KTH Industrial Engineering and Management	**Master of Science Thesis** **TRITA-ITM-EX 2018:710** **Potential for seasonal electricity storage in borehole thermal energy stores with heat pumps** Elisa Razzetti

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Abstract

In Sweden, there is a substantial increase in renewable power generation that affects the electricity market. At the residential, PV diffusion spreads in the last years due to price drop, while use of heat pump is consolidated. This thesis aims to evaluate the technological potential and economic value of seasonal storage of electricity in a thermal medium using boreholes and heat pump for a multi-family house in Sweden in a context of high renewable market.

An existing GSHP-PV system model is implemented in TRNSYS with the addition of an inline heater on the boreholes circuit. Its function is to heat the borehole field during PV peaks or low electricity price. The performance of the system is evaluated in terms of renewable and consumption impact with Self-Consumption, Solar Fraction and Seasonal Performance Factor, while Total Life Cycle Cost defines the economic feasibility of the system.

In order to estimate several price scenario, an electricity market model is developed and applied to forecast the hourly electricity price in future in Sweden with high wind and solar penetration.

The results suggest that the configuration studied does not benefit from seasonal storage of electricity. Since the increase of electric demand due to the borehole heater, self-consumption is generally improved despite solar fraction depends greatly from the only use of PV over production or grid prices. Seasonal peak shift and SPF improvement are not demonstrated, although there is an increase of TLCC. This leaves the system without storage the most profitable, despite the use of electric boilers or heat pumps at the borehole heater.

Sammanfattning

I Sverige sker en kraftig ökning av förnybar kraftproduktion som påverkar elmarknaden. På bostadsnivå har en PV-diffusion spridits under de senaste åren tack vare prisfall samt det faktum att värmepumpar har konsoliderats.

Med fokus på en högre förnybar marknad så syftar denna avhandling till att utvärdera den tekniska potentialen och det ekonomiska värdet med att säsongsförvara elektricitet genom att använda sig ett termiskt medium, borrhål och värmepump i ett flerfamiljshus i Sverige.

Ett befintligt GSHP-PV system har implementerats i TRNSYS. Utöver detta så har en värmare tillagts i borrhållskretsen med syfte att värma borrhålsfältet under PV-toppar eller vid lågt elpris. Systemets prestanda har utvärderats med avseende på förnybar- och konsumtionspåverkan; egen förbrukning (SC), andel sol (SF) samt säsongsmässig prestationsfaktor (SPF). Den totala livscykelkostnaden (TLCC) har beräknats för att ge ett mått på systemets ekonomiska genomförbarhet.

För att kunna estimera olika prisscenarion så har en elektricitetsmarknadsmodell utformats och tillämpats. Denna modell använder prognoser för hur det framtida elpriset i Sverige kan se ut vid höga vind- och solpenetrationer.

Resultaten tyder på att den studerade konfigurationen inte kommer att ha nytta av säsongsförvaring av el, mest på grund av den höga självkonsumeringsgraden av borrhållsvärmaren. Den egna elförbrukningen är generellt sett förbättrad trots att andelen sol beror starkt på produktion samt nätpriser. Varierande säsongstoppar och förbättring av SPF visas inte även om det finns en ökning av TLCC. Detta gör att det mest lönsamma systemet är utan lagring, trots att användning av elpannor eller värmepumpar vid borrhållsvärmaren förekommer.

Acknowledgement

This work was supported by the Effsys Expand program (Project no. 40936-1).

I would like to show my deepest gratitude to Nelson Sommerfeldt, my supervisor at KTH, for the inestimable support and inspiration throughout the work and for sharing his knowledge on the subject with me.

I am eternally grateful to my parents, for their love, support and continuous encouragement to pursue my dreams. I owe them all everything.

Many thanks to the colleagues of the MTR. With a special mention to my friend Gigi, Antti and José, for the mutual support through those months. It was great sharing tons of simulations and coffee with you.

A special gratitude goes to Bala, for the very appreciated reviewing work and friendship.

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Units

^oC	Degree Celsius
J	Joule
K	Kelvin
m	Meter
MSEK	Million of Swedish Krona
öre	Hundredth of Swedish Krona
SEK	Swedish Krona
W	Watt
Wh	Watt Hour

Abbreviations

ASHP Air Source Heat Pump

Aux Auxiliary

Avg. Average

BH Borehole

BHE Borehole Heat Exchanger

CAES Compressed Air Energy Storage

CHP Combined Heat and Power

CO_2 Carbon Dioxide

COP Coefficient Of Performance

DHW Domestic Hot Water

DR Demand Response

DSM Demand Side Management

DSO Distribution Grid Operator

Ei Energimarknadsinspektionen (Swedish Energy Market Inspectorate)

EH Electric Heater

EU European Union

GSHP Ground Source Heat Pump

HP Heat Pump

HTF Heat Transfer Fluid

HVAC Heating, Ventilation and Air Conditioning

KPI Key Performance Indicator

LCC Life Cycle Cost

nZEB Nearly Zeto-Energy Building

PPA Power Purchase Agreements

PV Photovoltaic

PVT Thermal-Photovoltaic

REN Renewable Energy

RM Regression Model

SAHP Solar Assisted Heat Pump

SAGSHP	Solar Assisted Ground Source Heat Pump
SC	Self-Consumption
SF	Solar Fraction
SH	Space Heating
SPF	Seasonal Performance Factor
TLCC	Total Life Cycle Cost
TRNSYS	Transient System Simulation
TSO	Transmission System Operator
UTES	Underground Thermal Energy Storage
VPP	Virtual Power Plant
VRE	Variable Renewable Energy

1 Introduction

In the context of the Paris Agreements, the Swedish Parliament (Riksdag) adopted a climate policy framework in 2017 and entered into force as January 2018. It pushes the goals for climate change and proposes to achieve negative greenhouse gas emissions by 2045 (Government Offices of Sweden, 2018). The energy sector plays an important role in the achievement of emission reduction addressing cleaner energy production while decreasing consumption. In order to do so, an increasing share of renewable (REN) in energy generation is pursued together with growing efficiency in both the production and demand side. Electricity is involved directly in this shift towards a high renewable share and trends are towards more wind and solar generation.

In 2015, Sweden had 10% of electricity generation from wind while the solar share was less 0.1% (IEA, 2018). The Swedish Energy Agency (Swedish Energy Agency, 2016) describes four possible scenarios where the share could rise up to about 50% wind and 20% solar. The drop of the price for solar photovoltaics (PV) and off-shore wind make these scenarios possible. Several countries encouraged the use of PV in the residential sector with dedicated policies, as Germany, Italy and France in the EU (Jaeger-Valdau, 2017). Nevertheless, PV and wind generation are subjected to resources availability rather than load request. Grid stability is one of the challenges to face when increasing intermittent REN. Variations on the grid are reflected on the electricity market and price fluctuation.

There is a need for storage and load management that could increase the flexibility of the whole system. Smart grid and demand side management (DMS) are established solutions for balance between generation and load curves and the integration with more complex systems occurring with distributed energy sources. Smart controls of heat pump provide a tool for grid balance and peak shift (Fischer and Madani, 2017). Hence, coupling PV and heat pumps is a future challenge. In fact, the heating demand in households is a major issue, in particular for cold climate as Sweden. The need for space heating is opposite to the presence of the sun, so that the increasing use of solar system in households is not fulfilling most of the peak loads both in short and long term. Thus, the need for storage.

Electricity storage is usually associated with batteries which prices are expected to decrease in future due to enhancement in research and industry driven by electric vehicles development. Hence, batteries have potential to become a storage mean also in grid connected systems and residential for daily or short-term. However, there is a strong likelihood that they would not be feasible and cost effective for seasonal storage. Thermal storage provides a valid alternative on the long-term. Some applications use underground as sink for seasonal storage of thermal energy. One example is the use of boreholes and their integration with heat pump, district heating and solar systems. Thermal coupling of boreholes and solar collector is the most established combination because of the direct use of thermal energy, while solar photovoltaics cover part of the electric demand. At present, research and applications tend to focus on heat-to-power or heat-to-heat conversion. Nevertheless, power-to-heat conversions appear necessary on a context with increasing seasonal mismatch in load and generation (Lott and Kim, 2014).

Installation of solar PV on residential building is expected to grow more in the near future, while the use of ground source heat pump for space heating and domestic hot water is common in Sweden. Research focuses on the implication of PV and heat pumps on the grid response, while it is lacking a comprehensive study on a grid integrated system with seasonal storage of electricity. A system consisting of ground source heat pump and borehole thermal storage could provide a potential alternative solution to increase PV self-consumption and help grid balance during overproduction by converting electricity to heat and dumping the excessive heat into the boreholes reaching higher storage temperature, hence decreasing the electricity consumption and support peak shift in winter.

1.1 Objectives

The aim of this thesis is to evaluate the technological potential and economic value of seasonal storage of electricity in a thermal medium using boreholes and heat pump for a multi-family house in a context of high renewable market.

The research investigates the technological feasibility of the system considered, so that

1. the system benefits from an increasing solar and renewable fraction;
2. there is shift of electricity consumption curve of the heating demand in winter;
3. evaluate if there is a case in which the system is cost effective.

The results are expected to provide insights into integration of PV with a ground source heat pump (GSHP) for installers and eventually for utility company into future development of power-to-thermal storage system in a distributed network and the market condition to consider.

1.2 Methodology

The project is based on a quantitative approach on building energy system, following a techno-economic method. The objectives of the thesis are met through model simulations with TRNSYS, a TRaNsient SYStems simulation tool (TRNSYS, 2018).

The thesis starts with a literature review with focus on the state-of-the-art for storage technologies, main components of the system and electricity market conditions. It follows the description of the building energy system; then, boundary conditions and performance indicators are consistently assessed.

An existing GSHP-PV system model is implemented in TRNSYS with the addition of an in-line heater on the boreholes circuit (Figure 1.1). The performances of the system are evaluated for an electric boiler operating when there is an excess in the PV power generation. An alternative with HP in place of electric boiler is also considered. A second control ruled by electricity price fluctuation is applied to the in-line heater.

Finally, techno-economic performance of the system models are evaluated under different price scenarios. Solar fraction (SF), self-consumption (SC), and seasonal performance factor (SPF) are the indicators used to compare the technical performance of system options, while price feasibility is estimated using the total life cycle cost (TLCC). The most promising alternative have ideally best performance with lower TLCC. Sensitivity analyses on the component sizing and economical input are implemented in order to evaluate their implication on the system performance.

The description and analysis of the storage system is preceded by the analysis and forecast of electricity market. The generated electricity prices are used as input value for the estimation of the storage system. The first step is the analysis of the existing data of the wholesale electricity market, including: price, total production, consumption and renewable generation. It follows the creation of a mathematical model based on a multiple linear regression. The results from the model are compared to the real data under the same conditions for validation. Forecast of electricity prices is performed under three scenarios with a different portfolio of power generation from renewable. The power generation is estimated from the expected installed capacity in a suitable way for the technology considered. Retail price and value of sold electricity to the grid is then calculated for each scenarios.

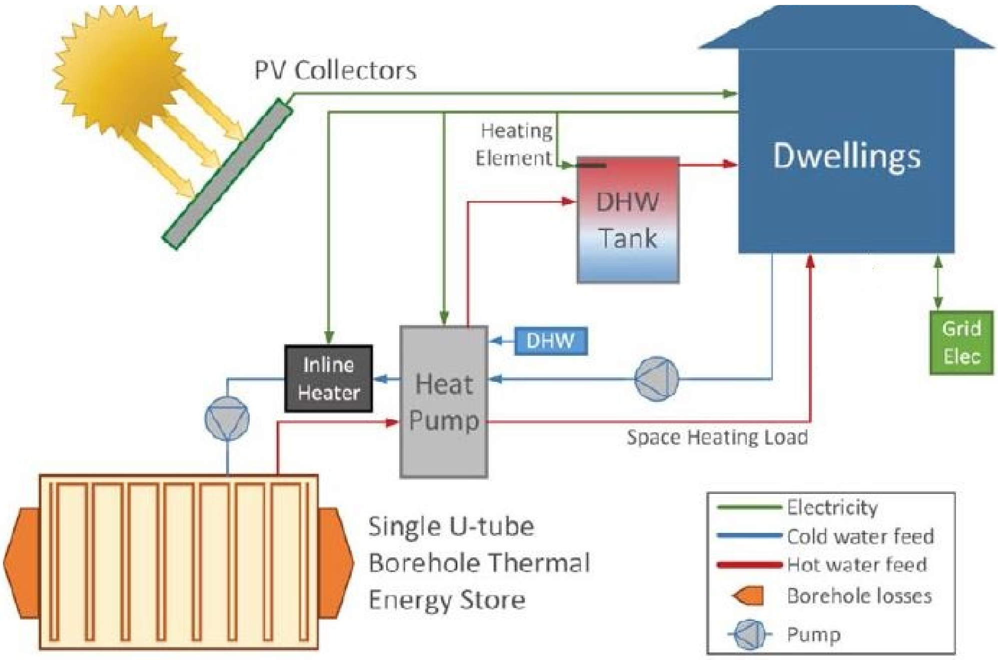

Figure 1.1: Building energy system scheme, adapted from (Sommerfeldt and Madani, 2016).

1.3 Scope and Limitations

Object of the analysis is a multi-family house in Sweden with ground source heat pump (GSHP), PV generation and grid connected. In particular, weather and ground specification represent the boundary conditions for the Stockholm area. Although similar conditions are found in most of Sweden and Norway, the validity of the outcome has geographical restrictions. As part of a larger project (Sommerfeldt and Madani, 2016), this study is based on an existing system model which incorporate the load profile of an existing building with the replication of a GSHP system.

As the study aims to estimate the potential of the storage system when large fluctuation in electricity price occur, electricity market forecast is limited to projection with a strong penetration of renewable power in the electric generation. Again, the results involving electricity prices and economic return are strictly bound to local specifications for Sweden.

Due to the complexity of system and the large number of factors involved, the outcome of this study should be thought as exploratory of the potential for seasonal storage with GSHP and an overall understanding of the system behaviour. Moreover, there are not existing application able to validate the model, so that the study is purely theoretical.

2 Literature Review

This chapter is meant to provide insights to the main components of the systems and analyse previous studies on topics related to the study. An introduction to photovoltaics and heat pump systems is followed by considerations of system integration and controls. Due to the complexity of the system studied, background information are given for some of the topic to complete the overview on electricity storage and Swedish market.

2.1 Photovoltaics

Worldwide installation of solar PV is increasing in the last decade, initially driven by European market and after by China and USA (IEA PVPS, 2017). In Europe, Germany is ahead of PV sector since 2000, followed by the UK in the last years, while Italy had an explosion on the annual solar PV installed capacity around 2011 (SolarPower Europe, 2016). In recent years, PV market experienced an exponential growth also in Sweden reaching about 200 MW of total PV capacity installed, while in Europe reached 104 GW cumulative capacity installed (IEA PVPS, 2017). Only in 2016 the installations were 65% more than the previous year, mostly grid-connected distributed PV of which 30% is residential. A combined effect of the technology price drop and direct capital subsidies fostered PV growth. Meanwhile, solar applications increased in popularity among public and utilities together with simplification of the regulation for micro producers (Lindahl, 2017), holding back solar thermal collector expansion. On the global scale, main policy drivers for solar PV included feed-in tariffs, power purchase agreements (PPA), net-metering, direct subsidies, and green certificates (SolarPower Europe, 2016). Although fast expansion of the PV installation, the market in Sweden is still marginal and represents 0.1% of the total electricity production in 2016 because of the low electricity prices and the low CO_2-foot-print of power technologies (Lindahl, 2017).

New policies for promoting the share of renewables are continuously implemented, together with improvement of the efficiency. Latterly, a policy framework addressing climate change and greenhouse gas emissions was adopted by the Swedish Parliament in 2018 (Government Offices of Sweden, 2017; Government Offices of Sweden, 2018) in respect to the Paris Agreement. In 2016, the Swedish Energy Agency drafted a report on the strategy for increasing the use of solar in electricity generation and storage in the residential sector (Swedish Energy Agency, 2017; Lindahl, 2017).

In order to increase the share of solar photovoltaics installed, the profitability of the system is taken into account. PV project profitability is conditioned by economic factors as electricity prices, support schemes, capital costs and grid revenues, as well as irradiation and self-consumption rates (Dunlop and Roesch, 2016).

One of the parameter most used to evaluate photovoltaic systems performance is self-consumption (Poppi et al., 2018) and it represents the share of total PV generation directly consumed in the households (Luthander et al., 2015). It is analyzed in several reports and research articles (Thygesen and Karlsson, 2013; Thygesen and Karlsson, 2013; Widén, 2014; Fischer, Rautenberg, et al., 2015; Luthander et al., 2015; Salpakari and P. Lund, 2016; Sommerfeldt, Muyingo, and Klintberg, 2016; Fischer and Madani, 2017), and addressed in policy to integrate PV in the electricity network (Dunlop and Roesch, 2016) without further financial incentives (Masson, Briano, and Baez, 2016). It was shown by Sommerfeldt, Muyingo, and Klintberg (2016) that profitability of photovoltaics system is boosted by the increasing rate of self-consumption in the particular case of Swedish prosumers. Electricity self-consumption becomes more attractive for low grid feed-in tariffs (Fischer, Rautenberg, et al., 2015) and reducing the amount of electricity purchased to the grid is the most effective way to use PV generation (Thygesen and Karlsson, 2013). Therefore, optimization and maximization strategies for self-consumption are assessed investigating the use of complementary technologies, storage systems or adjusting the load demand to the PV generation curve, in particular the use (occasionally combined) of battery storage and demand side management (DSM) (Luthander et al., 2015). The use of batteries in domestic energy storage can increase the extent of self-consumption up to 20-50%, but there is a practical maximum range affected by the seasonality of PV, in particular for high latitudes (Nyholm et al., 2016) and battery capacity to supply only a daily buffer (i.e. from day to night) in order to be feasible for size and price (Zakeri and Syri, 2016).

Grid utility company and TSO claim for consumption within the same households in order to assure grid stability when increasing the share of distributed PV generation. The "duck-curve" demonstrates mismatch between peak generation and peak consumption, and exposure the over-production (Janko, Arnold, and Johnson, 2016). Moreover, grid-connected PV systems affect the electricity network in terms of power quality (harmonics, current backflow and mismatch in pack demand) that could be managed with distributed storage or local solutions (Energy Storage Association, 2018).

2.2 Heat pumps

Electricity price fluctuation accounts for many factors, but it is mostly influenced by the climate in Sweden (Swedenergy, 2015; Hirth, 2016). One reason is that many households use electric heating (Swedish Energy Markets Inspectorate, 2017). Together with district heating network, heat pumps are employed in the residential heating sector decreasing the electricity consumption for domestic heating purpose because of the higher efficiency compared to electric boilers (Swedish Energy Agency, 2015). Due to better efficiency and potential for electric supply from renewables, heat pumps are promoted in EU for nearly Zero-Energy Building (nZEB) and their market is expected to continue growing in the next years (EHPA, 2017). Besides, heat pumps offer a range of features during operation or coupled with other technologies, making them a pragmatic technology to tackle current energy challenges. On the other hand, there is the risk that an increase of heat pump would increase electricity demand and enlarge peak load because of increase in load simultaneity. Overload and voltage stability could affect the grid for large use of ASHP, as highlighted for a study for Belgian feeders (Protopapadaki and Saelens, 2016). Hence, the need to avoid drawback through development of strategies and support the change towards low-carbon and renewable deployment.

System analysis and categorization of heat pump systems can be described with the following characteristics, provided in (Hadorn, 2015):

1. type of heat demand to be served;
2. low-temperature heat source(s) of the heat pump;
3. form(s) of energy used to drive the system;
4. function and placement of storages in the system;
5. interactions between these components.

A heat pump takes a low temperature heat source and lifts it to a higher temperature demand with use of electricity. The most common typology of heat pump are air source, that use ambient air has heat sink, and ground source (Hadorn, 2015). Other sink mediums have been used and several concepts of heat pump have been developed and tested. Solar assisted heat pump (SAHP) is a solar thermal system that supports the heat pump operation providing thermal heat with the aim of decreasing the electric load of the system both as refrigerant in the evaporator or direct the heat flow to the DHW tank. There is an lack of studies including an economic assessment of solar PV and heat pumps (Poppi et al., 2018).

Ground source heat pump (GSHP) is connected to a heat exchanger on the ground in order to decrease the volatility temperature gap and increase efficiency of heating system. Several layouts are possible for the ground installation for type, size, and geometry. HP have great potential when coupled with boreholes dug in the ground. Operational strategies can increase the efficiency of the system by charging the ground during summer. One season of charging provides increasing ground temperature (Giordano et al., 2016) and makes the borehole thermal energy storage (BTES) a competitive option for seasonal storage (Nordell and Hellström, 2000).

2.3 Storage

The advantage of thermal energy storage is that can provide short and long-term storage, compared to battery, offering lower energy density but longer lifetime (Lanahan and Tabares-Velasco, 2017). Moreover, a combined use of diurnal and seasonal storage is more technical effective when assisting solar systems in building because of the mismatch between the solar resource and the heating demand that usually peaks when there is no sun (Rad and Fung, 2016; Lanahan and Tabares-Velasco, 2017). Study on the optimization of PV system for high latitude resulted that storage outperforms for high penetration level, while DSM maximize the solar fraction for low overproduction (Widén, Wäckelgård, and P. D. Lund, 2009). In addition, a system with PV and hot water storage was found to achieve the same self-consumption with half of the LCOE than storage with battery (Thygesen and Karlsson, 2014). On the other hand, residential battery prices are decreasing fast (Nykvist and Nilsson, 2015), at present the installed cost for a 14 kWh Tesla Powerwall station is about 70,500 SEK, that is about 5,000 SEK/kWh (Tesla, 2018).

There are many application and studies on borehole thermal energy storage (BTES), throughout application from the early stage to modern systems (Gehlin, 2016). Boreholes transfer heat from or to the ground by a heat transfer fluid (HTF), suppling heating or cooling needs. Conjunction with heat pump is common for low temperature BTES. Benefits of using BTES are that relative low cost for the storage capacity achievable and the geographical potential (less limited than other underground thermal energy storage UTES as ice or aquifer). The environmental risk appears to be limited to a general level for human activity (buildings and road infrastructure) for low temperature borehole, while it is higher for high temperature storage (> 40 °C) for groundwater. A system analysis shows that high temperature storage boreholes are usually coupled with solar thermal and ideally without heat pump for storage purpose and/or large scale. Low temperature storage systems are usually coupled with heat pump and can provide seasonal heat storage. Operational schemes affect the efficiency of the storage, thus turning into savings.

Returns from charging the ground for small systems are insignificant due to very low efficiency, because the ground temperature is restored naturally when the fields counts few boreholes, e.g. single family house (Lanahan and Tabares-Velasco, 2017). While single borehole is not suitable for storage, the optimal geometry for storage is a cylindrical volume with diameter twice the height, not deeper than 100 m to avoid excessive losses in the HTF and drilling cost (Lanini et al., 2014). Optimal design of BTES with solar collectors depends on the location (Flynn and Sirén, 2015), but similar consideration can be done also for PV. At high latitudes the design of the system is the most challenging because of the uneven and low radiation, but high solar fraction (SF) can be achieved with high passive building standard (Flynn and Sirén, 2015).

2.4 System Integration

Systems with PV, heat pump and BTES have been investigate, but the literature review shows that the storage in the borehole is usually done involving coupling with district heating (Rad and Fung, 2016) or solar thermal collectors(Nordell, 2000; Flynn and Sirén, 2015; Reda, Arcuri, et al., 2015; Reda and Laitinen, 2015; Rad and Fung, 2016), while solar power is sized to cover the electricity load of the heat pump or part of the building. For this reason, hybrid solar collectors (PV/T) have high potential to be integrated in the system (Sommerfeldt and Madani, 2016). The use of direct thermal heat for regeneration and storage is effective, and even short storage could increase the total efficiency (Giordano et al., 2016). Moreover, including PV adds complication to the system boundaries whose conditions influence the payback time results (Poppi et al., 2018). Sommerfeldt and Madani propose several concepts of a system combining PV/Thermal collectors, GSHP, BTES and battery for a multi-family house in Sweden, plus one configuration where PV modules are used in place of PV/T (Sommerfeldt and Madani, 2016).

There is an increasing interest in thermal energy storage in distributed and large scale plans and power-to-thermal conversion is becoming a real option for enhancing the energy system in terms of grid balance and storage both on the short and long period as shown in Table 2.1 (Lott and Kim, 2014). The likelihood to happen is enforced by electricity price drop in countries like Germany and Sweden, due to the increased share of renewable, hydroelectric surplus and electricity consumption (Hirth, 2016).

Table 2.1: Options for various energy system applications for storage and grid balance. Adapted (Lott and Kim, 2014).

Service	Current options	Future storage options
Temporal imbalances	• Curtailments of renewables • Electricity storage • Gas turbines and fossil power plants • Thermal storage	• Batteries in households with roof-mounted PV systems • Thermal and electricity storage in decentralised CHP • Thermal storage • Fuel cells • Electricity storage
Regional imbalances	• Electricity imports and exports • Transmission grid enhancement	• Large-scale batteries (MW) at the distribution grid • Compressed air energy storage (CAES) systems • Thermal storage
Long-term storage	• Thermal storage	• Hydrogen storage • Thermal storage • Power-to-gas

Several research investigated heat pump integration in smart grid and controls (Fischer and Madani, 2017), but also a number evaluated systems where heat pumps are combined with solar thermal or PV, ground source or other storage option as hot water tank and battery (Thygesen and Karlsson, 2014; Carvalho et al., 2015; Sliwa and Rosen, 2015; Poppi et al., 2018).

Traditionally, heat pumps are controlled upon thermal load demand. However, it can be integrated in demand response strategies or smart grids when run with more complex controls. As an example, active control of residential heat pump contributes to peak shaving of the house and decrease electricity injection to the grid when coupled with PV or wind generation, while increasing the power purchased from the grid (Vanhoudt et al., 2014). Similarly, another study (Fischer, Rautenberg, et al., 2015) concluded that variable speed heat pump controlled by real-time smart strategies could increase PV self-consumption. Demand response (DR) algorithms enhanced a system with heat pump and TES in water tank (Alimohammadisagvand et al., 2016). Other studies evaluate different control approaches that consider forecasting and predictive control over real-time simulation, but real-time simulation appears to improve self-consumption against efficiency (Poppi et al., 2018).

An overall literature review done by Fischer and Madani (Fischer and Madani, 2017) concluded with the importance of a holistic approach to the study of heat pump in a smart grid, where DSM is integrated with electricity, heating and transportation (P. D. Lund et al., 2015). Their analysis focused on the application of heat pump in smart grid and control scheme. Grid-friendly operation as provision of ancillary services and variation in the heat pump operation according to electricity price fluctuation could facilitate the integration of renewable electricity generation on building-, distribution- and power system-levels. Besides, control schemes can support smart grid integration by addressing different target, level of integration (boundary conditions), autonomy level of the building system and predictability of the control. However, there is the necessity to think a new business model, with strategic partnership, in order to develop a proper smart grid with heat pump integration, able to support the increasing complexity and risks (Fischer, Triebel, et al., 2017).

The adoption of demand-based time-of-use tariff for electricity affects the behavior of customers, promote off-peak electricity consumption, and hence enhance demand response potential (Bartusch et al., 2011; NordREG, 2015). Besides, development of algorithms and control for distributed generation and building integration with the grid is earning attention in the last years (Raza, Nadarajah, and Ekanayake, 2017; Solano, Olivieri, and Caamaño-Martín, 2017; Sun et al., 2018). Energy cost mitigation for both customers and network operators can be achieved by adopting a charging envelope approach for combined PV and battery system connected to the grid, in which either PV overproduction or grid overvoltage flow charge the battery (Wang, Gu, and Li, 2018). For a low energy house in Finland, cost-optimal control increases peak power, but achieved annual economic savings buying electricity at lower prices (Salpakari and P. Lund, 2016).

TRNSYS is used in several studies for the simulation of energy system and in particular for solar building integration (Pinel et al., 2011; Vanhoudt et al., 2014; Hadorn, 2015; Reda, 2015; Sommerfeldt and Madani, 2016; Ruiz-Calvo et al., 2017). Lanahan and Tabares-Velasco evaluates limitation when analyze boreholes and ground behavior (Lanahan and Tabares-Velasco, 2017). Constraint on the time step on the simulation of building and PV systems arises to limit simulation error (hour to minutes time step) (Poppi et al., 2018).

Coupling PV with BTES is in interesting opportunity also for Sweden as thermal storage allows diurnal and seasonal cycling and low cost if the system is properly sized. In addition, employing an approach promoting self-consumption and cost-optimal control employing hourly market price have the potential to improve the profitability of grid connected PV system in buildings, also providing benefits to the grid. The literature review shows a gap in knowledge between the use of PV and seasonal storage, considering the challenge to convert electricity into heat for seasonal storage on the residential scale. Moreover, there is lack of a comprehensive study concerning both technological potential and economical value of systems combining PV, heat pump, seasonal storage in boreholes and electricity price fluctuation.

2.5 Performance Indicators

Apart from the self-consumption already discussed, there are other common performance indicators used in literature for solar-heat pump system. Among the economic parameters, payback time and net present value (NPV) provide an evaluation over the system life cycle cost (LCC), but also yearly or total economic savings (Poppi et al., 2018). The same study asserts that energetic performance indicators in techno-economic analysis are seasonal performance factor (SPF) and total electricity use, while solar fraction is less common. SPF covers an important role in the evaluation of the heat pump as part of the Intelligent Energy Europe platform (European Commission, 2018). Defining the boundary conditions at a component or system level affects the resulting SPF. A graphical description is presented in 2.1 which represents a single family house with PVT and GSHP (Brischoux and Bernier, 2016).

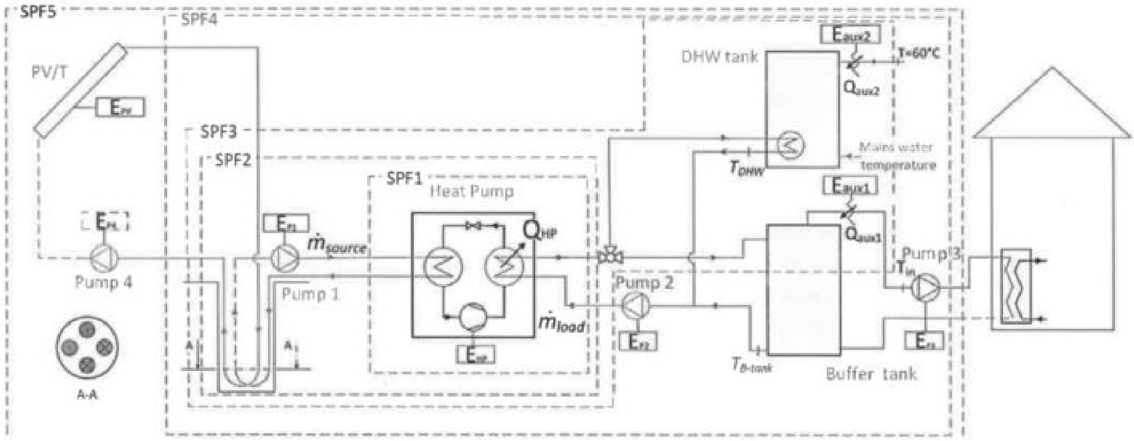

Figure 2.1: PVT-GSHP concept and SPF boundary conditions (Brischoux and Bernier, 2016)

2.6 Swedish Market

The Ei report (Swedish Energy Markets Inspectorate, 2017) explains in detail the grid and the electricity market in Sweden. Peak demand and supply shortages are currently managed by the Svenska Kraftnät and Nord Pool. The Nord Pool trades the electricity exchange in wholesale market under the ELSPOT Day-ahead and Nord Pool intraday trading regulation (Nord Pool, 2018c).

Swedish grid quality is good which implies the balance between input and output in the grid is maintained. An overview of the price tariff for customers shows that the electricity network charges a fixed subscription fee and a flexible portion for the electricity transmission and consumption (Swedish Energy Markets Inspectorate, 2017). Network charges differs from types of household and heating systems (Swedish Energy Agency, 2017). Beside average annual price drops in the spot market (Hirth, 2016), annual household charges increased over the last years.

The type of tariff for network companies are classified under (i) flat rate tariff (low consumption customer), (ii) time tariff, and (iii) output based tariff that implies a fixed fuse rating fee plus the electricity use over time, depending on which part of the day and year (Swedish Energy Agency, 2017).

There are four bidding area in Sweden but prices are usually uniform, whereas differences occurs most of the time between northern/southern bidding areas (Swedish Energy Markets Inspectorate, 2017). In Sweden and Nordics grid congestions are due to high hydroelectric production in the North or large production and transmission northward (e.g. from Denmark) (Swedish Energy Markets Inspectorate, 2017). In 2016, average peak price occurred in January 21st and June 28th (82.38 öre/kWh and 73.49 öre/kWh), while the lower average price was also in January 30th (12.75 öre/kWh). Wind power had largest production in November and December 2016. The Swedish market is influenced also by cross-border exchange, e.g. from Germany (Swedish Energy Markets Inspectorate, 2017).

Ei's report on the regulation of electricity market network tariffs in Sweden (Wallnerström et al., 2016) provides insights on Swedish electricity network organization and regulation for the period 2016-2019 and expected development in the following period starting in 2020. For the future, no significant changes are expected, indeed more study on the smart grid incentives are pending as increase in solar power in a network could have a negative impact on load factor and network losses according to the indicator analyzed (Wigenborg, 2016).

Ancillary services are part of grid balancing and are contracted by TSOs to guarantee system security; some examples are black start capability, frequency response, fast reserve, provision of reactive power. ENTSOE's Group Ancillary Services combines services from providers and DR from customers enhancing TSOs flexibility for efficient management (ENTSO-E, 2015). Apart from smart grid, distributed generation can be grouped and managed as Virtual Power Plant (VPP) (Dunlop and Roesch, 2016). Mäntysaari claimed the different prospective from which wholesales and end-user perceive ancillary services (Mäntysaari, 2015). Two studies analyzed the ancillary service viability from different prospects in Germany. The results of a questionnaire concludes that PV owner are willing to invest in PV-storage (battery), but less willing to accept grid interference with electricity usage (Gährs et al., 2015). On the other hand, Fischer et al. (2017) showed that with the current situation in Germany only some services are more attractive after an economical and technical analysis. For example, business model that look at reducing grid fees as well as enhancing renewables integration and efficiency are adequate for the HP, while grid services as primary balance could be technically damaging.

Overall, the electricity price at the end customer differs depending on several factors and detailed information are provided by (Lindahl, 2017; Swedish Energy Agency, 2017; Swedish Energy Markets Inspectorate, 2017). In general, the electricity price for household is the sum of several components over the base Nord Pool spot price, grid fees and taxes, i.e. energy tax, cost of green electricity certificate, variable and fixed grid charge, VAT and other trading fee. According to the national survey (Lindahl, 2017), the variable part of the electricity price is saved with self-generation in place of purchased electricity by micro-producers. Other benefits could be obtained when excess electricity is compensated with indirect support scheme (grid, utility, tax, certificate) (Lindahl, 2017). Moreover, provision of ancillary services could provide further income , but the attractiveness depends strongly on the system and service involved; e.g. primary response is too risky and complex to be fulfilled by heat pump, while purchasing at the spot market or business involving grid fees reduction better suit heat pump features (Fischer, Triebel, et al., 2017).

3 Electricity Market and Forecast

The creation a price forecast model rises from the need to have an hourly price profile within testing the electricity storage. Nord Pool Elspot market, the wholesale electricity market in Sweden, is based on hourly price exchange and it results from the balance between demand and supply (Nord Pool, 2018b). As a consequence, customers buy the electricity at a retail price that is based on the wholesale (spot) price. Due to the increase of variable renewable (VRE) generation in the power sector and merit order effect (Hirth, 2016), price fluctuation is larger and presenting different patterns compared to the past (Seel et al., 2018). This affects retail contracts, turning to different type of metering and tariff design (NordREG, 2015).

In this chapter it is explained how the market model is created based on existing data and the assumptions made to forecast electricity generation and price fluctuation in Sweden under different scenarios. The results of the investigation and the price forecast for spot and retail price are presented at the end of the chapter. The calculated retail prices serve as input parameter for the PV-GSHP model that is the main object of this thesis.

The analysis is done for 30 years that is the expected lifetime for the PV system. Real prices are used and the influence of inflation is not included the analysis.

3.1 Analysis of existing data

Historical market data are provided by Nord Pool (2018) at different time resolution for the past years. Despite Swedish wholesale market is divided into four bidding area since 2011 (Nord Pool, 2018a), it will be investigated as a whole. Data are shown in Figure 3.1 and 3.2.

The following section presents the analysis of the existing data from Nord Pool of hourly value of spot price, wind power, production, consumption and the weekly hydro reservoir data. Data concern years 2016-2017. The choice of hourly resolution is decisive to catch the volatility of price fluctuation at the smaller time step.

Among the several factors with influence in electricity price, the parameters selected for this study are wind and solar power as VRE indicator, hydro reservoir as climate and seasonal index, production and consumption as direct actors in the bidding market. Although solar power is later considered in the electricity market model, hourly data of electricity production by solar plan are not available for Sweden because of the low incidence of technology in the power market.

According to Nord Pool data, the total generation in 2016 was 15.5 TWh, an average generation of 1.8 GWh and peaks over 5 GWh in an hour. Data for 2017 are not complete at the time this analysis is performed with last availabe data as at December 11^{th}, 2017. According to the available values, wind power reached 15.8 TWh by December 11^{th} with 1.9 GWh as a maximum value. In both years, peaks are more common in winter months.

Nord Pool weekly value of the hydro reservoir are showed in Figure 3.1. As data for hydro are available only on weekly intervals, constant hourly value is considered for each week. Hydro reservoir oscillates through the seasons with a peak in autumn around September and hit the bottom in spring about April. The larger variation is in 2017 from 50 GWh to over 150 GWh.

Per hour consumption has similar trend in both years, spreading from 25 GW in winter to 10 GW in summer. Despite hourly oscillations of load during the day, daily profile has a similar shape during the year moved up in winter because of larger consumption while it is lower in summer.

Production follows a trend similar to consumption. On average production is 10% larger than the load, but there are spikes over 30% difference and minimum production under 10% the consumption. They show a similar trend on the influence on price.

The spot price at day-ahead market had a mean value of 0.282 SEK/kWh in 2016 and 0.301 SEK/kWh in 2017 with peaks over 1.0 SEK/kWh. During the first months of 2016, spot prices at the day-ahead market experienced a minimum due to the combined effect of high temperatures and low fuel prices (Swedish Energy Markets Inspectorate, 2017).

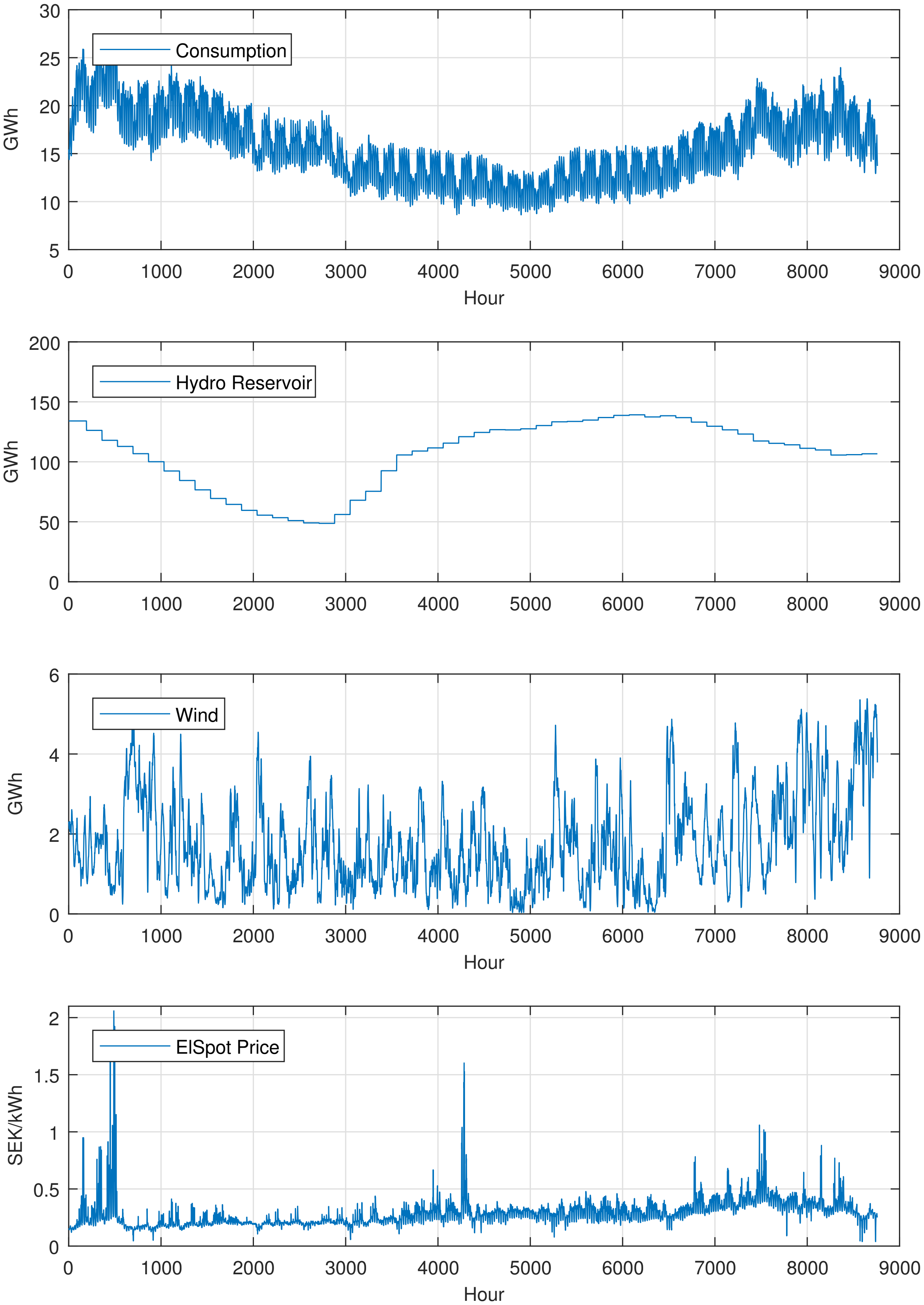

Figure 3.1: Historical data 2016 (Nord Pool, 2018a).

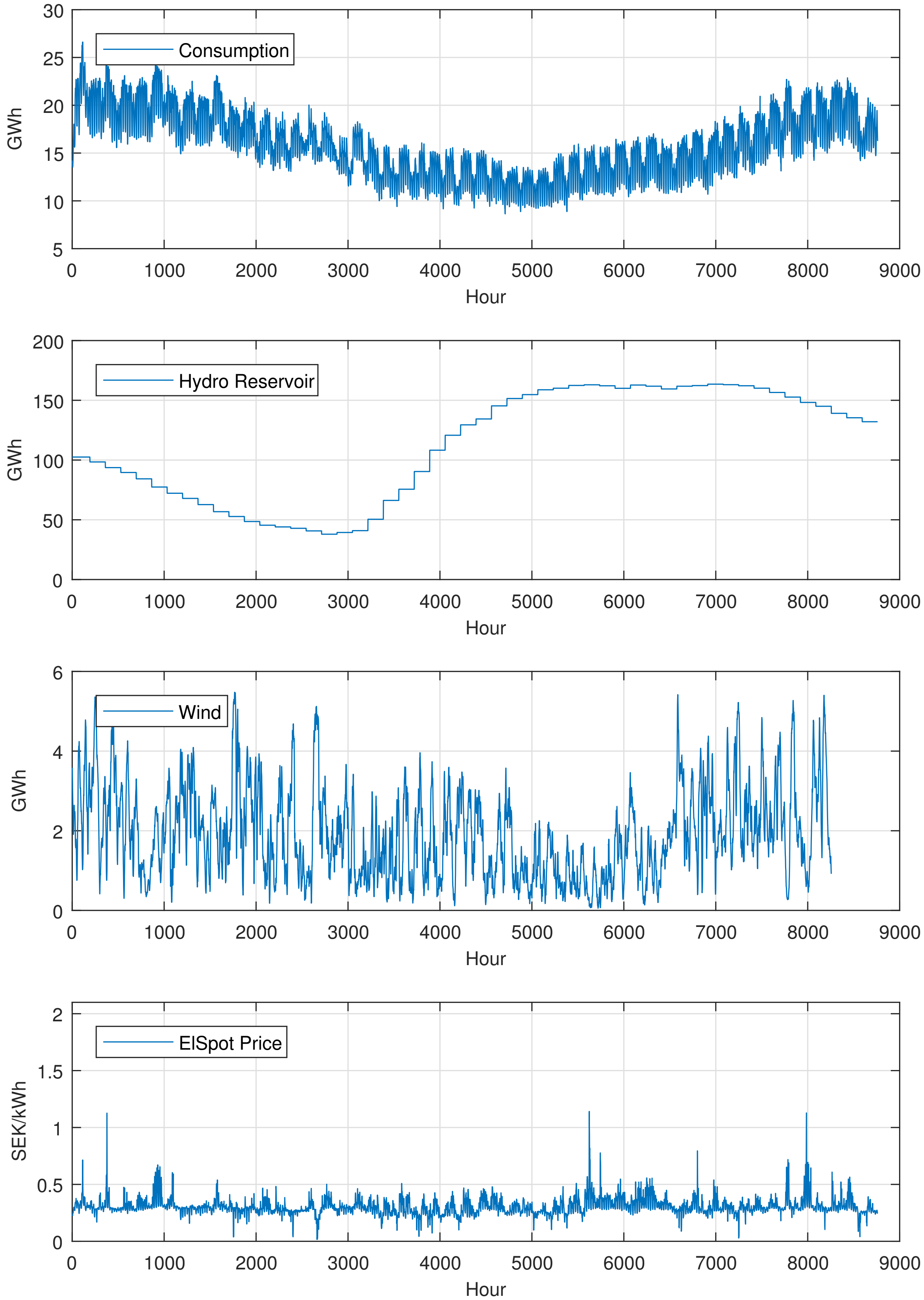

Figure 3.2: Historical data 2017 (Nord Pool, 2018a).

3.2 Spot Price Model

The comparison of the data and trends demonstrate a correlation between spot price and the other parameter taken into account. The spot price can then be thought as a function of wind generation, hydro reservoir and load. In order to find the extent each parameter influence the electricity price, it is necessary a quantitative analysis that is done with a linear regression analysis.

The equation describing the spot price is define as in Equation 3.1, where the spot price P_s is calculated at each hour h depending on the renewable generation $REN(h)$, the hydro reservoir $HYD(h)$ and the consumption $CNS(h)$. The $REN(h)$ variable is the sum of solar and wind power generation, hence the same coefficient is assumed for both technologies because of the lack of solar data.

$$P_s(h) = a_0 + b_1 \times REN(h) + b_2 \times CSN(h) + b_3 \times HYD(h) \tag{3.1}$$

The units of the parameter are SEK/MWh for spot price $P_s(h)$, MWh for renewables $REN(h)$ and consumption $CNS(h)$, and GWh for $HYD(h)$. Although production was considered in the analysis of existing data, the total production is not taken as a factor in the model because of the increasing complexity due to the dependence with renewable generation.

In order to estimate the numerical value of the coefficients in equation 3.1, a multiple linear regression analysis is performed having the wind, hydro and consumption data as predictors spot price as response. Data are divided into years and the regression is done:

1. over the entire database (2016-2017);
2. for each year separately.

In the second case, the model is validated on the other year.

Table 3.1: Coefficients and R-squared value resulting from multiple linear regression of the data in 2016, 2017 and entire dataset 2016-2017.

	Coefficient	**RM-2016**	**RM-2017**	**RM-2016-17**
Constant	a_0	-65.0791	100.0690	-65.0791
Renewable (Wind)	b_1	-0.0192	-0.0285	-0.0192
Consumption	b_2	0.0119	0.0133	0.0119
Hydro Reservoir	b_3	1.8309	0.4279	1.8309
R-squared	R^2	0.2672	0.4449	0.2672

Regression coefficients and R-statistic are reported in Table 3.1. RM-2016 and RM-2017 represent the regression model based on the data from year 2016 and 2017 respectively, while RM-2016-17 is the model considering the entire data sample. To notice that the analysis of the year 2017 alone provide different results compare to the other models which return the same coefficients. The outcome is that models built on data from 2017 have larger R-squared, hence generating a model that better explain the data analyzed even though it never exceed 0.5, meaning that the model has low accuracy in the description of the real data.

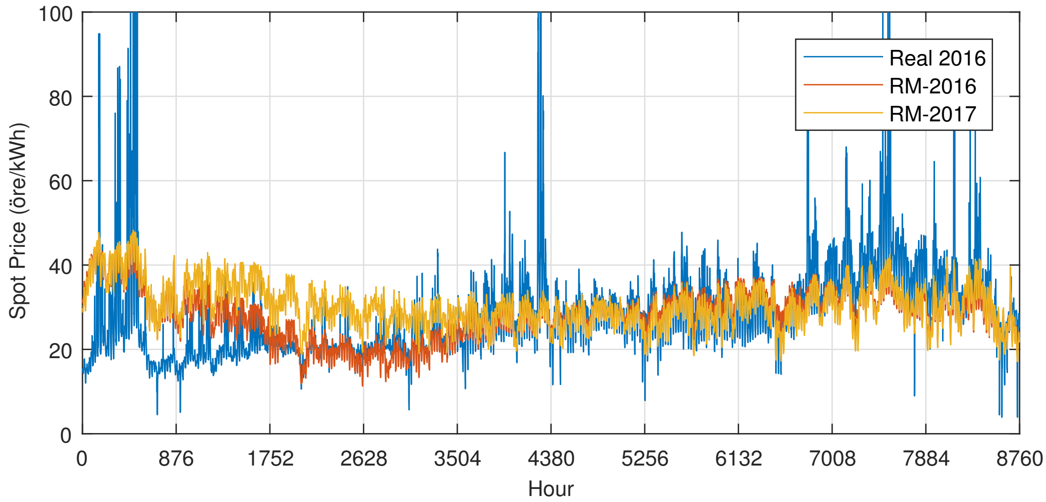

Figure 3.3: Price model validation. Real and calculated spot price for 2016.

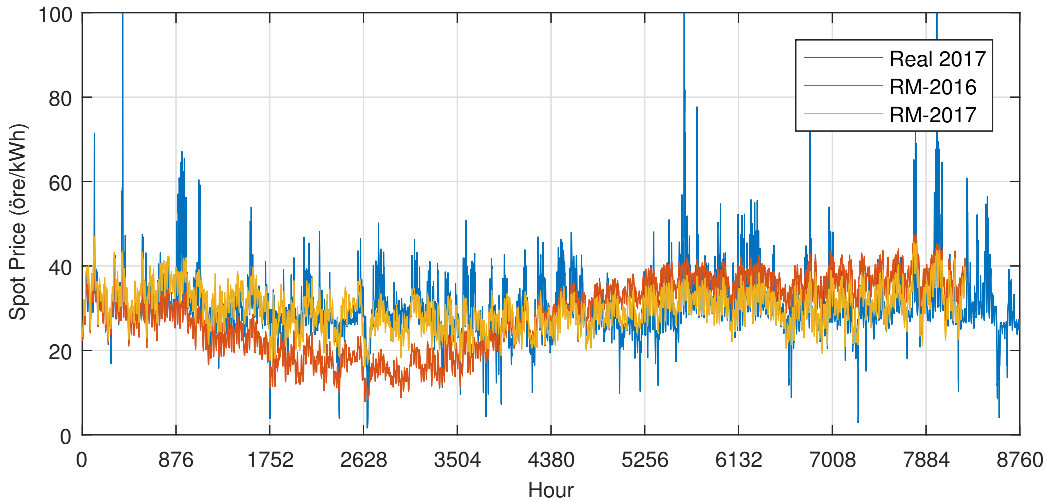

Figure 3.4: Price model validation. Real and calculated spot price for 2017.

Figures 3.3 and 3.4 shows the results of the validation of each model on the other year data and the historical spot price value (Real). The model with coefficients based on 2017 (RM-2017) is compared on the data 2016 and predicts higher prices during the first part of 2016, although following the variability. It catches up the trend during the spring and throughout 2017. The price drop in 2016 is due to the combined effect of high temperature, cutting down consumption, and low fuel prices occurred during the first months (Swedish Energy Markets Inspectorate, 2017). RM-2016 has a similar trend during the same year. Since fuel price is an external factor to the model, it is considered satisfactory but only as a reasonable approximation of a market price model. It does not claim to accurate capture price spikes and factors outside consumption, hydro, and wind.

The comparison in 2017 (Figure 3.4) confirms the RM-2017 model more accurate, in particular between the hour 1752 and 3504 when the price calculated by RM-2016 drops.

As final consideration, price distribution is wider for real data than for the model. That means that the volatility of electricity price is higher than the volatility captured by the price model.

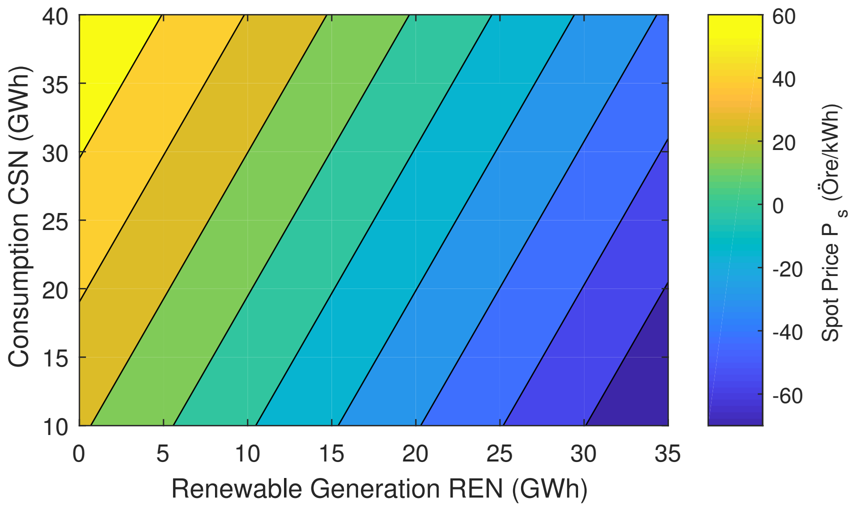

Figure 3.5: Spot price map.

The final model created to calculate electricity price at the wholesale market is based on the equation 3.1 with the coefficients base on 2017 (RM-2017) presented in Table 3.1. The illustration of the spot price generated by the market model (Eq.3.1) as a function of consumption and renewable generation is shown in Figure 3.5.

3.3 Scenarios and forecast

The forecast of electricity price is based on the capacity installed for wind, solar and total consumption. Their values are extracted from three of the four exploratory scenarios on the future of power generation presented by the Swedish Energy Agency (Swedish Energy Agency, 2016). Considering a 28% wind capacity factor and an annual solar generation of 950 kWh/kW, the installed capacities for key years are presented in Figure 3.6.

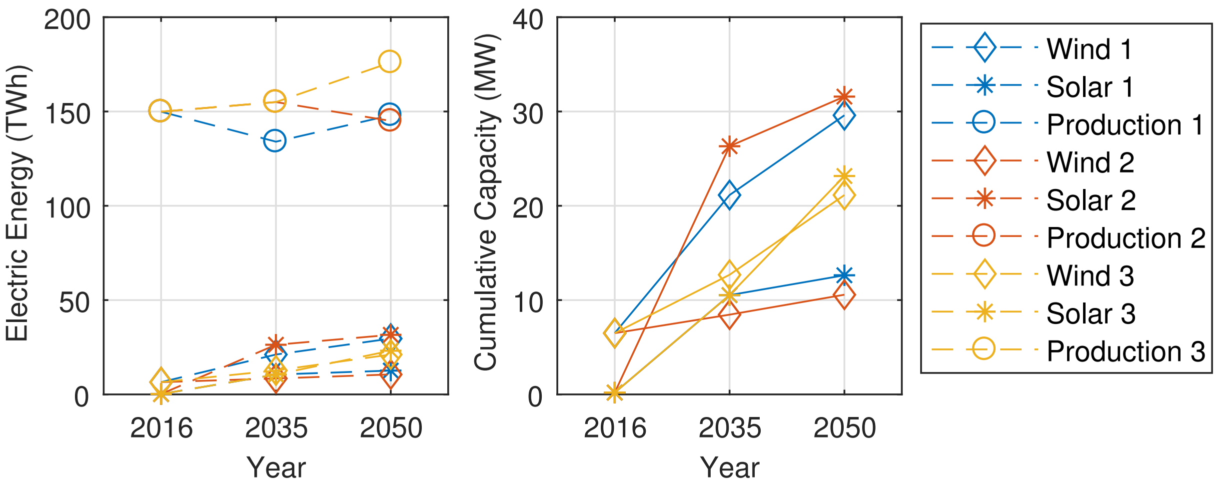

Figure 3.6: Annual power generation and cumulative installed capacity for each scenarios. Elaboration (Lindahl, 2017; Swedish Energy Agency, 2016; Svensk Vindenergi, 2018)

3.3.1 Wind power

In order to have hourly value from 2016 to 2050, wind capacity for 2035 and 2050 is estimated considering a capacity factor of wind installation of 28%. This value is calculated from the total wind production and the capacity installed in 2016 according to Svensk Vindenergi (2018). The annual capacity are then linearly interpolated from 2016 to 2035 and 2050.

Since the unpredictability nature of wind, its hourly production has to be assessed from the expected installed capacity. Here, a proportional model to 2016 is applied. Hourly wind power generation is directly proportional to the installed capacity for that year, with the constant of proportionality equal to hourly values evaluated for 2016. Hence, the hourly function of wind generation is

$$W_y(h) = \frac{W_{2016}(h)}{cap_{w,2016}} \times cap_{w,y} \tag{3.2}$$

where $W_y(h)$ is the wind production at the hour h of the year y, $cap_{w,2016}$ and $cap_{w,y}$ are the wind capacity in 2016 and in year y, respectively.

3.3.2 Solar Power

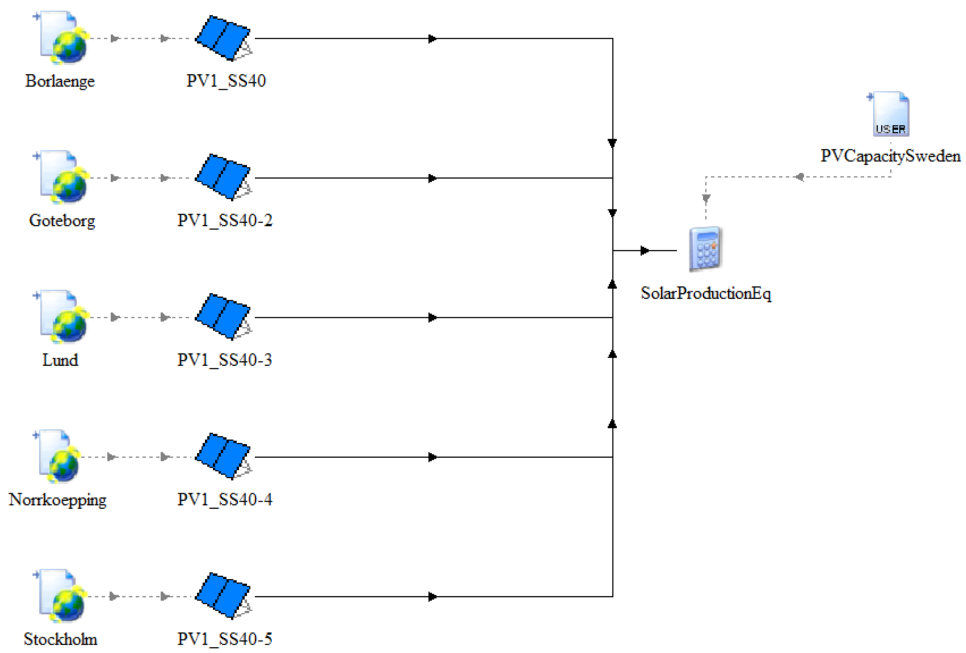

Figure 3.7: Screenshot of the TRNSYS systems model for solar PV generation in Sweden.

As for wind power, the installed capacity of solar PV is calculated from the annual generation expected in 2035 and 2050 with the initial assumption that annual production is 950 kWh/kW as according to Lindahl 2017. Knowing both capacity and power generation in 2016 (Lindahl, 2017), PV installed capacity is linearly interpolated between 2016 and 2050.

The hourly production from solar PV is then calculated through TRNSYS systems model simulation with 1 hour time-step (Figure 3.7). The TRNSYS system model calculates the power generated hourly using photovoltaic array (Type 194) facing South at 40 degree slope with weather files from five different location in Sweden (Borlaenge, Goteborg, Lund, Norrköping, and Stockholm). The installed capacity is considered to be equally distributed among the five location. An overall factor of 85% is used to address losses due to aging, inverter and others. With the assumption done in the TRNSYS model, the resulting annual production is 914 kWh/kW$_p$; therefore, the annual solar generation used in this study is about 4% lower that the expected production assumed by the Swedish Energy Agency's forecast for the same scenario.

3.3.3 Consumption

Similar considerations are done for consumption, but with two main differences. The first is that it is considered the total annual consumption instead of installed capacity. Secondly, the annual consumption is calculated as a share of the total annual production as the consumption is not considered in the analysis done by the Swedish Energy Agency (Swedish Energy Agency, 2016). Equation 3.3 shows the function used for hourly consumption value at a year different than 2016.

$$CNS(h) = CNS_{2016}(h) \times (1 - \Delta_{PRD}) \times \frac{PRD_{tot,y}(h)}{PRD_{tot,2016}} \tag{3.3}$$

where $CNS_{2016}(h)$ is the consumption at the hour h of the year y, the difference between production and consumption coefficient Δ_{PRD} is set to 10%, $PRD_{tot,2016}$ and $PRD_{tot,y}$ are the annual production in the year 2016 and another year, respectively. Renewable supply is curtailed when renewable generation exceeds consumption by 30%.

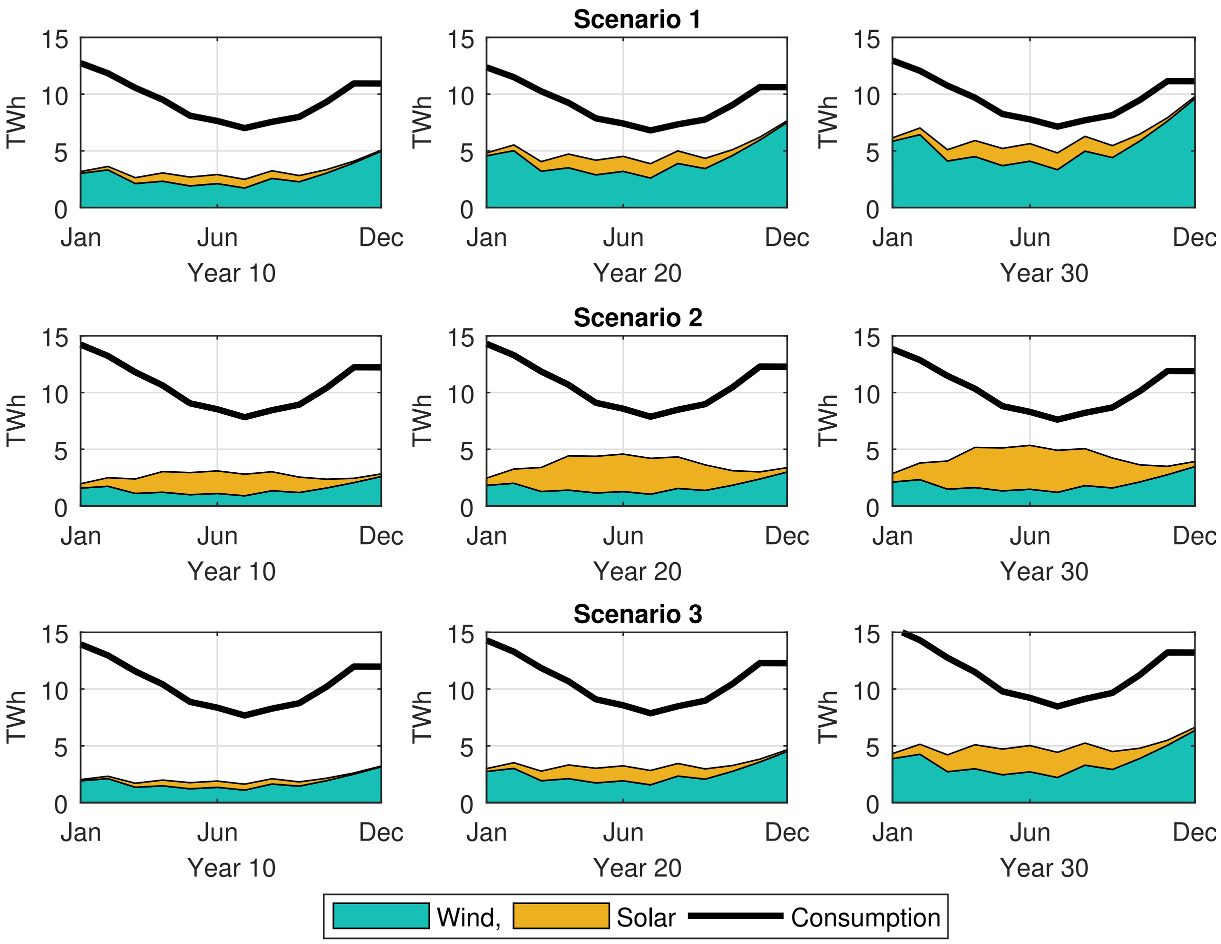

Figure 3.8: Overview of renewable generation and consumption forecast.

The results of power forecast are calculated in hourly value for 30 year. Their annual yield is presented in Figure 3.8 with monthly variation for three representative year. While the consumption is quite stable, as expected there is an increase of renewable production in all scenarios. Wind drives the generation in Scenario 1, while solar in scenario 2. That is the reason why total REN generation has different annual profile in time and scenario. High penetration of solar increases the summer production and seasonal disparity. On the other hand, increase of wind appear to balance the production as it is higher in the winter months.

3.3.4 Spot Price

With the foretasted value of consumption, wind, solar and hydro, the spot price for each scenarios is calculated accordingly with the spot price model described previously. The average results are given in Figure 3.9 to shows the trend over time. Average spot price drop in each scenarios from an initial annual average of 0.29 SEK/kWh. The first scenarios, with the highest share of wind shows the grater price reduction to above 0.15 SEK/kWh after 15 years and about 0.8 SEK/kWh after 30 years. The trend is similar for scenario 2 and 3 that have a 40% price reduction in 30 years, although average spot price after 20 years is double than in scenario 1. Price reduction is be found in historical values from 2010 to 2015 where renewable energy is estimated to count for the 35% Hirth (2016).

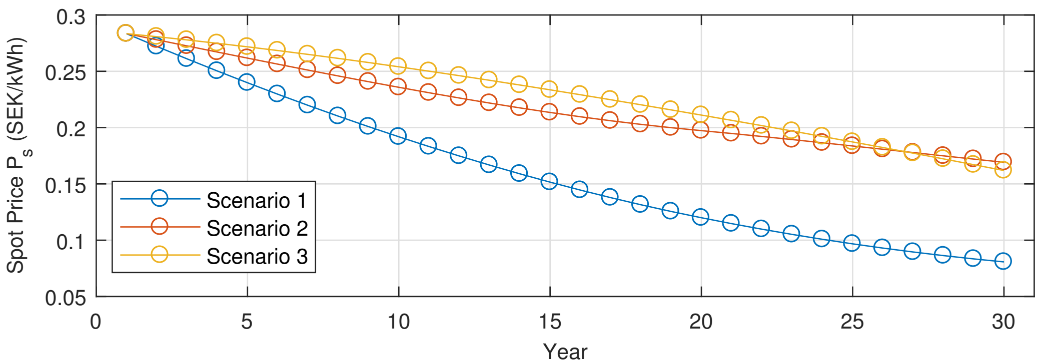

Figure 3.9: Spot price annual average.

3.3.5 Retail Price

Table 3.2: Retail and sales electricity price input value at the first year and annual growth.

Parameter		Unit	Value	Growth Rate
Spot price	P_s	SEK/kWh		*Calculated*
Grid owner compensation	R_g	SEK/kWh	0.02	1%
Grid fees	$P_{g,1}$	SEK/kWh	0.20	1.5%
Retailer profit	$P_{g,2}$	SEK/kWh	0.05	1%
Green support	P_{gc}	SEK/kWh	0.03	0%
Energy Tax	P_{eTax}	SEK/kWh	0.32	1%
VAT	VAT		25%	

Retail price is based on wholesale electricity prices plus network charges and taxes compose as equation 3.4. The output spot price P_s, calculated with the model previously described, is then combined with grid charge $P_{g,1}, P_{g,2}$, green subsidy P_{gc}, energy tax P_{eTax} and VAT. Grid charges consist of grid fees (0.2 SEK/kWh) and retailer profit (0.05 SEK/kWh) (Sommerfeldt, Muyingo, and Klintberg, 2016). An additional 0.03 SEK/kWh is considered for green support (Sommerfeldt, Muyingo, and Klintberg, 2016). Electricity tax and VAT constitute about 44% of retail price for large consumers (20,000 kWh/year) (Swedish Energy Markets Inspectorate, 2017). Hence, energy tax are assumed 0.319 SEK/kWh with a 1% growth rate. A summary of the factors and their growth rate is given in Table 3.2.

$$P_r(h) = \left(P_s(h) + P_{g,1} + P_{g,2} + P_{eTax} + P_{gc}\right) \times (1 + VAT) \tag{3.4}$$

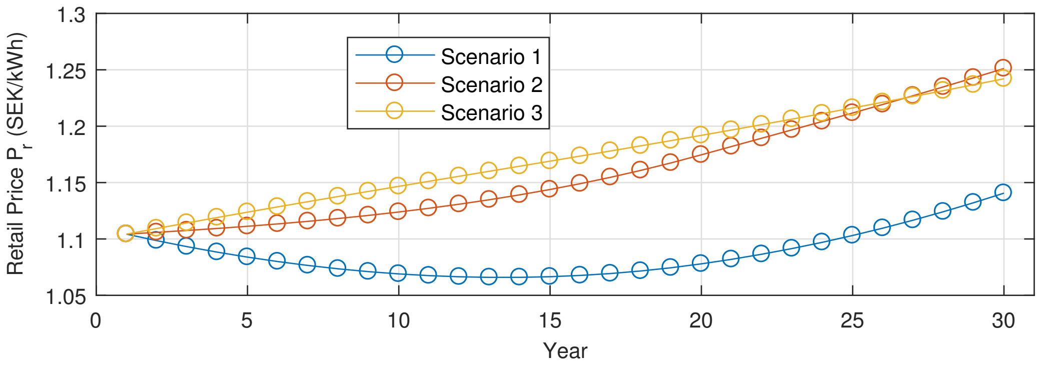

Figure 3.10: Retail price annual average.

The resulting retail price is calculated hourly for each scenario. Figure 3.10 shows the annual average and the trend in the different market prospective. A detailed picture of the factors development during time is given in the Appendix.

3.3.6 Sales Revenue

Sales revenue P_{PV} is the price at which the electricity produced by PV generation is sold to the grid. Revenue price is calculated based on the spot price plus grid compensation as in Equation 3.5. Grid compensation P_g is assumed to a minimum of 0.02 SEK/kWh (Lindahl, 2017) and same growth rate as for retailer profit (1%) (Figure 3.2). At present there are dedicated supports for PV generation (Lindahl, 2017), but it is assumed that with high penetration of PV subsidies are reduced or removed.

$$P_{PV}(h) = P_s(h) + P_g \tag{3.5}$$

As for retail price, hourly price for sales revenue are calculated, while Figure 3.11 shows its trend over time. Sales revenue follows the trend for spot price, decreasing in all scenarios from an initial annual average of 0.3 SEK/kWh to 0.15 SEK/kWh after 20 years in the scenario with lower spot price.

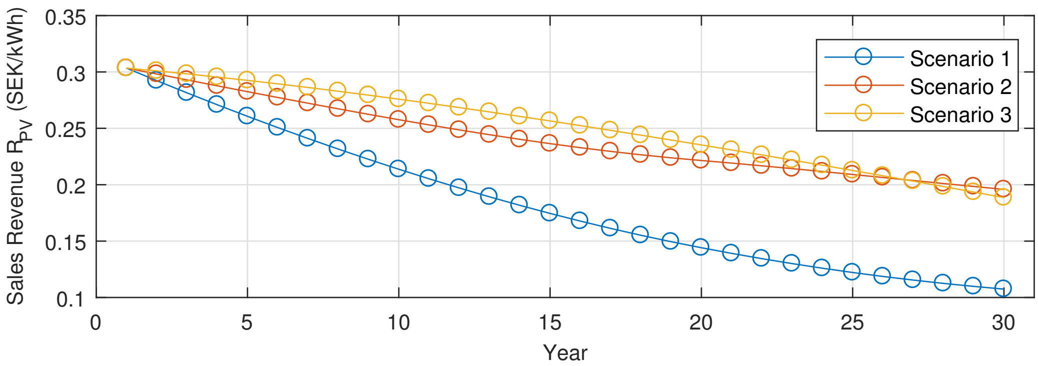

Figure 3.11: Sales revenue P_{PV} annual average.

3.3.7 Threshold Price

The threshold price refers to a price value that represents the limit under which retail prices can be considered low. This price limit is an input value in the operational control of the BH-heater in the PV-GSHP system as described in Model Description. In order to decide when the BH-heater should be turned ON or OFF, the control needs to know in advance the value of the threshold price which it is described here.

As seen early in the chapter, electricity price has hourly fluctuation and annual average price have different trend for scenario. It results that the probability distribution of electricity price changes the annual profile.

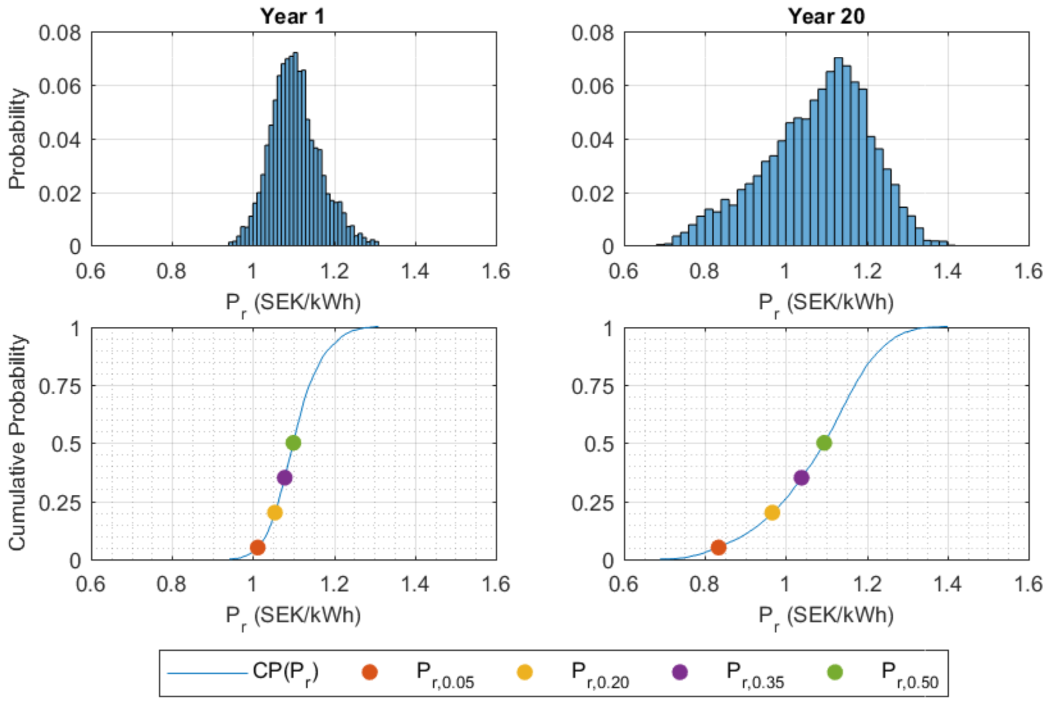

Figure 3.12: Probability and cumulative probability function of retail price.

Figure 3.12 (top graphs) shows the probability distribution of retail electricity price as an example of the first and twentieth year in Scenario 1. Due to the increasing share of VRE, price range spreads and the possibility to find lower price increases. In this circumstance, it is difficult to define a value of low price valid in both years. If retail prices at values lower than 1.0 SEK/kWh are rare and 1.0 is a low price during the first year, it can not be said the same 20 years later when the same value is still in under the average price but it is not that rare and the probability to find cheaper electricity is higher. Similarly, it can be said for high prices.

In this context, level prices can be set only defining a function that defines reference values. Cumulative probability is used to delineate price levels. The cumulative probability function $CP(P_r)$ is defined as the proportion of values less than or equal to that P_r value (The MathWorks, n.d.). If the cumulative probability for a value is 1, 100% of the price lie beneath and then that price is the highest for that year. 0.5 cumulative probability means that 50% of the prices are lower than that value.

Four reference prices are calculated as quantiles for the cumulative probabilities at 0.05, 0.20, 0.35, and 0.5, defining four price level respectively (Figure 3.12, bottom graphs). Reference price values ($P_{r,0.05}$,$P_{r,0.20}$,$P_{r,0.35}$,$P_{r,0.50}$) are referred in this study as threshold price.

4 Model Description

This study is based on one of the system combination presented by Sommerfieldt and Madani 2016. As the model described inherits component and design of the cited project, here it is given only a partial description of the system prioritizing the component more relevant and peculiar to this research. For a complete description of the TRNSYS model refer to (Sommerfeldt, 2018).

The PV-GSHP system model is created and simulated in TRNSYS that is a transient but discrete simulation tool. A steady state solution is reached at every time step. To optimize running costs without undermine the reliability of PV and HP output, a 3 minute time step is used. In TRNSYS the model is build by several components connected to each other with pipes, valves or controls. A screenshot of the model is shown in Figure 4.1 where the main parts are visible.

The structure of the original TRNSYS model is untouched and only the borehole in-line heater and its control are added, plus the economic calculation.

This chapter provides an overview of the model with a detailed description of the BH-heater and its controls introduced in this work.

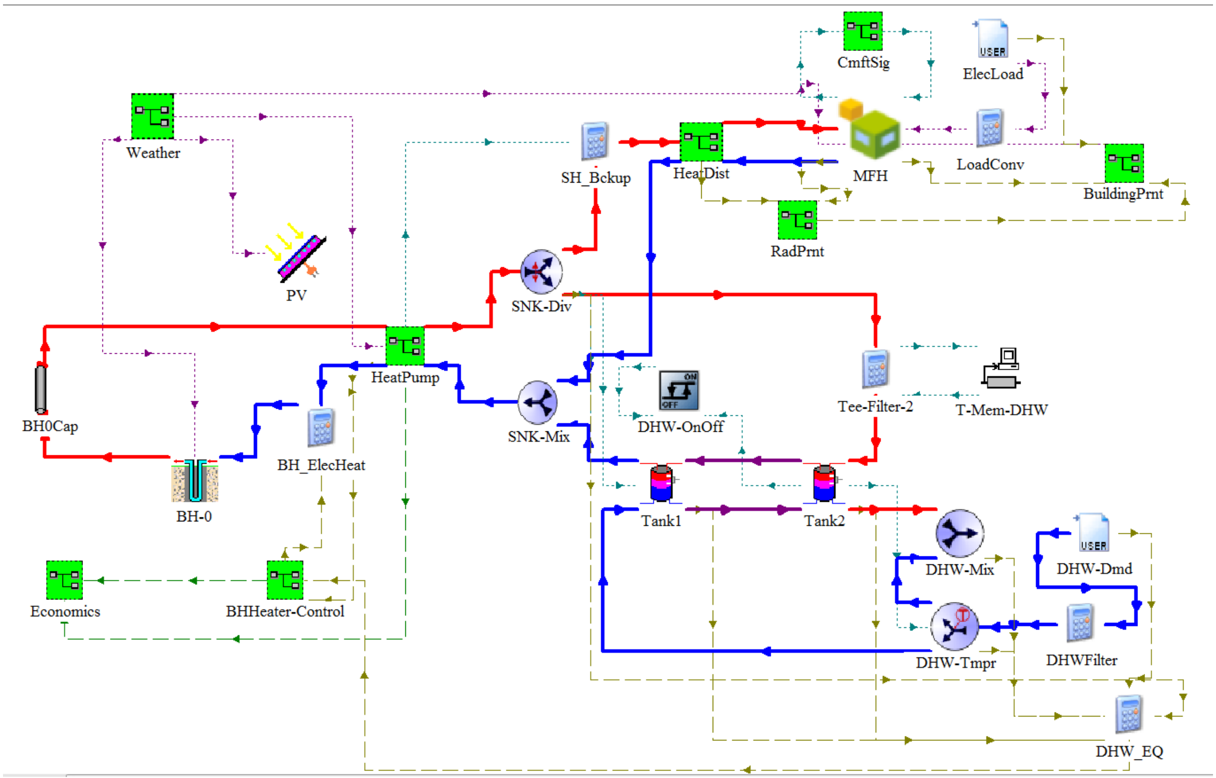

Figure 4.1: TRNSYS system model scheme.

4.1 Climate

The climate conditions differ from the Northern to the Southern part of Sweden. However, this study investigates the performance of the system only for one climatic region and Stockholm weather data as specimen because of the higher population density of the area.

The 3 minute time step is impose solar irradiation that strongly affect the share of PV self-consumption (Cao and Sirén, 2014). From the weather file created by Meteonorm (Remund and Kunz, 2018), the solar radiation is calculated for 1 minute time step with a stochastic method (Hofmann et al., 2014). In TRANSYS climate data are processed and average values are calculated over 3 minutes, while Type 16a process the solar radiation.

4.2 Building

The building is designed to represent a typical Swedish MFH. It is created in TRNSYS with multi-zone building Type 56. The long side of the building faces south with a window-to-wall ratio of 40% and the roof is 20 deg tilted. The net SH demand is 100 $kWh/m^2 - yr$.

Wall-mounted radiators supply the SH demand at a supply temperature set by the heating curve at the HP. DHW require 38 kWh/m^2yr, while internal gains reach 56 kWh/m^2yr.

4.3 Heat pump

The heat pump model present in TRNSYS recreates a variable speed HP with 88 kW rated thermal power. It is a macro-model build from several components. A three-variable interpolator (Type 581) calculates the electricity demand of the compressor $\dot{E}_{comp}$ and heat transfer rate at the condenser $\dot{Q}_1$. The heat transfer extracted from the evaporator is then calculated as

$$\dot{Q}_2 = \dot{Q}_1 - \dot{E}_{comp} \tag{4.1}$$

While the outlet temperature at the evaporator $T_{out,evap}$ and condenser $T_{out,cond}$ are calculated from the inlet temperature T_{in} respectively as

$$T_{out,cond} = T_{in,cond} + \frac{\dot{Q}_1}{\dot{m}_{H2O} \cdot c_{p,H2O}} \tag{4.2}$$

$$T_{out,evap} = T_{in,evap} + \frac{\dot{Q}_2}{\dot{m}_{BRN} \cdot c_{p,BRN}} \tag{4.3}$$

with $\dot{m}$ mass flow rate and c_p heat capacity of water and brine.

The controller for the HP is a proportional/integral controller (TRNSYS Type 23). The HP ON-OFF switch has a temporal limitation of 15 minutes; it means that the HP must stay in the same state for at least 15 minutes.

The heating system is equipped with electric backup heaters.

4.4 Borehole Heat Exchanger

The borehole field is modelled in TRNSYS using Type 557a that is included in the TESS library and based on the Duct Storage model (DST) (Hellström, 1989; Pahud, 2000). This type is created for modelling BTES fields assuming a equally spaced boreholes in a compact array. This limit the reliability for other type of boreholes. A plug-flow pipe is connected to the BHE to reproduce heat transfer when the circulation fluid is paused, not directly implemented in Type 557 (Pärisch et al., 2015).

The borehole is modelled as installed in Swedish granite and ground water filled boreholes (Acuña, 2013). The design tested counts 12 U-tube boreholes with 275 m depth and 20 m distance calculated according to the implemented ASHRAE method presented in (Rolando, Acuna, and Fossa, 2015). Sizing and thermal characteristics of the BHE are presented in Table 4.1. Ground water flow is not considered. The BHE working fluid is a 30/70 ethanol-water mixture.

Table 4.1: BHE parameter in TRNSYS Type 557a.

BH Parameter	Value	Unit
Number		12
Depth	m	275
Spacing	m	20
Diameter	m	0.15
Ground Conductivity	W/mK	2.8
Ground Thermal Capacity	kJ/m^3K	2016
U-tube Inner Diameter	m	0.036
U-tube Outer Diameter	m	0.040

4.5 PV system

Since it inherits a PVT model in place of the PV system, the PVT loop is kept for sake of reliability on the model but the thermal circuit is neutralized, so that the PVT system works like a PV array.

TRNSYS Type 560 is used as PV by turning off the thermal factor. Considering the roof area facing South equal to 266 m^2, up to 144 solar module can be placed for a total area of 236 m^2 and rated power of 40 kW_p.

4.6 Borehole Heater

The BH heater is installed in series with the BHE between the HP evaporator and the borehole field. The working fluid enters the BH heater component *BH_ElecHeat* at the evaporator outlet temperature $T_{out,evap}$ and leave the BH heater at the outlet temperature $T_{out,BHHeat}$ calculated as

$$T_{out,BH} = T_{out,evap} + \frac{\dot{Q}_{BH}}{\dot{m}_{BRN} \cdot c_{p,BRN}} \tag{4.4}$$

where $\dot{Q}_{BH}$ is the heat rate of the BH heater. This depends on the nominal electric power of the heater $\dot{E}_{BH}$, its efficiency η_{BH}, and the control signal δ:

$$\dot{Q}_{BH} = \delta \cdot \dot{E}_{BH} \cdot \eta_{BH} \tag{4.5}$$

The control signal δ is sent by a BH-Heater controller and ranges between 0 and 1. A detailed description of its value is given in the Control Strategy section.

Two different type of heater are investigated: electric boiler and air source heat pump. Efficiency is assumed 1 for the electric boiler, while it is 3 for the heat pump which is assumed to have a constant COP. The base case considers a 30 kW_{th} electric boiler, while other rated power are analysed in the results. Despite the higher efficiency of the heat pump, the electric boiler is preferred for this application because its reliability to work under discontinuous and irregular periods, while hp are more vulnerable.

4.7 Control Strategies

The BH heater is regulated with a smart controller that in TRNSYS is modelled as a *macro* in which economic and electric input are perused.

4.7.1 PV-Control

The BH heater operates only when there is surplus in PV generation in order to maximise self-consumption. This SC-control (or *PV*-control) algorithm defines whether the electrical load of the HVAC system is lower than the PV power generated on the same moment. If it is, the heater is turned on according to the power surplus, otherwise the heater is off. The BH heater is assumed to allow a minimum load 30% the rated electric power. The control signal δ_{PV} is calculated as

$$\delta_{PV} = \begin{cases} 0 & \text{if} \quad \dfrac{\dot{E}_{PV} - SC_{hvac}}{\dot{E}_{BH}} < 0.3 \\ \dfrac{\dot{E}_{PV} - SC_{hvac}}{\dot{E}_{BH}} & \text{if} \quad 0.3 \leqslant \dfrac{\dot{E}_{PV} - SC_{hvac}}{\dot{E}_{BH}} \leqslant 1 \\ 1 & \text{if} \quad \dfrac{\dot{E}_{PV} - SC_{hvac}}{\dot{E}_{BH}} > 1 \end{cases} \tag{4.6}$$

The control calculates SC_{hvac} at each time step as the sum of the electricity consumption of GSHP compressor, pumps at the condenser and evaporator, and DHW auxiliary heater.

4.7.2 EP-Control

The second control (*EP*-control) adds to the SC-control a price strategy. That means that the boreholes heater is operating at maximum power when the electricity price falls below a certain limit. Threshold price P_o is tailed by annual retail price distribution as described in Chapter 3.3.7. The resulting signal δ_{EP} is the maximum value between PV signal δ_{PV} and price signal δ_p (Equation 4.7,4.8).

$$\delta_p = \begin{cases} 0 & \text{if} \quad P_r > P_o \\ 1 & \text{if} \quad P_r \leqslant P_o \end{cases} \tag{4.7}$$

$$\delta_{EP} = max(\delta_{PV}; \delta_p) \tag{4.8}$$

4.8 Economics

Costs are calculated for each component depending on fixed and variable costs, which have large uncertainty. The overall investment cost for the heat pump are estimated around 375 thousand SEK inclusive of 25% VAT. The investment required for the borehole field is based on a drilling cost model that takes into account the number of holes and their depth plus some additional cost (Sommerfeldt, 2018); the total amount is about 1.3 million SEK (w/VAT).

The price for PV modules varies with the size of the installed system. Since the large system considered, the price for power unit is 14.5 SEK, which is the price for large commercial (Lindahl, 2017) inclusive of VAT. Total cost amounts to 406 thousand SEK when considering current direct PV subsidy at 30% of the total cost.

Equipment costing for BH heater are assumed and not verified with real example. The price of BH electric boiler is estimated to be 100 SEK/kW at the nominal power with 7,000 SEK of fix cost for installation. Variable and fix costs for an air source heat pump are expected to be around 15,000 SEK/kW_{el} and 27,000 SEK respectively. With this assumptions a 30 kW_{th} boiler costs 12,5 thousand SEK, while the heat pump with same thermal power is worth 315 thousand SEK. More details are given in Appendix.

The economical cash flow is evaluated in TRNSYS at each time step with a dedicated macro. Retail and sale electricity prices are input in TRNSYS as constant hour value. The way the electricity cost are obtained are widely described in Chapter 3.

4.9 Performance Indicators

In order to perform a techno-economic analysis of the system, it is necessary to define clear boundary conditions so to provide clear results. The PV-GSHP system model in this study is complex because it is made up of several components interacting and integrated in a comprehensive environment, that is the building.

Although analysing the system at the building level would be more exhaustive, this study aim attention to a restricted system with consist of PV system and GSHP. The GSHP is by is own a subsystem composed of several components whose of most importance are the heat pump, the borehole field and the borehole in-line heater (BH heater).

Heat transfer and electricity flows are exchange within and outside the system boundary. The building in which the system is integrated has a thermal and electric demand. The thermal demand is supplied by the heating system, here analysed.

Heating, ventilation and air conditioning system, known as HVAC, includes the thermal demand for domestic hot water DHW and space heating SH for the dwellings in the building. Its power consumption is composed of the electrical demand of heat pump and auxiliary heaters. The components counting for electrical demand of the heating system E_{hvac} are compressor E_{comp}, circulation pumps E_{pump}, auxiliary heater E_{aux} and boreholes in-line heater E_{bh}.

$$E_{hvac} = E_{comp} + E_{pump} + E_{aux} + E_{bh} \tag{4.9}$$

The following section explains the key performance indicators (KPI) and the boundary conditions applied for the evaluation of the system model as self-consumption, solar fraction, seasonal performance factor. The method used for the economic value is presented according to the total life circle cost.

4.9.1 Self-Consumption

Self-consumption of the HVAC system SC_{hvac} is calculated as the PV power E_{PV} consumed by the heating system electric load E_{hvac} and measured with 3 minutes time steps as

$$SC_{hvac} = min(E_{PV}, E_{hvac}) \tag{4.10}$$

It is also presented as a share of the total PV generation as

$$SC_{hvac}\,(\%) = \frac{min(E_{PV}, E_{tot})}{E_{PV}} \tag{4.11}$$

Similarly, self-consumption is calculated specifically for the BH heater as

$$SC_{bh} = min(E_{PV}, E_{bh}) \tag{4.12}$$

$$SC_{bh}\,(\%) = \frac{min(E_{PV}, E_{bh})}{E_{PV}} \tag{4.13}$$

4.9.2 Solar Fraction

Solar fraction SF, also called self-sufficiency (Luthander et al., 2015), is the share of PV power covering the electricity demand of the heating system (Eq.4.14). For comparison, the solar fraction is also calculated for the borehole heater in particular as in Equation 4.15.

$$SF_{hvac} = \frac{SC_{hvac}}{E_{hvac}} \tag{4.14}$$

$$SF_{bh} = \frac{SC_{bh}}{E_{bh}} \tag{4.15}$$

4.9.3 Seasonal Performance Factor

The seasonal performance factor *SPF* evaluates the performance of GSHP and it express the efficiency of the overall system including all auxiliary components such as circulation pumps, storages, and backup heaters (Hadorn, 2015). Three index for SPF are presented that refer to different system level and boundary conditions.

SPF_1 is the total heat supplied at the condenser Q_{cond} to the electric consumption of the compressor E_{comp}, which is also known as COP (Coefficient of Performance) and it is relative to the heat pump itself.

$$SPF_1 = \frac{Q_{cond}}{E_{comp}} \tag{4.16}$$

A second index of performance of the GSHP is presented in equation 4.17 where boundary conditions are enlarged. SPF_4 defines the efficiency of the GSHP by the final heat provided to supply the heating demand (hence Q_{DHW} and Q_{SH}) to the total power consumed by the HVAC system E_{hvac} calculated as in Eq.4.9.

$$SPF_4 = \frac{Q_{SH} + Q_{DHW}}{E_{hvac}} \tag{4.17}$$

Finally, SPF_5in Eq.4.18 represents the seasonal performance factor of the GSHP as in SPF_4 including the HVAC self-consumption. This assumption encourage the use of higher share of self-consumption weighting differently the source of electricity whether from the grid or from the PV system.

$$SPF_5 = \frac{Q_{SH} + Q_{DHW}}{E_{hvac} - SC_{hvac}} \tag{4.18}$$

4.9.4 Total Life Cycle Cost

Total life cycle cost TLCC is the parameter used in this study to assess the economic value of the systems tested. The comparison is done based on the TLCC of the PV-GSHP system. The TLCC is the net cost for component during the system lifetime. The system lifetime is assumed to be 20 years as expected to last the HP. On the other hand, PV systems decay after 30 years while BTES have 60 years lifetime. For this reason, their longer life is rewarded with a residual factor RV_{BHE} for boreholes field and RV_{PV} for PV array. Investments costs for heat pump I_{HP}, boreholes field (I_{BHE}), BH heater (I_{bh}) and PV system (I_{PV}) are calculated together with the net operating costs for electricity ($C_{el,net}$) in Equation 4.19 that is the system TLCC for 20 years lifetime.

$$TLCC_{hvac} = I_{HP} + I_{BHE} + I_{bh} + I_{PV} + C_{el,net} - RV_{PV} - RV_{BHE} \tag{4.19}$$

The cost of electricity takes into account the expenses for retail electricity P_r relieved of the return from PV electricity sold to the grid at the price P_{PV}. The discount rate d is set at 3% and it is real as all the prices in this study.

$$C_{el,net} = \sum_{y=0}^{19} \left(\frac{E_{hvac} \times P_r - (E_{PV} - SC_{hvac}) \times P_{PV}}{(1+d)^y} \right) \tag{4.20}$$

The present value of PV generation represent the residual value of the PV array calculated with annual average price of electricity and PV generation as at the 20^{th} year with degradation rate of 0.3%.

$$RV_{PV} = \sum_{y=20}^{29} \left(\frac{SC_{hvac} \times \overline{P}_r + (E_{PV} - SC_{hvac}) \times \overline{P}_s}{(1+d)^y} \right) \tag{4.21}$$

The residual value of the boreholes is calculated with the Equivalent Annual Cost EAC method so that the costs of the BH investment cost is distributed over time (Eq.4.22).

$$RV_{BHE} = \sum_{y=20}^{59} \left(\frac{I_{BH}}{1-(\frac{1}{1+d})^{59}} \cdot \frac{d}{(1+d)^y} \right) \tag{4.22}$$

5 Results

The results of a GSHP system coupled with a boreholes in-line heater as previously described are reported in this chapter. The results address the performance of the system for different power, control strategies, and electricity market scenarios. A one-year simulation introduces the model's behaviour in details before presenting the achievement of the storage system in the long term. The results of a sensitivity analysis are presented on selected input values for economic indicator. The outcomes of the original GSHP system without boreholes heater represent the baseline in to the performance of the other configurations. An outline of the main parameters of the baseline are presented in Table 5.1.

Table 5.1: Performance indicator for the base GSHP system without BH heater.

Indicator	Year 1	Year 10	Year 20
PV generation (MWh/yr)	36.4	35.5	35.5
HVAC Electricity Demand (MWh/yr)	73.2	75.8	76.9
SF_{hvac} (%)	15.5	15.0	14.9
SC_{hvac} (%)	31.7	32.1	32.4
SPF_1	3.71	3.62	3.57
SPF_4	3.50	3.42	3.37
SPF_5	4.11	4.00	3.94
Avg. BH Temperature (°C)	4.11	4.00	3.94
TLCC		2.34 million SEK	

5.1 System Behaviour

This section describes the operational mode of the GSHP with storage over a short period in order to provide the necessary explanation for its behaviour over the system lifetime. One year simulation is presented for the GSHP system coupled with a 30kW electric boiler run by PV production surplus. As to clarify also price control behaviour, the energy flows is given for the same configuration but running under favourable electricity price. The results for the system configurations presented aim to show the operational mode and energy flows similar to all layouts, while performance and comparison are provided later in the chapter.

5.1.1 Self-Consumption Control Strategy

The graph in Figure 5.1 shows the electrical energy flows of the system including the GSHP system coupled with PV and BH heater over one year. Electricity consumption for the heating system is compared to the PV generation, demonstrating the mismatch between the solar availability and demand during the summer and winter season. The use of BH electric heater increases the consumption when the PV production is higher. The line on the graph represents the HVAC electric demand for the baseline system without BH heater. It highlights the increase in consumption during summer due to the use of the BH heater, but no reduction during other seasons with the current type of power and control.

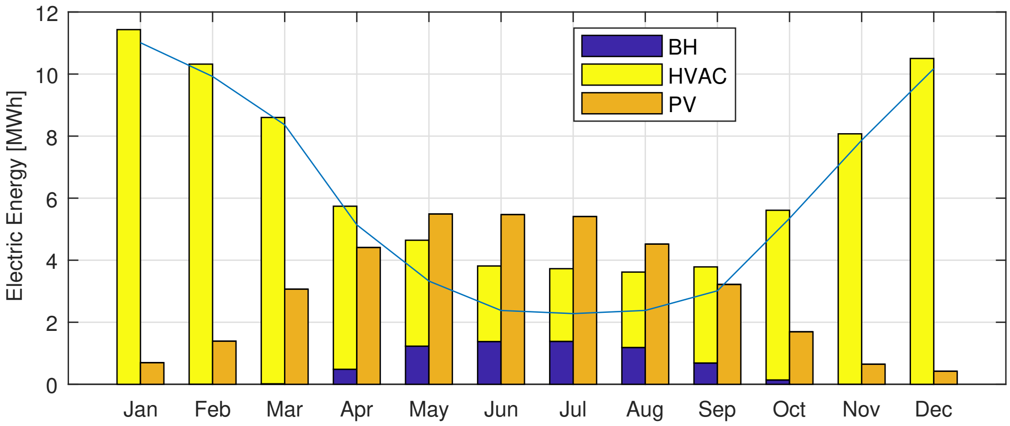

Figure 5.1: Electric energy flows of the PV-GSHP system with BH heater.

A more detailed use of PV generation is given in Figure 5.2. The results shows that the major consumers is dwellings appliances because of the lower use of the heating system for higher irradiation months. With the introduction of BH heater it would be expected a lower share going to the buildings. The reason for higher building self-consumption than the BH heater is that the instantaneous generation is lower than the minimum power necessary for the functioning of the BH heater at minimum power, in particular during spring and autumn. This is expected to improve when using air heat pump as BH heater because of the lower electricity required for the same nominal thermal power, while increasing the size of the electric boiler would leave the situation unchanged or increase the difference. The use of electricity from the PV system is virtually managed so that the primary user is the heat pump system, followed by the BH heater and then other load in the building, so that eventual surplus from all the load in the buildings is finally sold to the grid. This assumption is fundamental as considering the building the primary user would considerably reduce the PV share consumed by the heat pump and the heater.

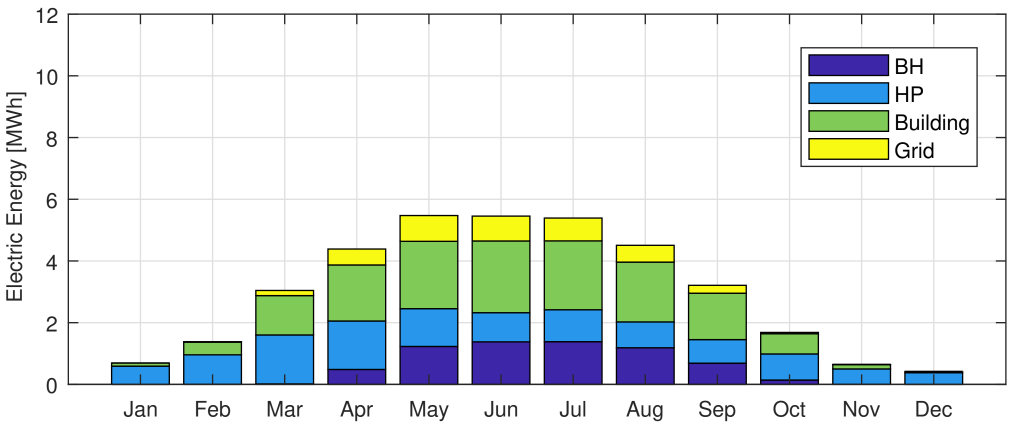

Figure 5.2: PV generation

Figure 5.3 presents the heat flows of the GSHP and BH heater system. The heat demand for heating and DHW is supplied by the heat pump at the condenser side, here expressed as HP. On the other side of the heat pump, the BHE supplies thermal energy at the evaporator following the demand. From March to September, the BH heater contributes to heat supply at the boreholes. Comparing the thermal and electric energy flows graphs it appears that the BH heater has a stronger impact on the electric side than in the thermal. For the low heat to the BHE, the net flow at the boreholes is negative. Hence, storage would be possible only with a larger heater or more working hours, later evaluated with other control strategy and power.

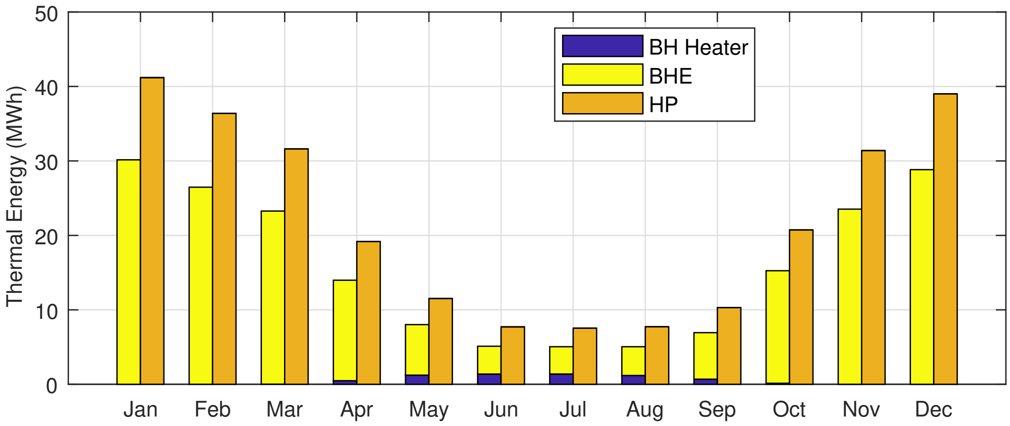

Figure 5.3: System thermal energy flows.

The details of BH heater behaviour is presented in Figure 5.4 during one operational day at the end of May. The graph on the top shows the extra power generated by the PV array at each time step and the thermal power of the electric heater in accordance with the control signals in the graph at the bottom. The $ON-OFF$ signal shows whether the heater is working, while the power signal define its intensity as a results of the available PV surplus. The total heat injected is 80 kWh with a peak power reaching the nominal 30 kW. Low extra PV power at 6 am and 5 pm does not allow the BH heater to operate even at minimum power. Temperature profile around the BH heater is presented in the central graph. When the BH heater is turned on, the outlet temperature T_{out} increases and, generally, the temperature at the outlet of the BHE $T_{bh,out}$ is also disturbed. The results demonstrate the advantage to use a variable power control for the BH heater under PV control in order to maximise the heat supplied.

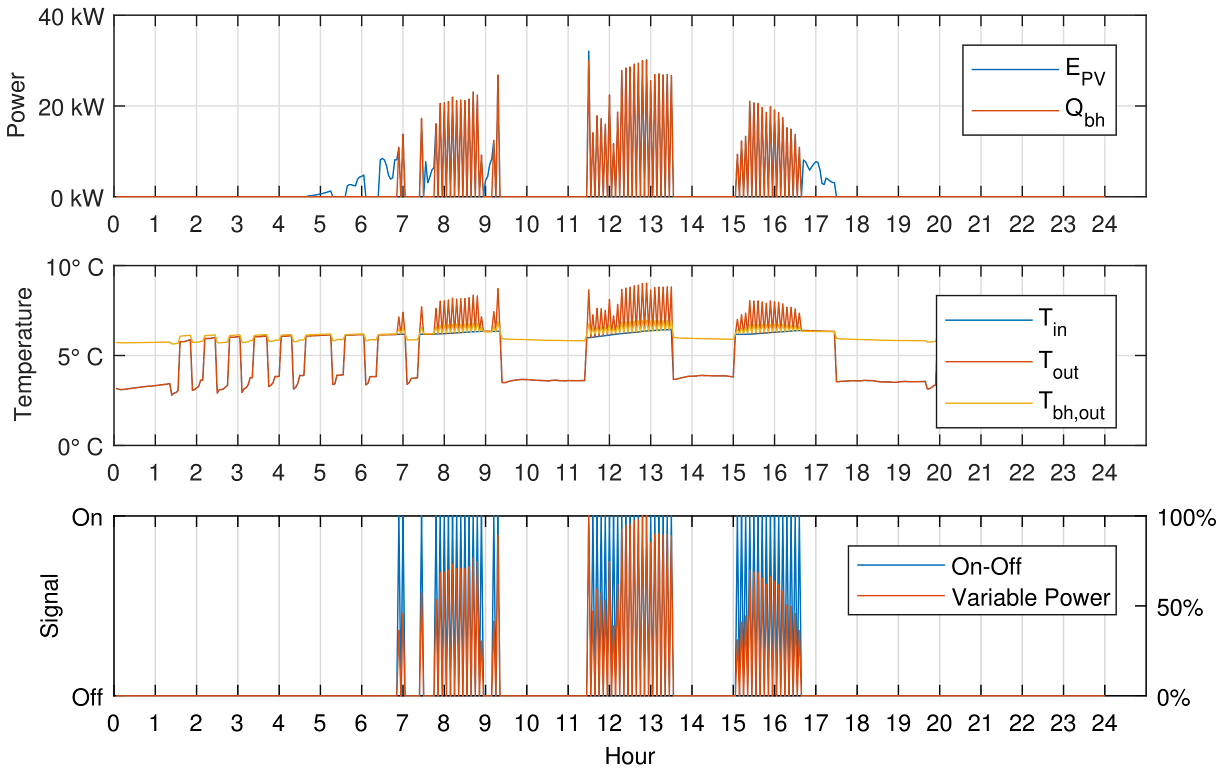

Figure 5.4: Boreholes in-line heater control and operative mode. Simulation for one day with a time scale of 3 minutes.

Later in the study, performance of different systems are compared with the use of KPIs. For the system here described, the total self-consumption SC_{hvac} is 17.9 MWh for the first year, that means 49% of the total PV generation goes to the HVAC system with a solar fraction SF_{hvac} equal to 22%, while the total building SC reaches 89%. The BH heater, that works only when there is PV surplus, consumes 6.5 MWh/yr that means 18% SC_{bh} and SF_{bh} equal to 10%. Due to the control, those values are stable over the system lifetime. In general, during summer the SF increases while the SC decreases because of the higher PV production. The performance of the GSHP is evaluated with different value of SPF. When considering the GSHP energy flow limited at the heat pump itself (i.e. compressor demand and heat delivered at the condenser), the SPF_1 is 3.71 which correspond to the one of the system without heater. Considering larger boundaries and including the BH heater among others, the SPF_4 decreases to 3.22, while subtracting the HVAC system self-consumption increases the SPF_5 to 4.12. The results shows that there are no technical benefit gained by using the BH heater with 30 kW power boiler and self-consumption control. Other configurations in terms of power and control are evaluated in the following sections.

5.1.2 Price Control Strategy

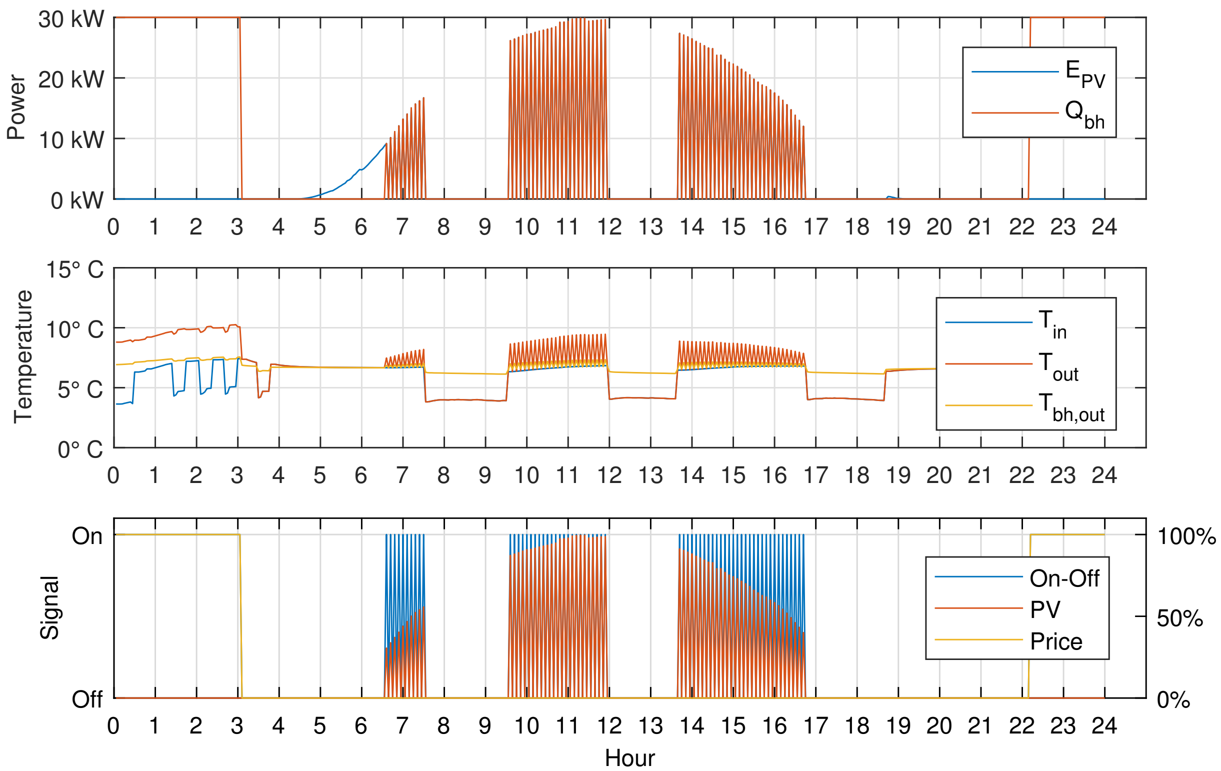

Figure 5.5: Boreholes in-line heater price-control and operative mode. Simulation for one day with a time scale of 3 minutes.

The increase of wind and PV generation in power generation is expected to increase the electricity price volatility in Sweden, process taking place in other country, as Germany, where VRE integration in the national grid is ahead. The electricity price model described in the Electricity Market and Forecast chapter confirms this trend also for the Swedish market. Thus, the results for the second control of the borehole in-line heater are here presented. As explained in the the Model Description, another strategy to charge the boreholes is to take advantages of increasing price fluctuation and turn on the BH heater when the electricity price is lower. Figure 5.5 provides an example of the working operation of the BH heater under cost-optimization control

(*EP*). When the price signal is positive, the BH heater turn on at maximum nominal power. In the day showed, the electricity price does not go under the limit during the day, so that the two signal do not overlap. When it happens, the system would benefit of maximum power and maximum self-consumption at the minimum price.

Borehole field has a natural fluctuation on temperature during the year, which influence the heat transfer to the GSHP. One effect is on the outlet temperature of the BTES, which is influenced by the control of the BH heater (Figure 5.6). There are two main effect on the temperature outlet, seasonal and on the long-term. The seasonal fluctuations vary the monthly average outlet temperature between winter and summer of about 2.5°C during the first year without heater or with low BH heater activity. When the working rate of the BH heater is increase by increasing the threshold price, there is an increase of outlet temperature up to 1.7°C when the threshold price correspond to the median price for the same year. On the long term, there is a decreasing trend for the temperature outlet in general, systems with higher threshold price control (EPx20, EPx35, EPx50) are more stable over time.

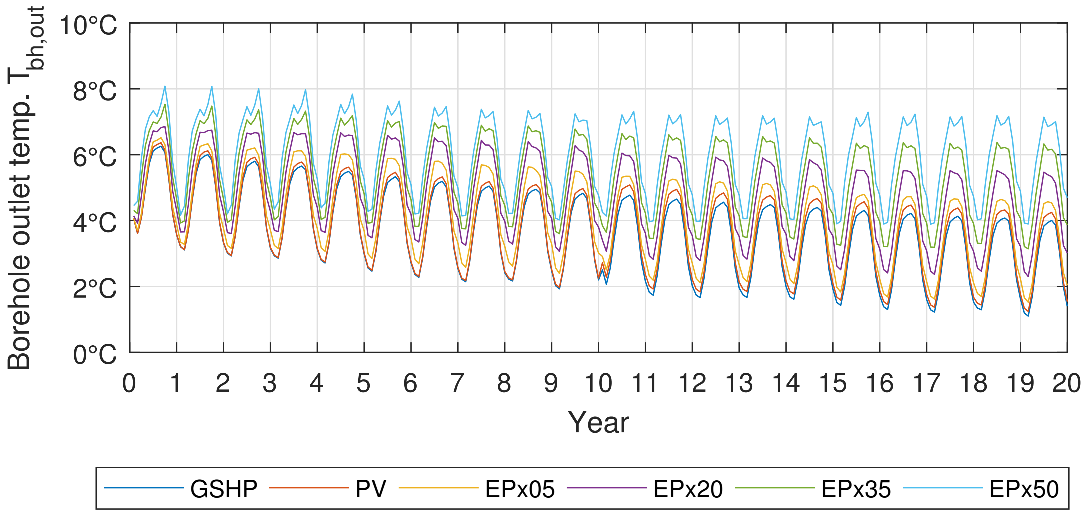

Figure 5.6: Boreholes outlet temperature when different control strategies are applied.

5.2 BH Heater Parametrics

Table 5.2: BH heater parametrics.

Type	Code	Thermal Power kW	Electric Consumption kW
Electric Boiler	Eh 30	30	30
	Eh 50	50	50
	Eh 70	70	70
Heat Pump	HP 30	30	10
	HP 45	45	15
	HP 60	60	20

To analyse the effect of the in-line heater on the storage performance, two categories of boiler are tested with different nominal power. As aiming to store electricity in form of thermal energy, an electric boiler is firstly analysed which is assumed to have 100% efficiency, hence the thermal power supplid is equal to the electric load required. Electric heater (Eh) is tested for 30 kW, 50 kW and 70 kW. The second type used is a air source heat pump (ASHP) that is assumed to have a fix COP equal to 3. Hence, the thermal power supplied is 3 times the electric power consumed. In this case, HP size tested are 30 kW, 45 kW and 60 kW thermal power in order to compare the two types. Thermal and electric power of the heater tested are presented in Table 5.2.

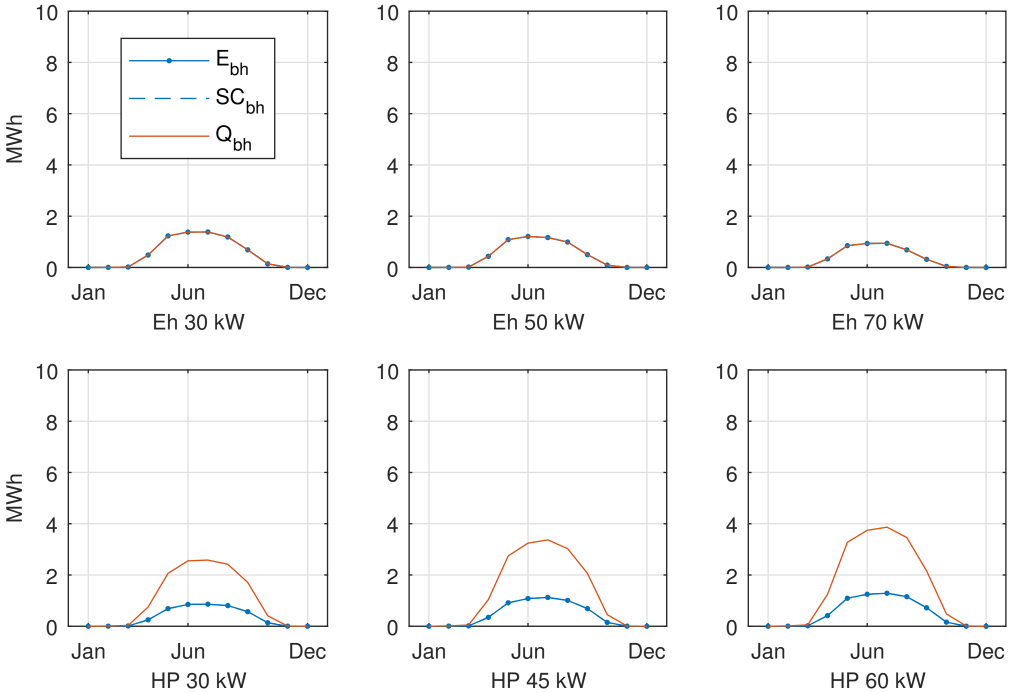

Figure 5.7: BH heaters energy flows under self-consumption control.

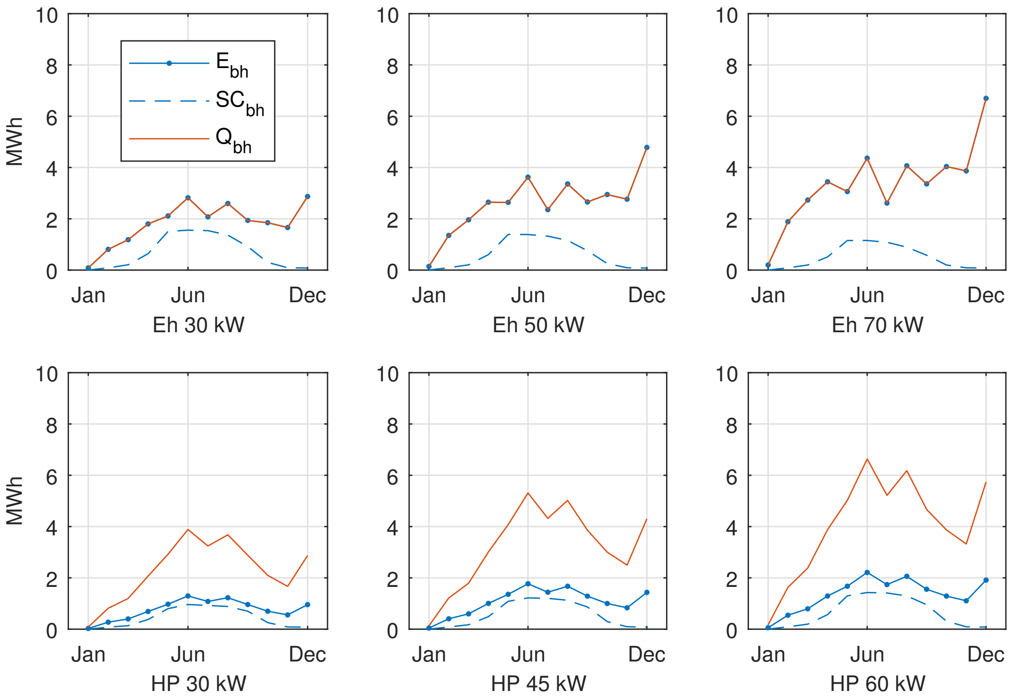

Figure 5.8: BH heaters energy flows under price control.

Electric consumption and heat delivered to the BTES differ for each type of BH heater. An annual analysis of the BH heater energy flows is presented for each type of heater operating under self-consumption control (Figure 5.7) and price control at the lowest threshold price (Figure 5.8). Increasing the size of the BH heater acts in different way depending on the control strategy used. Under self-consumption control increasing the size decrease operative time of the electric BH heater so that both electric consumption and self-consumption share decrease. As a consequence, the heat supplied is reduced. Contrarily, increasing the size of the heat pump as BH heater boosts the thermal energy to the BHE together with increasing self-consumption. This is due to the better use of limited amount of PV surplus. Comparing electric boiler to heat pump, the use of heat pump at same thermal power is also more thermally convenient, especially considering larger size (60 and 70 kW_{th}), when the heat provided is several time larger than with boilers. Under price control strategy the nominal power of the heater is more influential and directly affects its load. In general, heat pumps have higher share of self-consumption, although the absolute value of SC are higher in the case of 30 kW boiler. To note the larger heat flow during summer for BH heat pumps compare to boilers. Opposite, the difference is less remarkable when electricity price are lower.

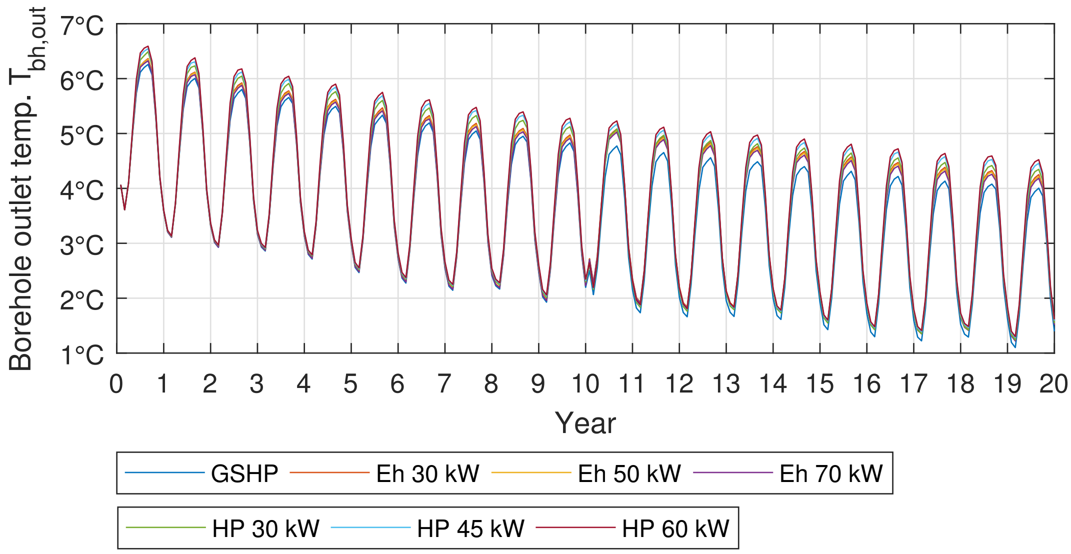

Figure 5.9: Boreholes outlet temperature for self-consumption control.

Figure 5.9 presents the impact of the size of the BH heater on the temperature at the outlet of the BHE. Compared to control strategies (Figure 5.6), the heater thermal power has less influence on the boreholes. In particular, the temperature is increased only during summer months, while the long-term effect is undetectable. Among the heaters, heat pumps increase the outlet temperature slightly more than the electric heater.

5.3 Performance Indicators

The overall results of the performance of the system model are given in this section. Value of the KPI described in the Performance Indicator chapter are here presented for different configuration and compared. Analyses of the technical indicators include the results under different price scenarios not yet introduce. Although electricity prices influence the economic analysis that will follow shortly after, fluctuation on the electricity prices affect also the operation of the BH heaters under price control strategies without modify the system behaviour.

5.3.1 Self-Consumption

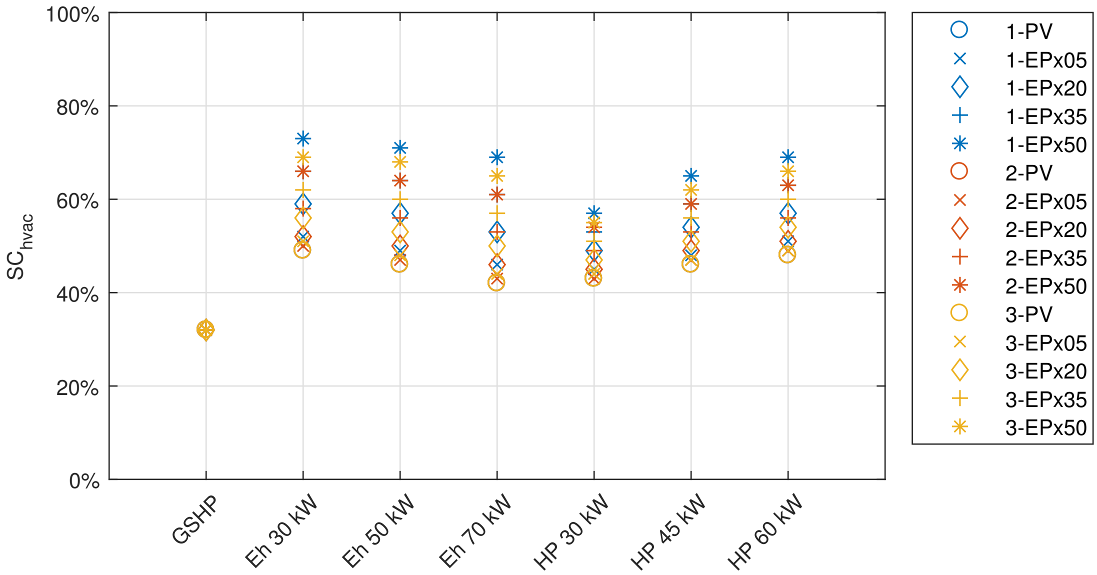

Figure 5.10: Self-consumption for the HVAC system.

As seen in previous sections, electricity consumption varies through the year for the HVAC system as for the BH heater. In order to compare different configuration through they life time, the overall values for self-consumption SC and solar fraction SF are analysed during the whole simulation time, that is 20 years. Figure 5.10 provides an overview of self-consumption as percentage of the total PV generation for all the system configurations in terms of power, control and scenario (1 to 3). Results show that use of BH heater increases the SC of HVAC system. The baseline without heater had a SC equal to 30% while the addition of BH-heater increases SC from a minimum of 40% to more than 70%. Larger SC is achieved for price control strategies with a relatively high threshold price because of the greater consumption and it affects especially electric boilers. A self-consumption control strategy (in the graph as 1-PV/2-PV/3-PV) has the lowest impact on the self-consumption on the BH heater and on the total HVAC system because of the limits to the minimum power needed to switch the heater on. SC values for the BH heater can vary from 10% to 70%. Similar to the HVAC SC, the SC tend to decrease with increasing nominal power for the boiler but increases for HP, as already observed in the previous section. SC_{bh} values are reported in the Appendix.

5.3.2 Solar Fraction

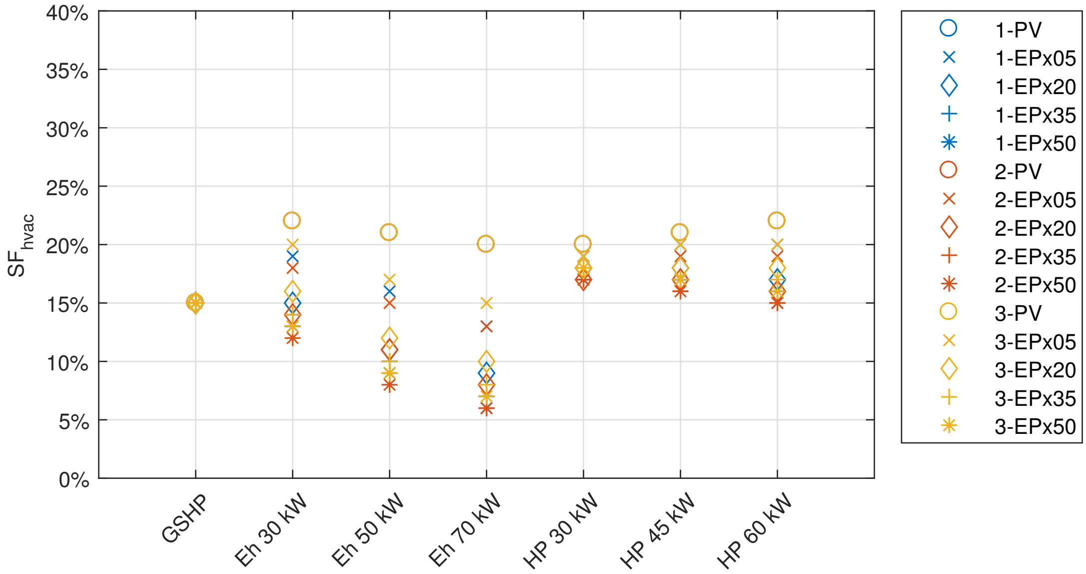

Figure 5.11: Solar fraction for the HVAC system.

Naturally, the higher shares of solar fraction are reached under self-consumption control both for the BH heater only and the whole HVAC system. The solar fraction of the HVAC system is larger for the systems with heat pumps compare to the baseline system without storage, while electric boiler swings from 5 to 20% SF depending on the nominal power and control. Although BH-heater SF can approach 100%, the HVAC values achieve maximum 23% of solar share. As expected, the increase of threshold in price control affects and reduces the solar fraction. The most effective example is the 70 kW electric boiler system whose SF is reduced from 20% to 15% by using price control strategies.

5.3.3 Seasonal Performance Factor

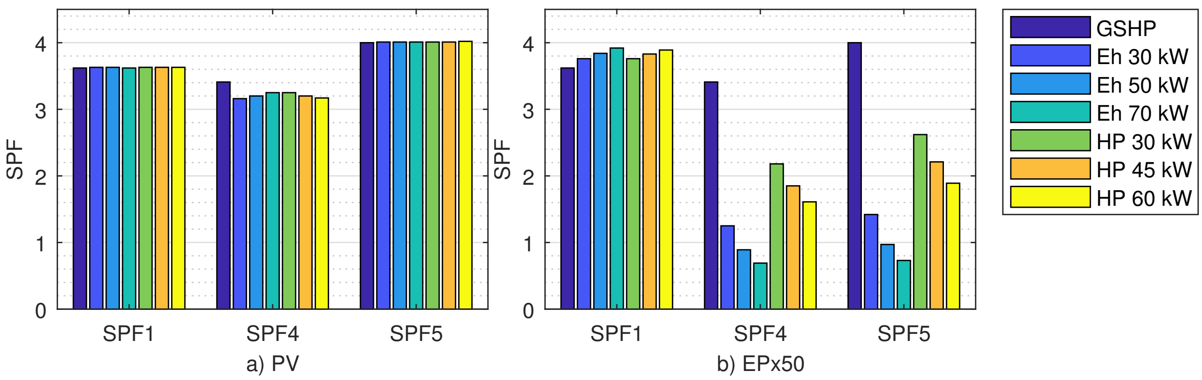

Figure 5.12: Seasonal Performance Factor. Systems under a) self-consumption control (PV) and b) price-control and maximum threshold price (EP-50).

One aspect to take into account when assessing the performance of storage with GSHP is to review the performance of the GSHP itself. Figure 5.12 provides the overall results for the systems configuration under self-consumption control and price control at the higher threshold. Those represent the limit cases respectively with the smallest and larger effect on the SPF of the GSHP, while other controls lie in between. The SPF_1 is rather stable for limited BH operation

(PV-control), while it slightly improve from 3.6 to a maximum 3.9 for about 60 kW thermal power heater (both boiler and HP). When enlarging the boundary conditions to the consumption of the BH heater, SPF4 decreases to about 3 under PV-control, but it drops to 1 in the worst case of large electric boiler and price control. Use of heat pumps in place of boiler reduces the losses and twofolds SPF_4 and SPF_5. The system benefits from self-consumption and SPF_5 is higher than SPF_4, although the system without BH heater is still higher.

5.4 Economic Analysis

The economic value of the system model is described by the total life cycle cost (TLCC) analysis. The results represent the TLCC of the HVAC system inclusive of the BH heater.

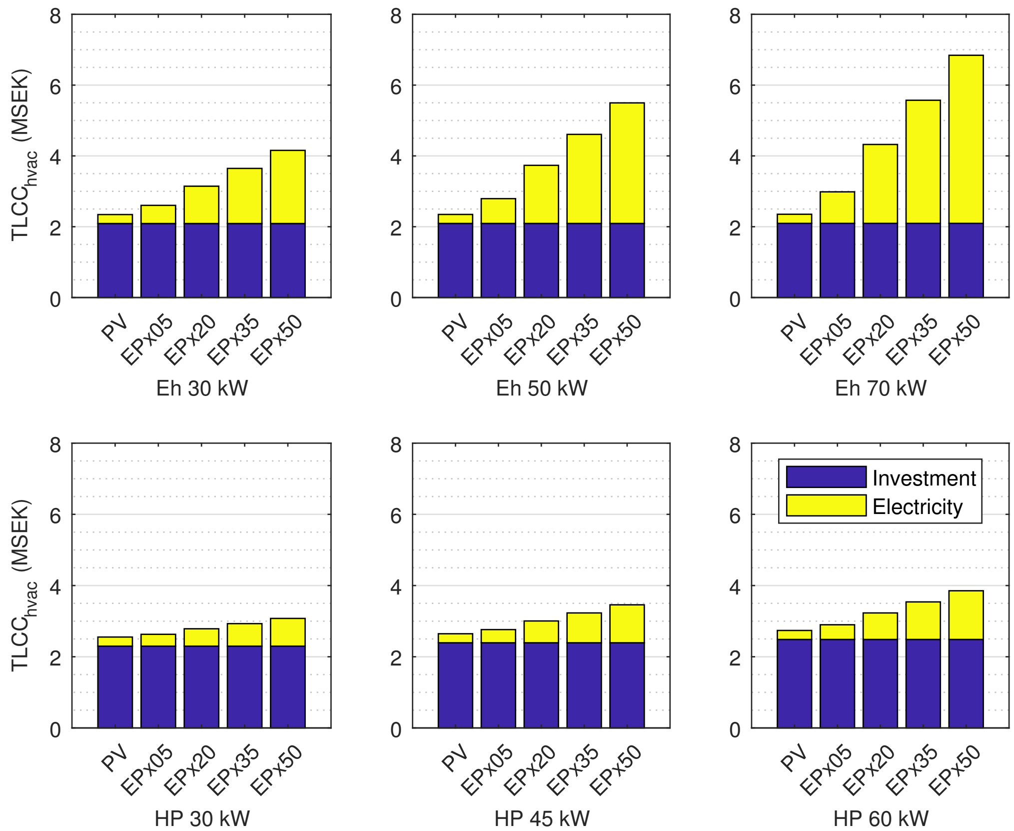

Figure 5.13: TLCC of the HVAC system for BH-heater type under different control.

Graphs in Figure 5.13 provide a overview on the TLCC for each BH heater with detail of investment and electric costs during the system lifetime. Compared to the baseline system without BH heater, the TLCC of system with storage have higher costs due to the increased electricity demand in particular under price-control and using electric boiler. Investment costs represent the larger share of expenses for all the system apart for electric boiler with high threshold price control which lead to triple the TLCC compare to the baseline and self-consumption control (in case of Eh 70 kW) or double it (Eh 30 kW).

Increasing the threshold price affects greatly electricity consumption and the cost related to purchasing. BH heater under 5% threshold control has electricity costs that are 2 to 3.5 times larger compared to the running costs under self-consumption control. The increase is more than double for each increase in the threshold price, leading to 18 times larger for the control EPx50.

Less affected to control strategy is the TLCC for the HP, although also in this case expenses for electricity can be up to 5 time larger, in the worst case with the larger threshold price.

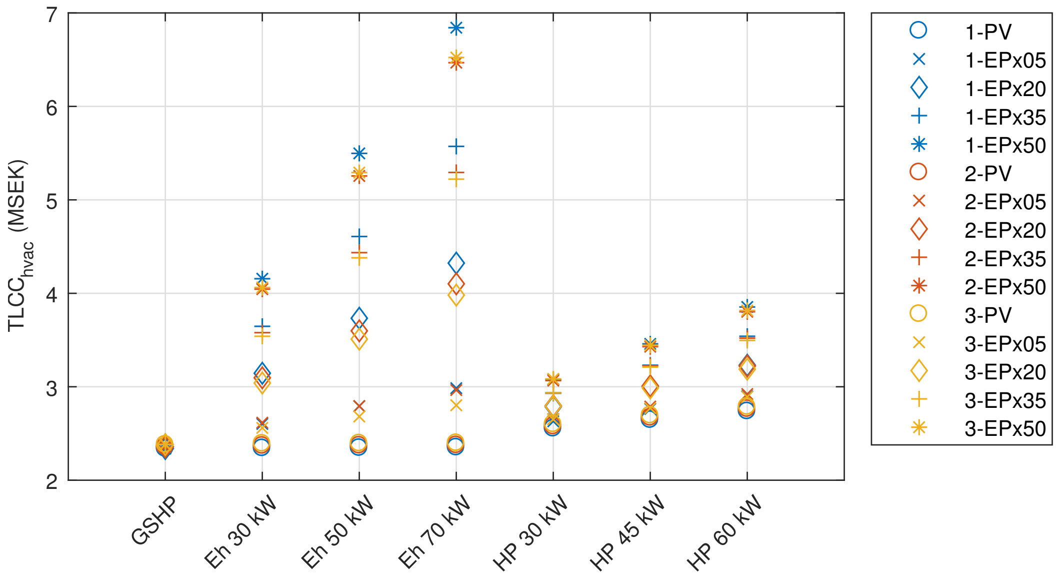

Figure 5.14: TLCC sensitivity to electricity price scenarios.

Figure 5.14 presents the TLCC results for all the configuration for the three electricity market scenarios. The results show that different market condition affects the economic value of the system but the influence is limited compared to the choice of BH heater and control strategy. While the TLCCs of systems with HP recur almost unchanged in each scenario, TLCC for electric heater are higher in the first scenario, which has lower average prices, when the control has high threshold.

5.5 Sensitivity Analyses

The investment costs and discount rate play a pivotal role in the assessment of the economic value of the system, but they are subjected to a high level of uncertainty. To evaluate their influence on the TLCC, a sensitivity analysis is performed for the initial investment cost for the boreholes heater and discount rate. The results of sensitivities are showed for systems under price control strategy (at 20% threshold) and electricity prices as for the first scenario.

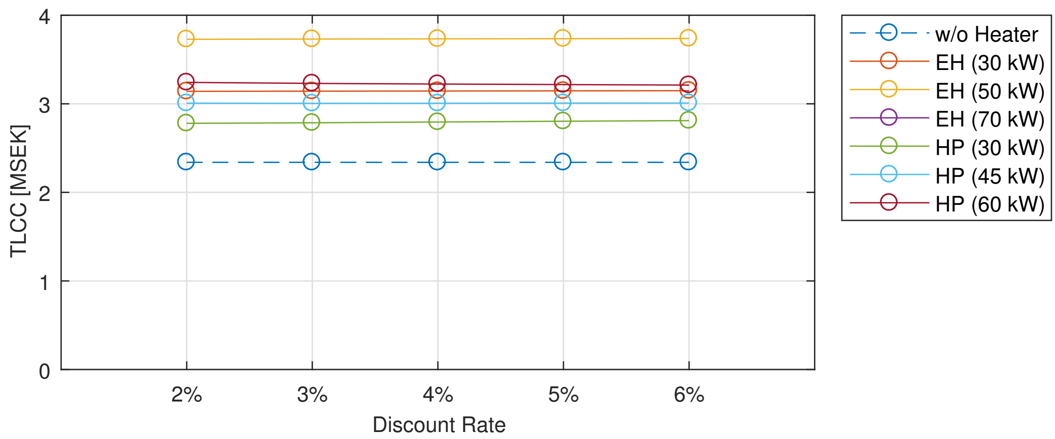

Figure 5.15: TLCC sensitivity to discount rate.

The increase of discount rate scales the present value of future costs down. As shown in figure 5.15, the TLCC is affected differently by increasing discounting depending on the heater type. TLCC decreases for the system with in-line heater more evidently in case of electric boiler. On the contrary, the baseline without heater appears to be more costly for higher rates because of the lower value of returns from electricity sales and benefits from the use of boreholes. Discounting are more beneficial for systems with larger electricity costs, although the overall results are not altered significantly so that the system without storage is the most economic-effective.

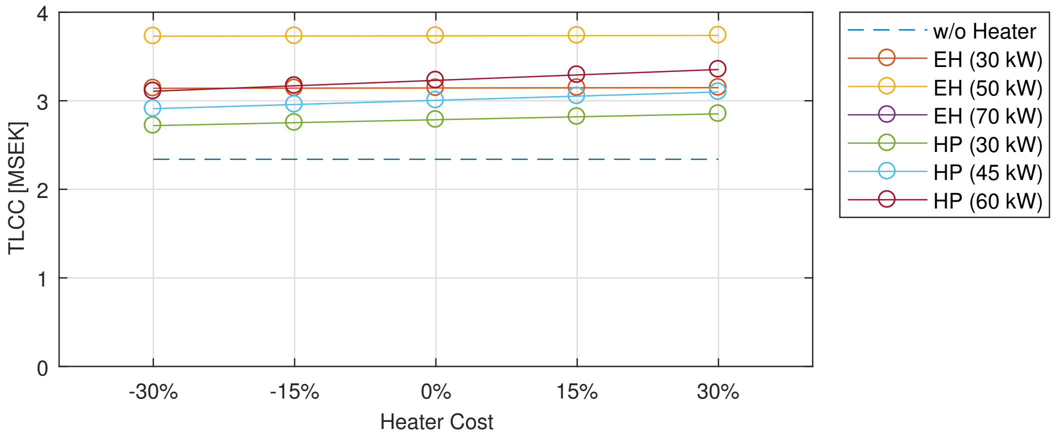

Figure 5.16: TLCC sensitivity to boreholes heater investment cost.

The price of heat pumps are higher than electric boiler resulting in higher investment costs, whereas the total costs benefits from lower use of electricity. The results of sensitivities to the initial cost for the boreholes in-line heater confirm that system with heat pump is more influenced by the heater costs. Decreasing price for heat pump would be an advantage for storage system to increase their competitiveness.

6 Discussion

Electricity market is a complex sector that requires more analysis that the one done in this study. The author is aware of the limitation of the electricity market model developed and the existence of dedicated research for market price forecast with more advanced methods with machine learning (Chen et al., 2012) and effect of wind and solar (Kasimoglu, 2018; Hirth, 2016; Cludius et al., 2014). The use of multiple linear regression was selected because its simplicity and it turned to be acceptable enough to demonstrate price jump with given REN generation, although the model is expected to underestimate price volatility.

An methodical analysis of the input parameter was performed before an extensive regression analysis. Several model equations were tested, for example considering the correlation between the factors. Second and third order equation were also analysed because of wind to load distribution against spot price. The improvement in the R-squared statistic and accuracy were limited despite an increasing complication of the model. The selected model was considered the optimal choice among those evaluated.

The results of the storage with PV-GHSP system achieve in this study are strongly influenced by the assumption made in the market model. One weak point of the forecast is the use of only one year as baseline; this is particularly relevant for the wind generation whose peak at the end of 2016 clearly enlarge over time. It results is an annual imbalanced generation with an increasing price shrinkage at the same time of the year that makes the BH heater be particularly active during that period.

Another obstacle is the choice of the threshold price at which the BH heater should operate. Beside the selection of the optimal price, also how to define it is a issue. In fact, the definition used in this study relies on knowledge of the annual distribution of price in advance, which is impossible in a real application. This underline the theoretical nature of the study.

Overall, electricity storage with the model analysed in this thesis is not practical. The reason has to be found in several causes some of them lying in the choice of the borehole and its efficiency, or in the costs related to the BH heater, together with electricity price trend.

As evinced in the KPI analysis, an increase in the total costs of the system is not followed by an increase of the performance of the GSHP. Although an heat pump at the BH heater performs better in the system in terms of SF and SPF compare to electric boiler, the total costs are higher under self-consumption control and low threshold in price control because of the higher investment costs. However, those shows also the lowest impact on the borehole fields. That makes hard to select an optimal configuration .

Larger PV array would increase the peak power and the storage system would benefit of higher share of solar fraction, as with the current PV array the peak of electricity surplus covers only the nominal power of the heat pumps, while larger boilers suffer from low SF.

All the simulations of the GSHP system are computed in two sequential runs of 10 years due to a bug in the TRNSYS model. This is an important limitation for the studies as it affects the reliability of the results, although several input variable were verified, e.g. boreholes temperature. PV degradation rate is inconsistent from the first to the second decade so that the second simulations are a 3% overestimate of the true PV generation. As the error is systematic, the results from the comparison of the configurations can be considered valid. It can be expected primarily an slight increase in SC and lower value of SF, although the difference might be neglected as the minor extent of the error.

The boreholes field evaluated in this study is sized correctly to fit the demand of the heating demand. It is not surprising then that the GSHP efficiency is not increased as the efficiency of small borehole system is very low when subjected to regeneration or storage (Lanahan and Tabares-Velasco, 2017; Lanini et al., 2014). An undersized BHE was also partially tested with the same methodology. The results shows an improvement of the BH temperature after 10 years compare to the baseline without regeneration in particular for the hp, also at low threshold price. Sommerfeldt (2018) found that regeneration with PVT collectors in the second BHE was more convenient than in the first case.

7 Conclusions

The results of electricity market forecast confirm the growing trend of electricity price despite a reduction in the wholesale price due to increasing share of wind and solar power (Grave et al., 2016), although an increase in price volatility.

Simulation of a PV-GSHP system for a multi-family house in Sweden suggests that the benefits from seasonal storage of electricity are ineffective for the configuration studied. When adding an electric heater in-line with the borehole field, the self-consumption of the GSHP system is increased independently from the control type. Indeed, SC is increased mainly for the larger electric load, while the solar fraction is more sensitive to control and heater type.

The electric load shift towards summer while having a reduction of the load in winter is not demonstrated. On the contrary, there is an overall increase in consumption both summer and winter. The performance of the heat pump shows almost no improvement in the SPF_1 of the GSHP and a strong reduction in the SPF of the whole system. The economic analysis suggests that the baseline system without BH-heater is the most profitable, while electric boiler and heat pump are relatively better under different boundary conditions despite never be cost effective on the whole.

The idea of seasonal electricity storage comes from the need to balance the summer larger production with the winter higher load in a market driven by renewable generation of wind and solar. Electricity market forecast shows that wind power generation is usually larger in winter than in summer. If this is the case and wind power will overcome the electricity sector in Sweden, then short term storage and DSM would be more promising than seasonal storage.

8 Future Work

Due to the complexity of the system analysed, there is a large potential for further research in several sub-topic. Easy to say that an attentive parametrisation of borehole field, BH heater and PV array is necessary to complete the study as well a more exhaustive sensitivity on the electricity price fluctuation.

One object of future works is to review boreholes field performance and behaviour considering results from other studies on BTES. More analysis should be done on shorter and more compact borehole fields, reducing borehole lengths if not increasing efficiency. A recommended index is the BTES efficiency as the total heat injected to the total heat injected in the storage (Lanahan and Tabares-Velasco, 2017), not investigated in this work. This would lead to a more complete evaluation of the system studied and suit for comparison with other studies. In fact, the impracticability to validate or compare the model is a limitation of this study.

A natural continuation of this study is the comparison of this PV-GSHP system with a solar-thermal or PVT-GSHP system. The aim is to highlight the main factors that make SAGSHP more technically feasible.

One important factor is the environment in which the system is set and its influence on the boundary conditions. Investigation of PV-GSHP system in areas with higher solar irradiation could lead to different results directly, on the PV generation, and indirectly, on the BHE behaviour and heating demand.

If the market model is sufficiently valid, the price trend resulted from the forecast open to the eventuality that seasonal storage is less valuable that demand-side management when there is a high wind component in the power sector. In this case, advantages for GSHP exist in the use of low price electricity to run the auxiliary heater in the demand side of the heat pump (i.e. in the hot water tank) rather than in the borehole loop. In this case, the losses for the low efficiency of the BHE would be reduced and the whole system will benefit from higher efficiency and possibly lower cost.

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Appendix A: Electricity Market Scenarios

A.1 Installed Capacity

Electricity market forecast is based on the input values assumed in Table A.1 where annual generation and installed capacity for wind, solar and total production in 2016 in Sweden (Lindahl, 2017; Svensk Vindenergi, 2018) and their expected values in 2035 and 2050 (Swedish Energy Agency, 2016) considering a 28% wind capacity factor and an annual solar generation of 950 kWh/kW.

Table A.1: Electricity generation and installed capacity for each scenarios.

	2016		**2035**		**2050**	
	Power (TWh)	Capacity (GW)	Power (TWh)	Capacity (GW)	Power (TWh)	Capacity (GW)
Scenario 1						
Wind	15.5	6.5	50	21.1	70	29.6
Solar	0.2	0.2	10	10.5	12	12.6
Production	137.6		134		148	
Scenario 2						
Wind	15.5	6.5	20	8.5	25	10.6
Solar	0.2	0.2	25	26.3	30	31.6
Production	137.6		155		145	
Scenario 3						
Wind	15.5	6.5	20	8.5	25	10.6
Solar	0.2	0.2	25	26.3	30	31.6
Production	137.6		155		176	

A.2 Retail Price

Retail price of electricity is based on the spot price plus other factor, explained in Electricity Market and Forecast Chapter. Figure A.1 shows the development of retail price in the three scenarios in key years.

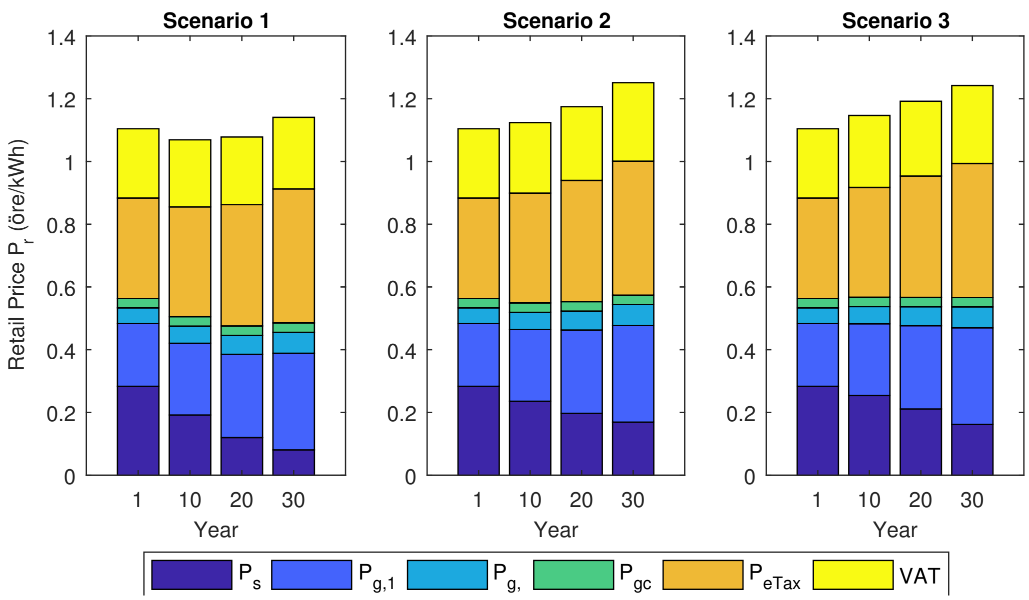

Figure A.1: Retail price.

A.3 Threshold prices

This study uses a hourly value for electricity prices at the spot market, therefore retail prices are calculated on hourly base as well. Hourly price fluctuation and relative thresholds value are shown in the graphs in Figure A.2 for 30 years. The aim is to show the variability of the price during time and compare the trend on the three scenarios. In particular, different level of threshold shows that scenario 1 and 2 have a similar trend, while the third scenarios has more compact price distribution around the average. In the second scenarios prices strech towards lower values. Prices tend to stabilise after 20 years because of curtailment.

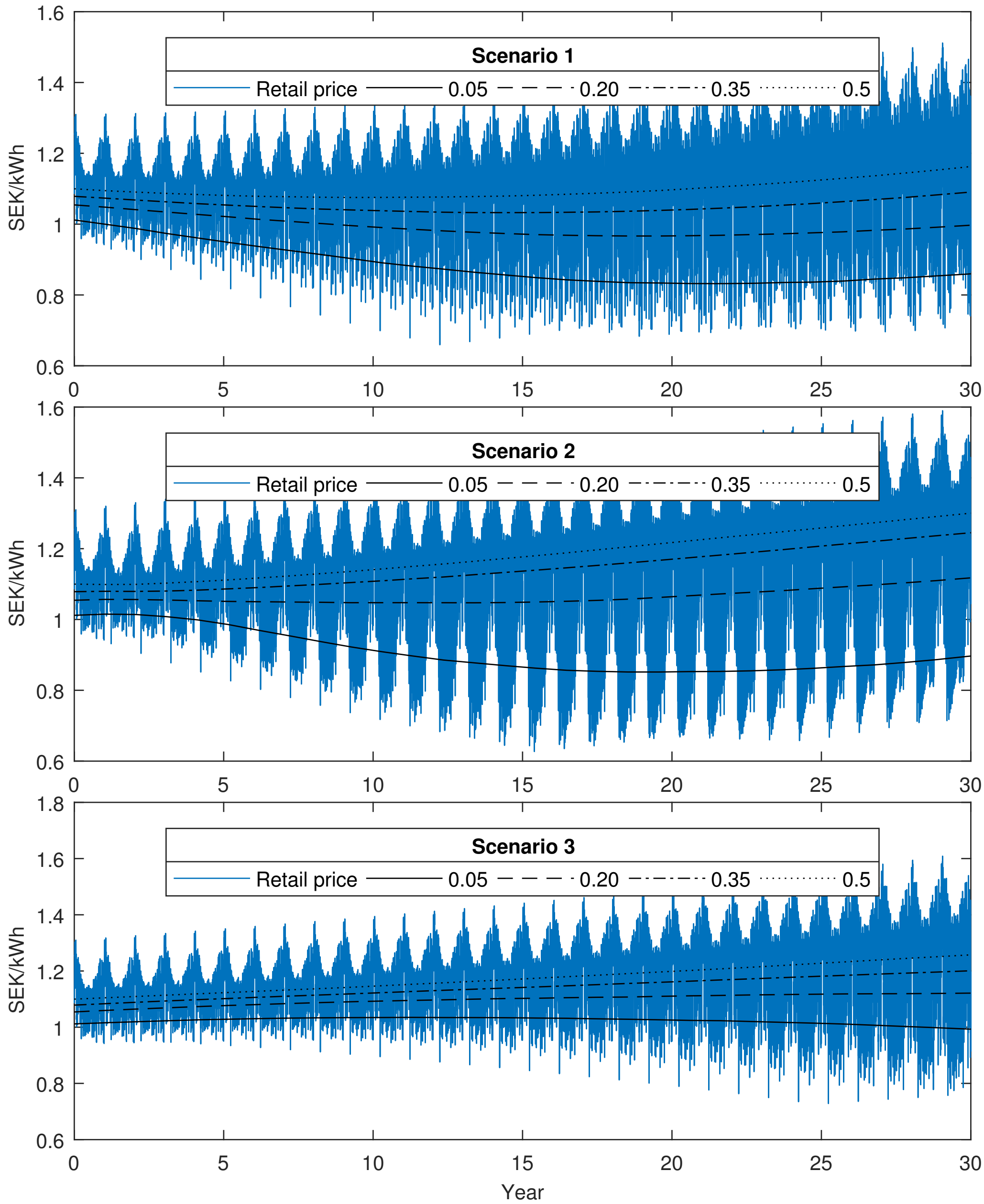

Figure A.2: Threshold price as quantile for 5% to 50% cumulative probability for each scenario.

Appendix B: Economics

B.1 Investment Costs

Investment costs have an important role in the establishment of the economic feasibility of the system. In this section a detailed account of the main components of the system is given. The overall price for the heat pump system is provided in Figure B.1, while boreholes investment costs are provided in Figure B.2 . Investment costs details for the PV system are give in Figure B.3. Figure B.4 and B.5 provide the assumed value for the borehole in-line heater when using electric boiler or air source heat pump respectively.

Table B.1: Investment cost for heat pump

GSHP		**Costs**
Overall costs	SEK	300,000
Total Costs w/VAT	SEK	375,000

Table B.2: Investment cost for boreholes system

Borehole Field		**Costs**
Number		12
Depth	m	275
Total Length	m	3,300
Installation	SEK/m	100
Drilling Cost	SEK/m	184
Fix cost	SEK	100,000
Total Costs w/VAT	SEK	1,296,300

Table B.3: Investment cost for photovoltaics modules

Photovoltaics System		**Costs**
Power	kW_p	40.3
Cost w/VAT	SEK/kW_p	14,500
Total Cost w/VAT	SEK	580,000
Subsidy		30%
Total Cost w/VAT	SEK	406,000

Table B.4: Borehole electric boiler investment costs

BH Electric Boiler Costs		**EH 1**	**EH 2**	**EH 3**
Electric power	kW_{el}	30	50	70
Cost (variable)	SEK/kW_{el}	100	100	100
Cost (fix)	SEK	7,000	7,000	7,000
Total Costs w/VAT	SEK	12,500	15,000	17,500

Table B.5: Boreholes auxiliary heat pump investment costs (Haddad and Trang, 2014; IVT, n.d.)

BH Heat Pump Costs		**HP 1**	**HP 2**	**HP 3**
Electric power	kW_{el}	10	15	20
Thermal power	kW_{th}	30	45	60
Cost (variable)	SEK/kW_{el}	15,000	15,000	15,000
Cost (fix)	SEK	27,000	27,000	27,000
Total Costs w/VAT	SEK	221,250	315,000	408,750

Appendix C: Results KPI

C.1 BH Heater

Self-consumption and solar fraction sensitivity are shown in Figure C.1 and C.2 for the BH heater only.

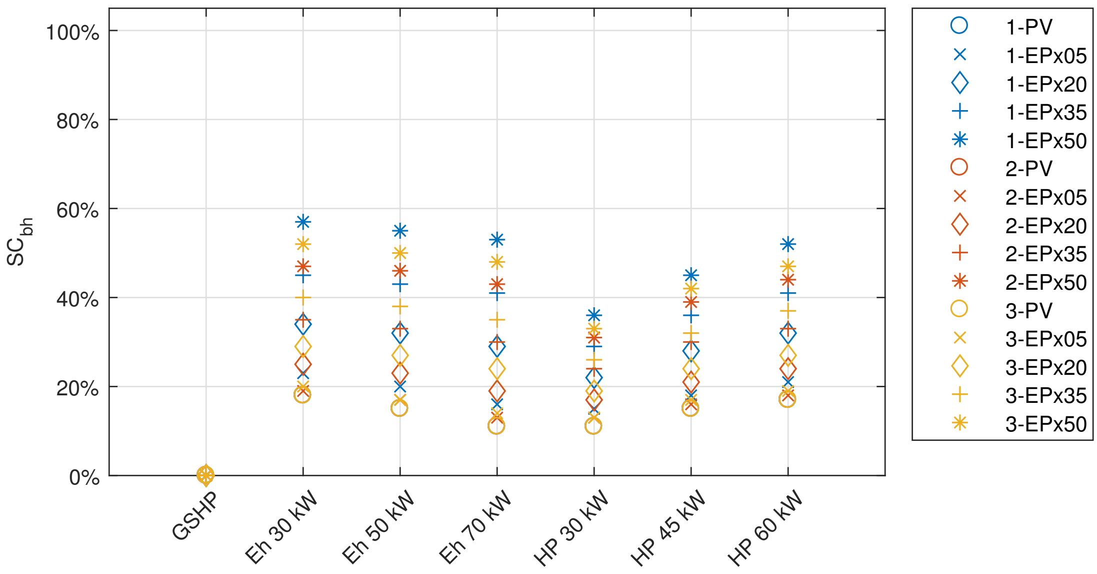

Figure C.1: BH-heater self-consumption.

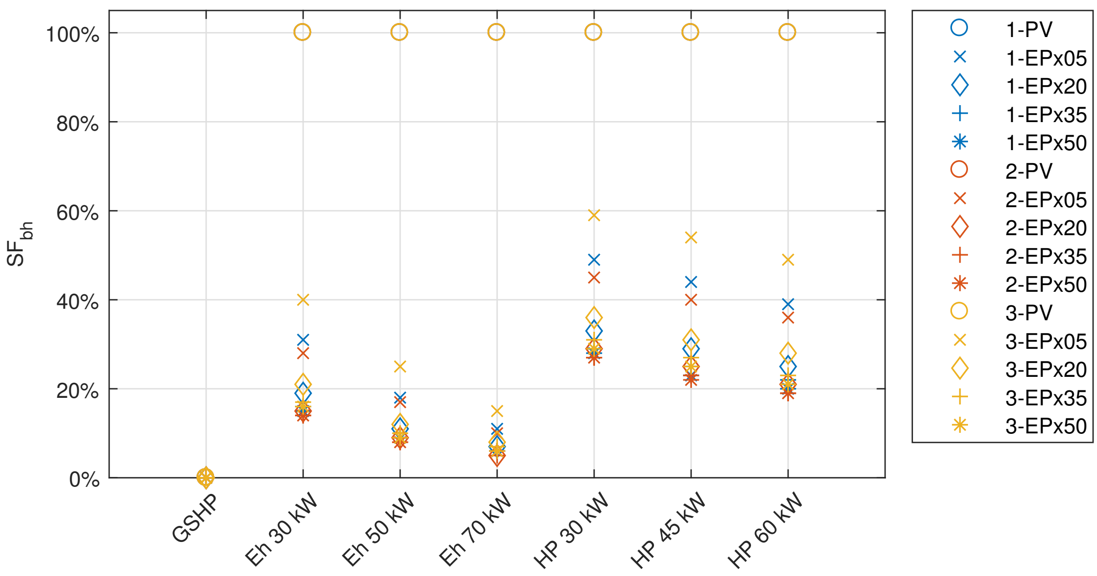

Figure C.2: BH-heater solar fraction.

C.2 SPF

The resulting SPF_1, SPF_4, and SPF_5 for all configurations are presented in Figure C.3.

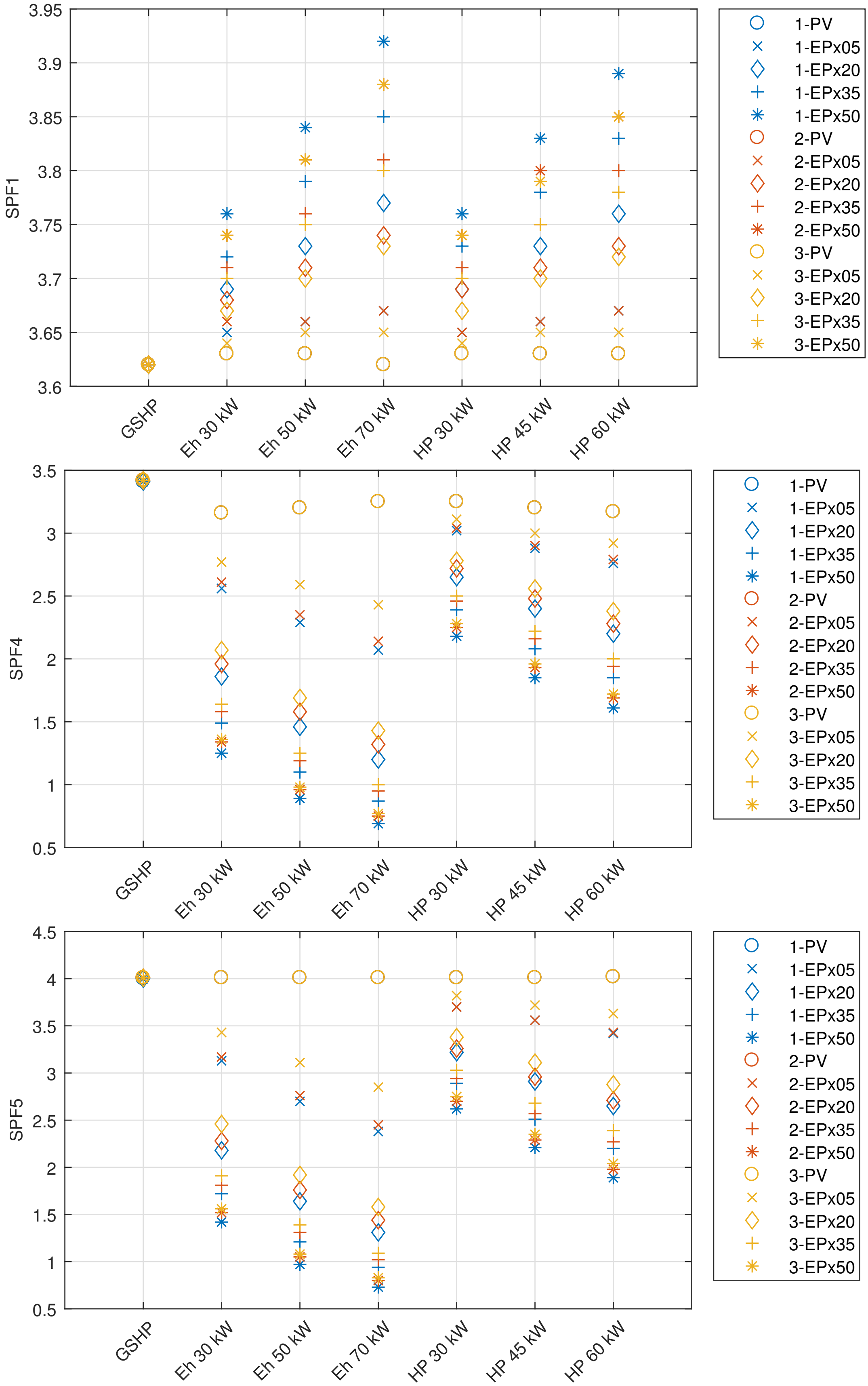

Figure C.3: Seasonal Performance Factor according to the definition for SPF_1, SPF_4, and SPF_5.