C for the years 1991-2020.*

It is evident from Figure 5 that the efficiency of the GSHP has improved over time, it is most clear in 1991 to 2012. After 2012, the curve is flattened. The number of GSHP models represented in the data points are limited in some years in 2012 to 2020, the actual value of COP during this time may deviate a little bit from the results. However, the data points are in the same range, around 3.6.

The manufacturers give a consistent explanation of the technical improvements that have contributed to increased efficiency; extensive improvements to the entire heat pump circuit and especially the compressor component. When heat pump production started in Sweden, the compressors available on the market were cooling compressors that were optimized for cooling only (Manufacturer A). When the heat pump market started to grow more seriously around year 2000, compressor producers saw a potential in heat pumps and started to produce compressors optimized for heating (Manufacturer A). This improved the compressor efficiency in the early phase (Manufacturer A). After that the compressor improvements have been new types of mechanics, finally resulting in the inverter compressor (Manufacturer B). Up until about 2010, GSHPs were limited to operate at a fixed power (Manufacturer A, B, C). When the desired indoor temperature was reached, the heat pump turned off completely. The inverter technology enables heat pumps to adjust the power depending on the heating requirements of the building (Manufacturer C). Different power levels may be optimal in different temperature operating modes (Manufacturer B).

Apart from the compressor, the components contributing to a better efficiency are circulation pumps, expansion valves and the steering of the heat pump (Manufacturer B). Together these constitute the technological explanation for the efficiency improvements *inside* the heat pump. According to the interviewed manufacturers, the largest efficiency improvement possibilities are not in the actual heat pump device but in the heat emitters, see section 5.1.2.

The interviews and literature show that the driving factors behind these technical improvements are research, regulations and competition. Kiss et al. (2012) show that long-term policy support was important in the learning process of the Swedish heat pump up until 2010. Support systems included research programs, subsidies, testing and different types of certification. Another important part of the government initiatives was networking in seminars, meetings and other platforms were actors could share knowledge (Kiss et al., 2012). The Swedish Energy Agency (2015), agrees that the successful development of Swedish heat pumps to a large extent is due to governmental investments in research programs. The academic research has continued after the study by Kiss et al. (2012). In the period 2010–2020, there have been two large research programs on heat pumps and energy efficiency, Effsys+ (Johansson, 2017) and Effsys Expand (Swedish Energy Agency, 2015a).

The manufacturers predict limited future improvements of COP. The economic benefits of improving efficiency are smaller with a higher COP (Manufacturer A, B). Converting from electric resistance heating to a heat pump with a COP of 2 lowers the operating expense by 50 %, a COP of 4 by 75 %, a COP of 5 by 80 % etc. The extra savings are small compared to the design investments that are required to raise COP slightly (for example between 4.5 and 5) (Manufacturer B). Manufacturer A believes it is more beneficial to society to install ten heat pumps with a COP of 4, rather than one with a COP of 5, which would motivate a focus shift from efficiency improvements to system concerns. Manufacturer B, too, has noticed a change in discussions on heat pump developments, from efficiency to other values that customers asks for.

However, manufacturers will aim to refine the product to raise COP slightly, for competitive reasons. It is considered advantageous to have the most efficient heat pump on the market (Manufacturer A, B). Manufacturer A predicts a plausible SCOP of 6 in the future, but stresses that this cannot be fully utilized in buildings that use the heat pump to heat tap water. Buildings are more and more energy efficient, which means that indoor air heating demand decreases, while demand for tap water is constant. It is not possible to lower the temperature of tap water, because of legionella bacteria. The consequence is that a larger share of the heat pump work goes to heat hot tap water (Manufacturer A). That kind of high supply temperature reduces the efficiency of the heat pump (see section 3.2). According to Johansson (2017), there is no reason to not expect further performance improvements. In projections of future scenarios regarding COP development, based on an increase of 2 % per year, the Swedish Energy Agency (2015b) estimate a GSHP COP of over 7 in 2048.

### 5.1.2 Efficiency development of the extended system

A trend in newly built houses and renovations is underfloor heating or other low temperature heat emitters (Manufacturer A, C). In those systems a supply temperature of around 35 °C is enough (Manufacturer C). This development is reflected in the extended system. In Figure 6, the efficiency is presented again, in the form of an experience curve with a log-log scale, with COP measured at 45 °C for 1991 to 2012 and seasonal coefficient of performance (SCOP) measured at 35 °C in 2014–2020.

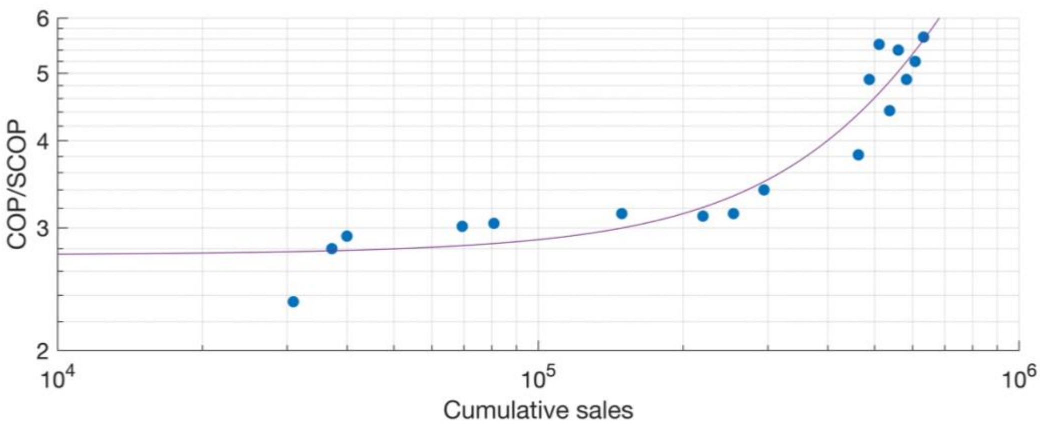


*Figure 6. Experience curve of the extended system including heat pump and low temperature heating, on a log-log scale. The line represents the quadratic regression.*

In 2014, the average efficiency reach above 5, and the highest value in the raw data is 5.86 in 2020. Average of 2020 is 5.09, compared to the theoretical maximum of 8.8 of COP measured at 0 °C/35 °C. The total efficiency improvement from 1991 to 2019 is 217 %, which is 7.5 % per year.

The calculated learning rate is 5.8 %. Junginger and Louwen (2019) get a learning rate of 5 %. Starting in 1991, when the cumulative sales up to that year were 30 900, there has been four doublings of sales, to 632 591 units in 2019. The doubling is most intense from 1998 to 2005, with two doublings in seven years (see Figure 2). The quadratic regression curve in Figure 6 has a R square value of 0.900, compared to 0.873 for linear regression. That means the quadratic regression fits the data points best. The learning rate has thus increased over time, since a constant learning rate would give a linear experience curve. The development rates and COP of the two studied systems are summarized in Table 1. Summary of development rates and efficiency for the heat pump system and the extended system. The GSHP model with maximum COP or SCOP are 3.77 and 5.86 for the respective systems, which is 53 % and 67 % of theoretical maximum.

*Table 1. Summary of development rates and efficiency for the heat pump system and the extended system*

| System boundary | Learning rate | Yearly development | Theoretical maximum COP[1] | Maximum COP/SCOP | Share of theoretical maximum |
|---|---|---|---|---|---|
| Heat pump system | 2.8 % | 2 % | 7.06 | 3.77 | 53 % |
| Extended system | 5.8 % | 7.5 % | 8.8 | 5.86 | 67 % |

[1]Calculated with a collector temperature of 0 °C and a supply temperature of 45 °C in the heat pump system and 35 °C in the extended system

## 5.2 Economy

### 5.2.1 Price development

The price distribution of all GSHP models for every year is shown in Figure 7. Each marker represents a specific model and size. The differently colored markers distinguish the size of the model, in kW. Heat pumps with inverter technology, meaning variable power, are represented by black diamond shaped markers. The data points at ca SEK 40 000 or lower may be models without water heaters that happened to be included when the data was gathered, since this is sometimes vaguely specified in 1985 and 1998.

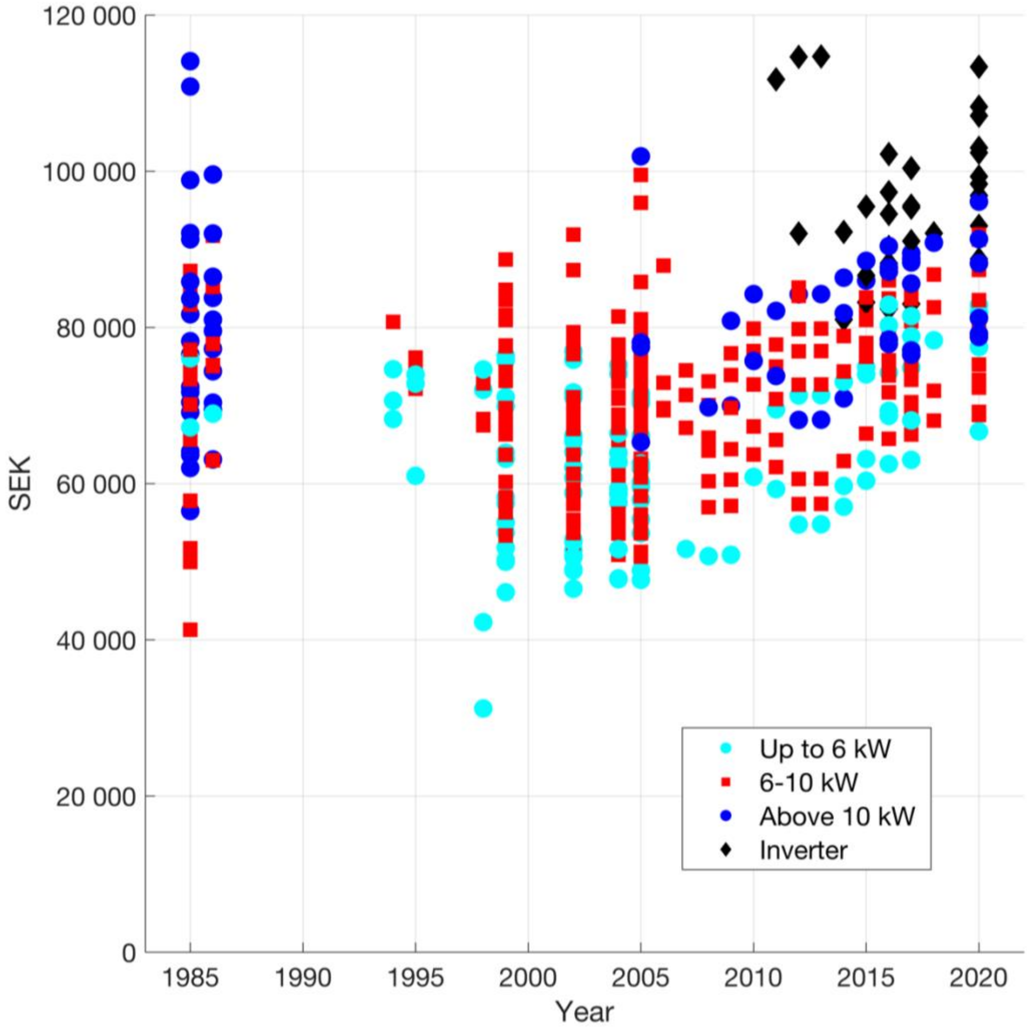


*Figure 7. Inflation-adjusted price distribution of GSHPs per year from 1985 to 2020. The price is the recommended price set by manufacturers. (CTC, 2020, 2018, 2017, 2016, 2015; Götberg, 2006; IVT, 2020; Lagergren, 1995; Nibe, 2020, 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007; Swedish Consumer Agency, 1998, 1995, 1994, 1991, 1986, 1985; Swedish Energy Agency, 2006, 2004, 2002, 1999)*

The result shows a substantial price variation between different models within the same year. The variations may depend on a number of factors. The most obvious is size in kW. A relation between heat pump price and power is indicated by the color pattern, where higher power generally means higher price. It is also evident that heat pumps with variable power in most cases have a higher price. Age of the GSHP model is not represented in the figure, because the same models appear in several years. The raw data indicate that old models may be sold at a lower price.

The average price per kW and per year is presented as an experience curve with a log-log scale in Figure 8. The first four scattered dots represents the price in the first ten year period of data. During that time the number of GSHPs increased from 20 000 in 1985 to 40 000 in 1995. The average price is more stable after 1995 and slightly declining until 2008, which is a turning point. From 2008 until 2020 the price increase with 29 %.

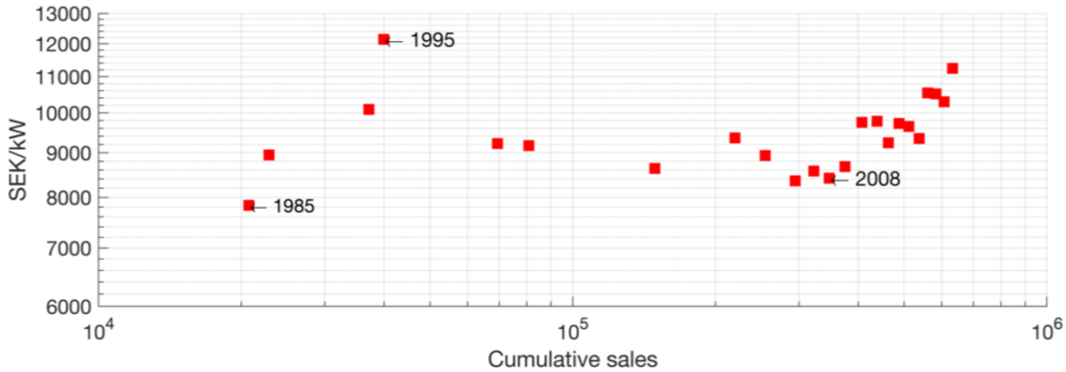


*Figure 8. Experience curve showing the average price per year of 6–10 kW heat pumps on a log-log scale. Note that the axes do not start at the origin.*

Because of the increasing price, no learning rate is calculated. In other studies, the price clearly decrease (Junginger and Louwen, 2019; Kiss et al., 2012; Martinus et al., 2005). Junginger and Louwen (2019) present a learning rate of 19 % for Swiss GSHP with borehole heat exchangers, in 1980-2018. They analyze the borehole heat exchanger separately and show that the learning of borehole heat exchangers explains the overall GSHP learning during the period 2012-2018. For the Netherlands they get a learning rate of 19 % for 2011–2017, but with a poor R square value (Junginger and Louwen, 2019).

One manufacturer underlined that the recommended price displayed on their website is meant to signal that the price will never be higher than that (Manufacturer A). The price is set high, and does not reflect what a customer would be expected to pay. When the recommended price is compared to the price on one online reseller site in 2020, the reseller price per kW is 24 % less on average (all heat pump sizes included) (Polarpumpen, n.d.).

In the study by Kiss et al. (2012), the average price curve of 6.8–8.8 kW heat pumps in Sweden 1994–2008 is slightly declining, matching the corresponding part of the curve in Figure 8. Kiss et al. (2012) say the explanation behind the almost constant price is not settled, it may be because of limited competition among the manufacturers or lack of stability in subsidies. Subsidies directed directly to heat pumps have been short-term, which has led to quick changes in demand, and that is difficult for the manufacturers to handle and may contribute to the price increase (Johansson, 2017). Kiss et al. (2012) find a steeper drop in prices in Switzerland, and speculate that it is because Switzerland imports cheap components, while Sweden produces all components domestically.

### 5.2.2 Factors affecting the price trends

The interviews with the three manufacturers show that the explanation of the price development from ca 2010–2020 lies partly in the designing and production process. All three manufacturers share the same view of the production; factories are located in Sweden, but several of the components are imported. The compressor, which is the core of the heat pump, is mass produced abroad because it would not be cost efficient to produce it in Sweden (Manufacturer A). The heat exchanger, on the other hand, is described as an innovation where Sweden is leading the market (Manufacturer A, B). In putting all the components together, Manufacturer C describes the production process as analogous to Lego, meaning a relatively simple process of joining together pieces into a product. In this step, the choice of components is decisive for the final price and performance of the heat pump. According to the manufacturers, this is a question of striking the right balance between cost and quality. The quality affects the performance and efficiency of the heat pump, and the manufacturers strive to improve those aspects as long as it is profitable. Manufacturer A says the EU is forcing them to make their products more and more efficient through the Ecodesign Directive, and this makes it difficult for them to lower the price.

A development step frequently emphasized by the manufacturers is inverter technology. The inverter improves the efficiency and performance of the heat pump, but is more expensive (Swedish Energy Agency, 2015a). The point where the average price curve increase in Figure 8 is around year 2008 and this can be partly explained by the occurrence of inverter heat pumps in the data. However, Figure 7 indicates that without the inverter models, the average price would increase anyway. Manufacturer C attributes this to the general trend of increased prices of raw material and salaries. Inverters have been used in other types of heat pumps for a longer time. In air-to-air heat pumps, inverter driven compressors existed in the 90's. At that time, the air-to-air heat pumps with inverters were 30–40 % more expensive than those without inverters (Swedish Energy Agency, 2015a). In 2012, the difference was nearly gone (Swedish Energy Agency, 2015a).

The compressor, expansion valve, refrigerant and heat exchangers constitute the core components required to make the heat pump technology work (Björk et al., 2013), but there are also circulation pumps, cabling, cover etc. (Manufacturer B). Additional components have evolved in recent years, such as more temperature sensors which have optimized the steering of the heat pump system (Manufacturer B). As of 2020, the degrees of freedom in the design is high, says manufacturer B. 20 years ago, the manufacturers had few choices to make in developing the product. Both the inverter technology, and the more advanced steering mechanisms have increased the price (Manufacturer B).

Other features that have been added in the last ten years, according to the manufacturers, are digitalization and wireless communication between heat pump and user and interactivity between the heat pump and the energy system of the house. The latter is described as a great future potential, see section 5.2.6. Design is another factor mentioned in the interviews. The aesthetics of the heat pump used to not be an issue, according to one manufacturer, but in the 2020s customers value such things as a frontage made of glass or a neat touch screen. One manufacturer compares the development of the heat pump to the car, which is a product that has increased in price partly because of new design and advanced features. In short, the manufacturers describe a more complex product as of 2020 compared to ten years earlier, and they mean that this explains the higher price.

In summary, the manufacturers stress the inverter technology, steering and additional features as the most important factors behind the increased price of the heat pump device in the ten year period leading up to 2020. It is not clear whether profit margins added by the manufacturers have changed over time.

### 5.2.3 Sweden specific conditions

Apart from the hardware and software, another expense in the production is labor costs. Multiple assembly lines are used in the production in Sweden, one for each type of heat pump (Manufacturer B). According to manufacturer B, it would not be profitable to automate further using robots, because the production volumes are not large enough and the production is often adjusted due to product development. In later years there is an expectation from customers to get heat pumps updated with the latest features, when earlier they could produce the same product for 5–7 years, says manufacturer B.

Labor cost, however, is described as low compared to total production price, which is one explanation as to why it is profitable to keep production in Sweden despite high salaries and taxation (Manufacturer B). When asked why the Swedish market is not taken over by cheap international brands, the manufacturers view is that Swedish GSHPs have been leading the market for a long time. Globally, they constitute a niche market, and multinational corporations seek large production volumes, leading them to focus on heat pump types in high demand, such as air-to-air (Manufacturer B).

Manufacturer B argues that starting up a heat pump production is not a simple process, because capacity in research, testing and certification is required. It is also necessary to have agreements with the resellers. The drilling and installing is described as a local business, the plumbing companies installing heat pumps are often small and family owned (Manufacturer B). They have agreements with heat pump manufacturers, agreements which are sprung from long relations between the plumbing company and the manufacturer. The manufacturers have built networks with installers and resellers during a long time, and worked on developing trust in heat pumps (Johansson, 2017). Manufacturer B claims it is difficult for international manufacturers to establish those kinds of relations, because customers have trust and confidence in the local plumbing firm.

According to Johansson (2017), one reason the production was kept in Sweden despite international procurements of Swedish companies in 2005, was the advantages in having production close to the development and to the customers (Johansson, 2017). On a reseller website in 2020, the average price per kW of international brands is 15 % more expensive than Swedish brands (Polarpumpen, n.d.).

Johansson (2017) shows that the rapid deployment of heat pumps in Sweden cannot be understood without looking at the networks and relations in the Swedish heat pump industry. Despite setbacks, for example in the form of periods of decreasing sales and malfunctioning heat pumps, the industry has survived. The reason is, among other factors, support from different actors such as the academia, regulations and the possibility of using heat pumps in combination with other parts of the energy system, e.g. in district heating (Johansson, 2017). Johansson argues that the introduction of heat pumps in Sweden was not seen as a threat but as a complement to the existing heating market.

### 5.2.4 The effect of the price of electricity

Along with technological development, new ways of using the heat pump are emerging. A new application of the heat pump, emphasized by the three manufacturers interviewed, is the possibility to steer the heat pump depending on the price of electricity. The volatile nature of the price of electricity makes it possible to minimize the electricity expenditures by decreasing the power of the heat pump when the price is high, by utilizing heat inertia in buildings (Manufacturer A). When the price declines, the power can be increased, the water heater filled with hot water and the indoor temperature increased a few degrees (Manufacturer A, B, C). According to one manufacturer it is possible to save about SEK 1000 per year by applying this technique.

Figure 9 shows the effect of the electricity price on the total yearly price. CAPEX is the total turnkey price for a GSHP installation divided by a twenty years lifetime, and OPEX is the yearly operating expense that depends on the variable price of electricity and COP. COP is kept constant to show only the effects of the electricity price. In 2019, the share of OPEX was 43 % of the total price. If the electricity price is varied with ± 30 %, the yearly price varies with almost SEK ± 2000.

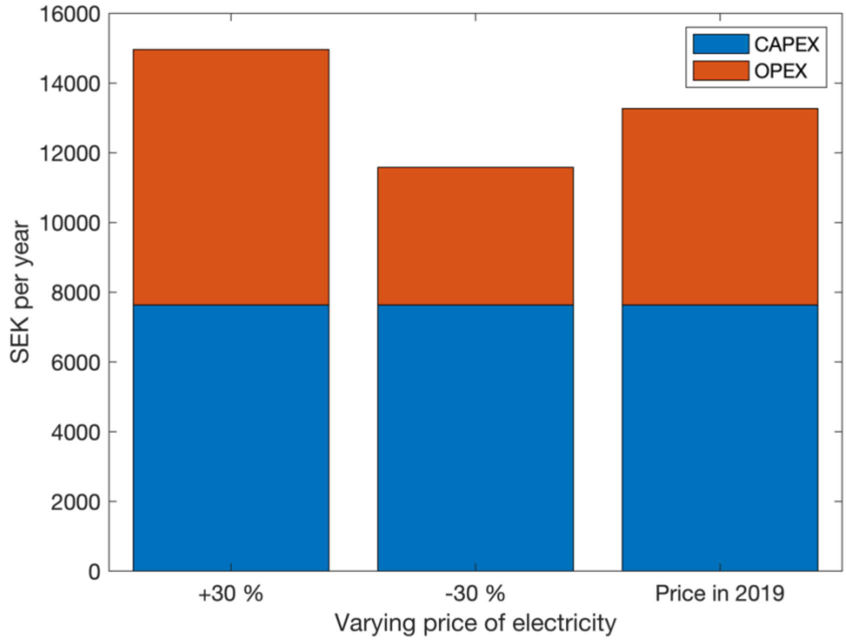


*Figure 9. Total price for three different electricity prices. CAPEX is the yearly cost if the lifetime of the GSHP installation is twenty years. (Swedish Energy Agency, 2020b; Swedish Refrigeration and Heat Pump Association, n.d.).*

### 5.2.5 Profitability

Manufacturer B says profitability is one of the most important reasons behind the growth of GSHP installations in general, despite a high investment cost. The opportunity cost, which is the cost of an alternative heating technology, is the factor that is decisive of whether the investment is profitable or not.

The opportunity cost was for a long time the price of oil. More relevant as of 2020 is to compare the price of electricity to the price of biofuels, since oil has been phased out (Johansson, 2017). However, important in the early years of heat pump development in Sweden, was the ratio between price of electricity and price of oil (Manufacturer A, B). As long as oil is cheaper than electricity, there is little reason to change from an oil boiler to electric-driven heating. But as soon as the price of electricity is lower, there is incentive to invest in electric resistance heating or a heat pump. When both the price of electricity and oil is high, the heat pump is more cost-effective than both oil boilers and electric resistance heating, since heat pumps use less electricity for the same amount of heat output (Björk et al., 2013). The fact that the price of electricity always has been relatively low in Sweden, combined with high taxation on fossil fuels, has laid the foundation for the Swedish heat pump boom (Manufacturer B). For a long time, the usual heat pump installation replaced an oil fired boiler (Manufacturer A). Price was not the only reason to this. After the oil crisis in the 70's, there was a desire to reduce dependency on oil (Johansson, 2017), as well as increased awareness of environmental issues (Manufacturer A, C).

A heating technology which increasingly is being contested by GSHPs in urban areas is district heating (Åberg et al., 2020; Johansson, 2017). When it comes to the profitability of these two alternatives, a calculation made by The Swedish Energy Markets Inspectorate in 2012 of initial investment of different heating alternatives showed that heat pumps were cheaper than the price of district heating in many municipalities (Abrahamsson et al., 2012). Compared to pellet boilers and natural gas the GSHP was cheaper as well. Figure 10 shows the comparative price development from 2012 to 2019.

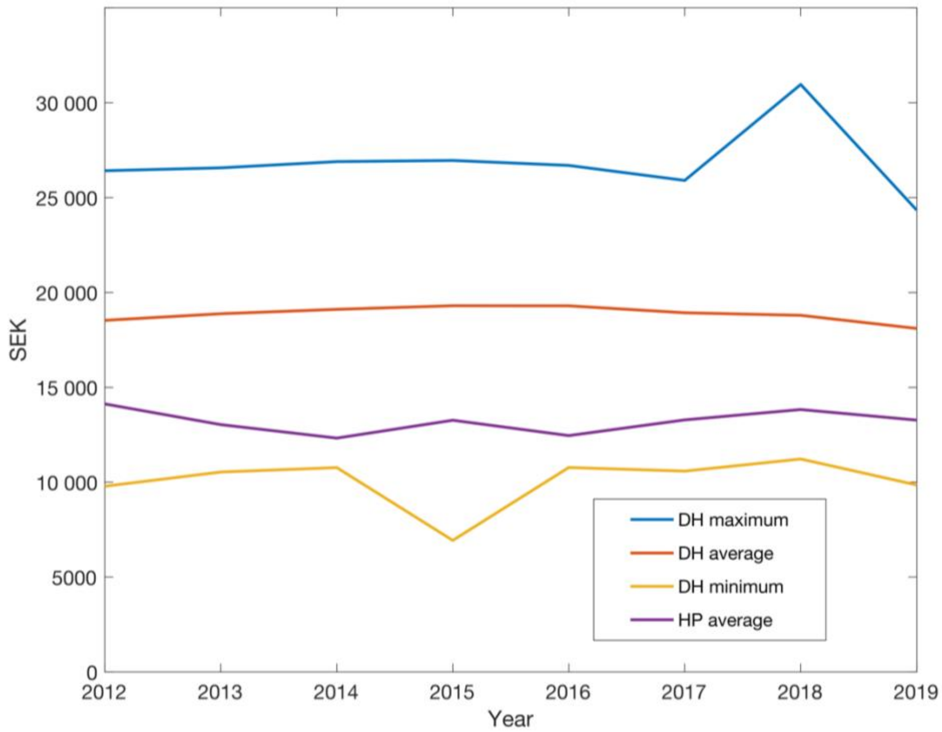


*Figure 10. Yearly price of GSHP installation for a lifetime of twenty years, compared to yearly price (maximum, average and minimum) of district heating. Both calculated for a heat demand of 20 000 kWh per year. (Johannesson, 2020; The Swedish Energy Markets Inspectorate, 2019)*

The price presented in the graph consists of a complete GSHP solution including installation, drilling and operating expense, and the operating price of district heating, for 2012–2019. The variations in price of district heating are high. The span between the minimum price and the maximum price is ca SEK 15 000. The average is around SEK 18 000–19 000, which is about SEK 5 000 more than the average heat pump price.

An economic aspect not included in the price in Figure 10, is the tax reduction ROT, which gives deductions for labor costs of renovation and construction work. The reduction covered 50 % of the labor cost of the installation from 2009 to 2016, after 2016 reduced to 30 % (Johansson, 2017). ROT has made the heat pump more affordable and increased its popularity as a result, manufacturer B says.

The price of the turnkey solution, estimated by installer firms and resellers, has remained at an almost constant level in 2012–2019, after inflation-adjustments. During the same time, the price of electricity has increased and the GSHP efficiency has slightly increased. The outcome is an operating expense that has remained at a stable level. This is compared to the operating expense of electric resistance heating (which is the same as the price of electricity) in Figure 11, where operating expenses are shown going back to 2004.

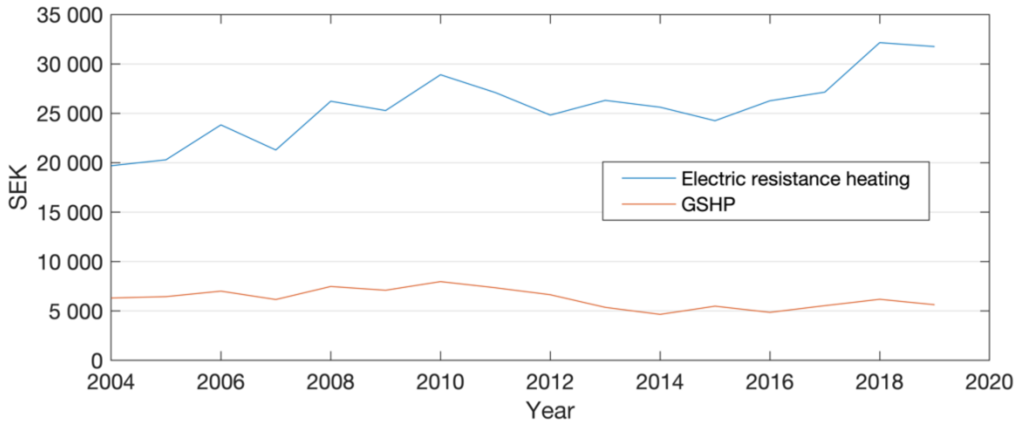


*Figure 11. Yearly operating expense of heat pumps and electric resistance heating for a heat demand of 20 000 kWh per year.*

Figure 11 clearly shows the effect of the improved efficiency of the GSHP on the operating expense. While the electricity price has steadily increased, the GSHP operating expense has remained at the same level since the amount of electricity needed to drive the heat pump has decreased drastically.

The profitability of replacing a broken GSHP is higher than for the initial investment, since the lifetime is longer for the borehole than for the heat pump. Heat pumps sold in the beginning of the 00's are reaching the end of their lifespan of 20 years around 2020. This opens up an exchange market. Old heat pumps can be replaced with new ones using the same borehole and collector (Manufacturer A). Manufacturer A estimates that half of the sales in 2020 are heat pump exchanges.

Another finding regarding the profitability of investing in GSHPs, is that the interviews and literature show that the geographical and cultural circumstances may affect the possibility to implement GSHPs as an alternative. Preconditions that made GSHP a suitable solution for Sweden in the first place, a part from the low electricity price, are knowledge in drilling and geological conditions (Björk et al., 2013), and the profitability of GSHP is dependent on the geological conditions (Swedish Energy Agency, 2015a). In some countries this solution cannot even be considered because the bedrock is not approachable (Manufacturer C). There are places in Sweden where the required borehole depth may be too deep to motivate GSHP cost wise, in Skåne for example, but otherwise, the Swedish bedrock conditions are good (Manufacturer B).

Another precondition that may have been favorable for GSHP was the knowledge of drilling water wells, a knowledge that could easily be converted to borehole drilling (Björk et al., 2013). Dimensioning the borehole contains many variables, like expected depth of bedrock. According to Björk et al. (2013), geological maps as well as experience lays ground for the estimated depth.

### 5.2.6 Future improvements

All three manufacturers talk about possible future advantages and applications of heat pumps. They all share the similar ideas of extending the role of the heat pump in the energy system. For example, the possibility of steering the heat pump depending on the price of electricity can be developed further. Manufacturer B says storage tanks could be used as heat storage to utilize the variations in the price of electricity even more. However, it is difficult to motivate the benefits to a customer, since the economic gain is small (Manufacturer B). Manufacturer A takes it a step further, suggesting heat pumps could function as a power reserve. This would be managed by a third party operator able to steer thousands of heat pumps at the same time. The customers would have a deal with the operator, who would get paid by the district system operator for the provided power flexibility. Manufacturer A predicts this will happen in 5–6 years. According to Johansson (2017), one of the historical advantages with heat pumps has been their ability to complement the rest of the energy system, and this seems to continue to be their role. The new dynamics in the energy system, caused by renewable energy production, means a new application of the heat pump, in using and storing excess electricity (Johansson, 2017).

The higher efficiency of the extended system compared to the heat pump system, shows the impact of the context in which the heat pump work. The interviews confirms this, and suggest that the context may be changing. The manufacturers predict extended use of interactivity between the energy technologies in a building, where solar cells, electric vehicles and heat pumps would work together to optimize the energy efficiency of the house. Excess electricity produced by solar cells could recharge the electric vehicle battery and be used in the heat pump to charge the building with heat (Manufacturer A). Manufacturer A describes this development as a paradigm shift, from a large scale energy system to one containing decentralized and small systems. This small system could also interact with the big system, the power grid, by adjusting to the power available in the grid (Manufacturer A). To make this possible, it is important that manufacturers create a market standard for communication technology in heat pumps (Manufacturer B).

Another potential new application for heat pumps is to integrate them in district heating grids (Manufacturer A). This can be done in different ways. One way is completely new grids utilizing low temperature excess heat from, e.g., data centers, energy that cannot be used in the ordinary district heating grid because it is not hot enough. The heat pump would be the connection between the grid and each building. With a water temperature of 20 °C in the grid and a supply temperature of 35 °C, the coefficient of performance would be 20.5. Furthermore, manufacturer A suggest that district heating grids that are sparse and therefore have a lot of losses could convert to low temperatures using heat pumps. Another idea is to create a low temperature grid with a central field of boreholes as an energy source, instead of one borehole per heat pump and house.

Apart from innovations with new applications and integration of heat pumps in the wider energy system, new business models are possibly emerging. Manufacturer C believes leasing of heat pumps may be a future service. In that scenario, the customer would not necessarily buy a heat pump, but a heating service. A report on heat market product to service shift, shows it is possible to improve service among heat pump actors (Hansson et al., 2019). A new business model would be to provide a comfortable indoor climate (Hansson et al., 2019). The heat supplier would own the heat pump, and have responsibility for maintenance, repairs and replacement. In a shift from product to service, digitalization would be central, and the report points out possibilities in improving the present applications and other digital tools (Hansson et al., 2019).

# 6. Discussion

The aim of this thesis is to increase the knowledge of the development of small scale green energy technology. The research questions are “How has the technology of ground source heat pumps developed with respect to performance and economy in 1982–2020?” and “What factors have caused this development?”. Below follows a discussion of the results of the research questions, divided in performance, section 6.1, and efficiency, section 6.2. A summary of the causes of this development are discussed in section 6.3. The impact of the local circumstances found in the results is discussed in section 6.4. A critical discussion on the methods and data is presented in section 6.5, and a summary of suggestions on future studies in section 6.6.

## 6.1 Performance development

The efficiency of the heat pump system, looking at the yearly development rate, has increased with about 2 % during 1991–2020. This is in line with previous estimates of 1.5–2 %. As expected from Figure 3, showing the theoretical maximum COP for different temperature intervals, a lower supply temperature than that of the heat pump system means a higher efficiency. When system aspects of lower temperature heat emitters are included, in the extended system, the resulting improvement is even higher than for the heat pump system, 7.5 %. This yearly development rate shows that the efficiency increases with time. The learning rate, on the other hand, shows that the efficiency increases because of learning that comes with an increased number of units produced. The learning rates are 2.8 % and 5.8 % for the two systems, respectively. Junginger and Louwen (2019) got a learning rate of 5 % between 1993 and 2017, but it is not clear how this was calculated, as there may be methodological differences from this study. However, the results are in the same range.

The efficiency development is driven by competition, research and regulations. Learning takes place in different environments. Apart from the development done by the manufacturers, learning occurs in the interaction between them and policy and the academia. In the heating system of the building, the learning has occurred in the construction process where low temperature heating has become more common. According to the manufacturers, this is the field of potential further efficiency development, going forward. They claim that the coefficient of performance will not continue to increase in any substantial way, only slightly. As Johansson (2017) shows, this could though be disputed, the efficiency is in fact not close to the theoretical maximum. Further interviews with, e.g., heat pump researchers could nuance this, possibly along with an investigation into how close to the theoretical maximum COP is likely to come.

### 6.1.1 The effects of the system boundaries

Regarding the system boundaries used in this thesis, the extended system show only one of many possible alternatives of temperature intervals. For example, a larger temperature interval would make a large difference on the resulting efficiency. However, this would follow the same pattern as the theory, in the extended system the learning would be even greater with a supply temperature of 35 °C and 55 °C, instead of 35 °C and 45 °C. Lack of available data limits the opportunity to test other temperature configurations. The two temperatures studied are the ones available generally for Swedish GSHP. Since the results to a high extent follow the expected pattern from the theory, a third or fourth temperature interval would probably only confirm the results in this thesis; that the efficiency in general has been improved and that a lowered supply temperature gives an even higher improvement.

The system boundaries could be further alternated. An alternative method to find the learning rate is to study the components in the heat pump as independent parts. A learning rate for each part could be derived and then added together. By only looking at the core components like the compressor, that would describe the learning of the core system in the heat pump and neglect aspects such as design. The boundary could also be extended to the whole house and include insulation. A learning analysis of the turnkey solution could also include installation and drilling. The result indicates that those aspects are crucial, such as local knowledge in drilling and knowledge in the local geological structures.

### 6.1.2 Future roles of the ground source heat pump

The efficiency development has been of large importance to the profitability and environmental impact of the GSHP. In a future energy system with an increased share of intermittent power, which may lead to more volatile and sometimes lower price of electricity, the high efficiency and ability to steer the heat pump based on electricity prices would be an even greater advantage. However, there may be a shift in focus from efficiency to a broader reconsideration of the role of the heat pump. In the future, heat pumps could increasingly work as a small component of a bigger system, perhaps as energy storage, in the national energy system or as part of a small gridless system. The development of the GSHP is strongly connected to present trends in the energy system; transition to renewable energy, increased energy efficiency, electrification, demand flexibility and focus on power instead of energy. Therefore, the GSHP seems to be relevant in the future energy technology landscape. The ground source heat pump's hitherto independent and passive role in the energy system could shift to a more active role.

## 6.2 Economic development

### 6.2.1 Price development in three phases

The result of the GSHP price development can be divided into three phases. The first phase is between 1985 and 1995, when there are four data points which are very scattered (Figure 8). The limited data points restrict the possibility to draw conclusions on the development during this phase. The early price variations could be a sign of the market mechanisms described by Boston Consulting Group (1970), where lowering market prices is a strategy to establish a product and high market price may be due to increased demand. However, the few data points and the fact that the data in 1994 and 1995 contains few models make it difficult to draw any conclusions.

The second phase, between 1998 and 2008, align with the study by Kiss et al. (2012). The same sources are used, but the chosen heat pump sizes differ. While Kiss et al. use heat pumps of 6.6–8.6 kW only, this study extends the interval to 6–10 kW. Other methodological differences may also contribute to small differences in the presented curves. Regardless, the curve presented in this study is similar to the one in Kiss et al. (2012) for this time period. The price decline slightly during this phase.

The third and final phase starts in 2008 and lasts until 2020. In this time period, the average price increase with 29 %. This is contrary to the expectation of a price decline in learning theory, and opposite to results found in studies in other countries. Other studies may use different methodology and delimitations, but it is not clear how much that would explain the large differences. Experience curves are often used to predict future price falls. The price increase eliminates the relevance of doing predictions in this case.

Kiss et al. (2012) speculate that a reason that the prices in Sweden show only slight price declines compared to Switzerland is because Sweden produces all components domestically. The interviews show that this is not the case in 2020, many of the components are imported to Sweden. Using the reasoning of Kiss et al. this would lower the price. But even without the more expensive inverter heat pumps, the price has increased in the twelve year period from 2008 so other factors influence too.

The shift from entirely new customers around year 2000 to an exchange market in 2020 makes it relevant to study both the heat pump device itself only, and the complete solution including installation and borehole. Unlike the price increase of the heat pump unit, the price of the total GSHP solution has been relatively stable during 2012–2019. However, that is based on estimates and may be inexact.

In Figure 7, the price distribution appears to be wider at the start of the time period and more convergent data points in the later years. This could possibly be explained by the number of active manufacturers. From 1985 to 2006, the data comes from publications by Swedish authorities and consists of between 4 manufacturers some years and up to

24 manufacturers some years. From 2007 to 2020, data are collected from the manufacturers websites, and only three of them lists price on their website. This reflects the development towards fewer but larger manufacturers, compared to the diversity in small heat pump manufacturers 30–40 years ago.

### 6.2.2 The relation between price and efficiency

The interviewed manufacturers present several reasons to the price increase, reasons that mainly concerns more expensive heat pump components. What should be kept in mind is that factors making the heat pump more efficient reduce the operating expense, as less electricity is needed to drive the heat pump. Efficiency is therefore crucial when considering long term investment. This is clear when the operating expense is analyzed. The improved efficiency has to a high degree kept the operating expense at a constant level while the price of electricity has increased. The observation from one manufacturer, that EU directives concerning efficiency prevent them from lowering the price, actualizes the question if a low price or a high efficiency is optimal from the system perspective. If the goal is a rapid deployment to replace oil and electric resistance heating, it may be more efficient on the system level to keep a lower price that makes the heat pump, which still would be relatively energy efficient, profitable. In a future with an abundance of completely renewable electricity, energy efficiency becomes less important from an environmental perspective, and this would motivate means to lower the price instead of making the GSHP even more energy efficient.

The assumption that efficiency improvements lead to price increase can however be contested. The picture that the manufacturers draw is that, in the trade-off between price and efficiency, efficiency has been favored at the expense of a higher price. Wind power show that it is possible to reduce the price over time, parallel to an efficiency improvement.

### 6.2.3 The time perspective of learning processes

The inconsistent price development of the GSHP rise the question of how far into a product’s lifetime the learning mechanisms affect its price, and whether it is the same product after many changes and additions. It could be argued that some of the learning processes starts over when new components are added, making it a new product again. That could explain the price increase. As the development of the air-to-air heat pump shows, the price increase due to the inverter may diminish eventually. It is not easy to know how far the GSHP has come in the learning process of product development. There is a limit of possible future doublings of GSHP, since heat pumps (of different types) are already used in half of the two million single family buildings in Sweden. However, the trend of applying GSHPs in multifamily houses and other types of buildings creates a larger pool of potential GSHP customers. There are over 600 000 GSHP produced in 2019, but naturally not all of them are still in use. When GSHP have reached all potential customers in Sweden, the doublings are dependent on the exchange market and lifetime of the installation.

A direct consequence of the learning theory is that price reductions requires more and more units produced for each doubling, and the number of doublings on the Swedish market are limited as long as the time perspective is in the near future. The reductions will not converge to zero, but eventually flatten. The GSHP may be closer to the flat part than for example PV, which has a learning rate of 23.5 %. However, it is difficult to make such a comparison since the learning rate for PV is on a global perspective while this study is delimited to Sweden. The development and production of GSHP is to a larger extent a local activity than for PV.

### 6.2.4 Effects on further deployment possibilities

As described in the introduction, the main purpose of using low emission technology is to reduce the environmental hazards of fossil fuel consumption. In climate change mitigation, deployment of green technology is crucial. As the efficiency of the GSHP increases, the environmental impact decreases (although depending on the electricity mix). There is thus an energy efficiency gain in exchanging twenty year old GSHPs to new ones, since the difference in efficiency is profound. Compared to alternative heating such as electric resistance heating and oil heating, the environmental gain may be even higher. So what is the effect of the price increase on the GSHP market's opportunity to expand further?

Comparisons to opportunity costs of district heating and electric resistance heating, show that the GSHP still has competitive advantages. Figure 10 confirm the result, of a lower price for GSHP than for district heating, by The Swedish Energy Markets Inspectorate. The total yearly price of a GSHP installation is around SEK 14 000–15 000. In comparison, the yearly average price of district heating is approximately SEK 18 000, and electric resistance heating is even more expensive, at SEK 25 000–30 000. The prices for the alternative heating solutions only include the operating expense, if the capital expenses would be included the difference would be even larger. The price is calculated for a twenty year lifetime of the GSHP installation. It would be even more profitable if the borehole lifetime of over 50 years was taken into account. Even with a significantly higher price of electricity, GSHP would in many cases have a lower price than district heating. To summarize, even if the investment cost of GSHPs is high, it is often profitable on a twenty years perspective.

The variables that impact the profitability hints at which factors are decisive in a successful deployment to other countries. The result shows that the price of electricity has a profound effect on the total GSHP price. Together with the electricity generation mix, the price of electricity therefore decides whether GSHP is a suitable solution for a certain country, economically and environmentally.

### 6.2.5 Continuing sales

Even though the results of a price increase contradict the theory on learning, the GSHP demand shows no signs of declination. The theory expects a decrease in price, but the

GSHP price has increased by 29 %. At the same time, from Figure 2, showing yearly sales numbers, it seems like this has not slowed down the sales. The 50 year lifetime of the borehole provides an incentive to retain GSHP as heating solution if a borehole already is in place. Because of this long borehole lifetime, the GSHP demand seem to be secured for the coming ca 30–50 years.

## 6.3 Important causes

The most important factors that have caused the performance development are regulations, research and competition between manufacturers. Regulation requirements force the manufacturers to meet certain standards. Research programs contributes to learning in development and deployment. Competition between manufacturers gives incentive to strive for the highest COP on the market.

When it comes to the price development of the GSHP unit, this is less discussed in literature and by the interviewees. The only certain factor is the introduction of more expensive components giving a higher price. To the total price, one important factor is the increased price of electricity.

It is difficult to determine whether some causes are more important, and there may be other causes, such as manufacturer profit margins, that is not revealed by the results.

The aim of this study is partly to gain knowledge that can be used in developing other technologies. It is hard to determine which of the factors described above that could be relevant for other technologies, so it is difficult to draw conclusions in this regard. However, design is a possible factor that could lead to a price increase in many technologies. It may, for example, happen to PV, which are very visible on buildings. Adjustments that make the outward appearance of PV more integrated into the roof, but also more expensive, are not unthinkable. However, this is only speculation.

## 6.4 Learning on the local scale

Just as Neij et al. (2017) shows for PV deployment, the result in this study show that the local context is part of the explanation of the GSHP learning processes, not only in the deployment, but also in production and development. The manufacturers argue that the GSHP is a quintessentially Swedish product and that it is difficult for international brands to establish on the Swedish market. There are practical and cultural aspects that are specific to Sweden, such as good bedrock conditions and a tradition of strong relations between manufacturers and small local plumbing companies and resellers. This imply that the networks and relations between manufacturers, resellers, installers and customers are strong and difficult to penetrate. Still, international brands are sold on Swedish reseller websites. The result show that the price of international brands is higher for year 2020. This is investigated for one year only, but it indicates that prices of international brands seems at least to not be lower than for Swedish ones.

GSHP manufacturing is to a high degree still a niche market. Deviations from the expected development could reflect the limits in measuring a small market with the same metrics as with large global markets. At the same time, other types of heat pumps such, as air-to-air, are bigger from a global perspective. Some components, shared by all types of heat pumps, are traded on the international market. In an extended study, the learning between Swedish and international industry, and between different heat pump types, could be investigated.

The local aspect also shows that the modularity of the GSHP could be disputed. In spite of the fact that heat pumps are small-scale and modular, in the sense that each individual building has its own heat pump and borehole, they exist in a context with established structures that influence developments. Given a future of less involved customers, if the business model of GSHP goes towards a leasing model, these structures could grow even stronger.

## 6.5 Limitations of methods and data

The methods used in this study consist of a quantitative and a qualitative part. The quantitative part is a collection of price and efficiency data. There are several aspects of the data that could be chosen differently. Some of them would definitely impact the result, other aspects are more uncertain. One limitation, that definitely impacts the result, is the focus on Sweden only. The analysis is based on a Swedish perspective and neglects the export to other markets. If the export was included, the number of doublings so far, and possible doublings in the future, would increase. That would make the calculated learning rates lower.

Another aspect that probably would affect the learning rates is the time delimitation. When studying the development from a learning perspective, the ideal situation would be to have access to data of price and efficiency from the earliest examples of heat pump technology. In the beginning, the doublings are fast and development intense. In the case of heat pumps, that would be inventions in the 19's century. In this thesis, the modern Swedish GSHP is studied, starting in 1985 when the first reliable data were found. It is possible that some important development steps were taken before the starting point of this investigation.

The learning theory as a theoretical framework has limitations. The equations calculating the learning rate (equation (1) and (2)) are only dependent on minimum and maximum values, and do not reflect the process in between. This makes the result sensitive to the accuracy of maximum and minimum values.

The scope of the data compilation also affects the results. If five GSHP models for each year would be considered reliable enough, the data sets are in some years more than sufficient, as seen in the scatter graph in Figure 7. In the same graph it is evident that some years have less coverage. A larger coverage would strengthen the results, especially if data from all years would be represented. The largest data gap in time is between 1986 and 1994 (Figure 7), this is however repressed when it is presented with cumulative sales on the x-axis in Figure 8.

Regarding the presentation of the data found, there are alternatives in how this can be made. The methodology chosen is to present price as yearly snapshots of the market. The method used to present the efficiency, i.e., to present each model only one time, could be an alternative approach for the price as well. In that case, the price increase could be even steeper because the yearly average would not include old models sold at a lower price.

The qualitative methods are interviews and literature study. The interviews are limited to three manufacturers. The interviewees have different roles at their respective companies, and this could affect their view on the questions asked. However, the exact roles of manufacturer A, B and C are not revealed in order to maintain their anonymity. Interviews with other stakeholders, such as installers, resellers, or heat pump researchers, could give a broader understanding of the investigated questions. Since manufacturers are the actors who are closest to the production development, they should have the greatest knowledge of the factors behind the price development. At the same time, it may be in their interest to not reveal everything.

## 6.6 Suggestions for future studies

As shown in the discussion above, there are several potential areas for further studies using an extended or narrowed approach in time, geography and technology.

Regarding the time aspect, it is possible to imagine both a shorter time period, taking additional features into account as the product develops into a "new" product when large changes are made, and a longer period that shows learning from the very first heat pump innovation in the 19th century. As the learning rate of PV shows, the time frame is definitely decisive to the result, as the development may take different paths in different stages of development.

This study is geographically isolated to Sweden. Since heat pumps are found to be closely related to Swedish circumstances, the results confirm that this is a valid delimitation. But, when learning is studied, an international approach is common since many products are produced and deployed on the global market. A more local perspective is also possible, as the results show that learning can take place on the local scale.

This study shows two of many possible technological delimitations. In a deconstructing analysis, the different components of the heat pump could be investigated separately. Conversely, it would be valuable to extend the system boundary to the heat pump, heat emitting system and borehole.

Another example of a future study could be whether there is a potential to make the Swedish production larger in scale, with a resulting price decline, or if it is likely to remain a niche market. An increased production would require a larger base of customers. This has to do with the potential of using GSHPs in other countries. If there is a possibility to further deploy GSHP on other markets, the export might grow.

Another interesting aspect that would deepen the understanding of the price development is how the supply and demand has shifted over time. The price increase from 2008 to 2020 could potentially be explained by a high demand during that time. However, the results in this thesis do not reveal whether the profit margin has changed or not.

It could also be interesting to make more interviews with representatives from different parts of the GSHP industry, not only manufacturers. Finally, comparative studies could show how potential learning knowledge flows between different heat pump types and different markets.

# 7. Conclusions

The results show that the experience curves of price and efficiency of the ground source heat pump do not align, rather they have developed at different paces during different time periods. With that said, their respective paths are highly dependent on each other. The relation between them in general is that higher efficiency lead to higher investment costs but lower costs during operation.

The performance of the GSHP has steadily increased, with a learning rate of 2.8 % for the heat pump unit and 5.8 % for a heat pump working with lower supply temperatures. The efficiency improvements inside the GSHP has been due to the introduction of components optimized for heat, improvements of the steering and the inverter compressor. An important improvement outside the heat pump is the usage of low temperature heating systems in buildings.

The GSHP price development has shifted from a decline seen in previous studies to a rise by 29 % in 2008–2020, contrary to the expectations in learning theory. According to the interviewed manufacturers, the price increase is due to more expensive components and additional features that meet user needs such as design and wireless control of the heat pump. The higher efficiency has contributed to keep the total price down, but the effect is limited because of an increased price of electricity.

The most important factors that have caused the development are regulations, research and competition between manufacturers. The regulations affect both efficiency and price, while research and competition first and foremost seems to have affected the efficiency.

Even though the prices have risen, the profitability remain advantageous compared to other types of heating. The total GSHP price is favorable compared to the operating expenses of electric resistance heating, and in many cases lower than the operating expenses of district heating. Since the price of electricity is crucial to the profitability, that may determine the opportunity for GSHPs to deploy on markets with different electricity price levels.

In understanding the development of the GSHP, the local aspects cannot be neglected. Favorable preconditions specific to Sweden has enabled a domestic industry, that is at the forefront of GSHP technology. The Swedish GSHP seems to be a highly local product, tightly connected to the context, and the learning processes seems to take place on the local scale.

The heat pump efficiency development rate may begin to decelerate. The increased possibilities to steer the heat pump through digitalization may reveal a future learning path for the heat pump, which is possible because of new dynamics in the energy system.

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# Appendix A

## Interview questions

*The production process*

- Is it correct that your production facilities are located in Sweden?
- In many areas of technology, the market has been taken over by products that are mass-produced in countries with low wages like China, while heat pumps are still manufactured in Sweden. Why is that?
- Do you produce all components of the heat pump or are some components imported from other countries? If so, which components?
- To what extent is the production process automated? Are assembly lines used?

*Development of technology*

- Could you describe the technological development of the GSHP, especially during the last ten years?
- Does the technological development of the GSHP differ from other types of heat pumps?
- Why has COP increased over time?
- Do you believe the heat pump technology will develop in the coming years? If so, how?
- What are the obstacles to further development?
- Do you think the lifetime of heat pumps will change?

*Price development*

- Could you describe how the price of the GSHP has developed during the last ten years?
- Does the price development of the GSHP differ from other types of heat pumps?
- How do you believe the price of the heat pump will develop in the coming years?
- What affects the pricing?

*Other*

- The number of heat pumps has increased drastically in Sweden during the last 30 years. Why is that?