EXAMENSARBETE INOM TEKNIKOMRÅDET
ENERGI OCH MILJÖ
OCH HUVUDOMRÅDET
MASKINTEKNIK,
AVANCERAD NIVÅ, 30 HP
STOCKHOLM, SVERIGE 2018

Comparison of solar thermal and photovoltaic assisted heat pumps for multi-family houses in Sweden

MARTIN ANDERSSON

KTH
SKOLAN FÖR INDUSTRIELL TEKNIK OCH MANAGEMENT

KTH Industrial Engineering and Management

Master of Science Thesis EGI

TRITA-ITM-EX 2018:719

Comparison of solar thermal and photovoltaic assisted heat pumps for multi-family houses in Sweden

Martin Andersson

Approved	Examiner	Supervisor
	Hatef Madani	Nelson Sommerfeldt
	Commissioner	Contact person
	Royal Institute of Technology	Nelson Sommerfeldt

Abstract

The building sector account for 40 % of the global energy demand, and an increasingly popular way to supply buildings with heat is through the use of heat pumps. Solar thermal (ST) can either be used as a low temperature energy source in the heat pump or to directly supply the building's heating demand.

The increasing market of PV has made it a favorite for roof-top solar installation. Its physical integration with buildings and HPs is simpler than that of ST and can supply any available electric load associated with the building and not just the HP system. It can also supply any excess power to the grid.

In order to properly compare these two options, key performance indicators (KPIs) were identified for several system boundaries within the building and HP system. Technical KPIs used were seasonal performance factor (SPF), solar fraction (SF) and self-consumption (SC), while internal rate of return (IRR), net present value (NPV), profitability index (PI) and payback time was used to evaluate their economic performance.

For the thesis a multi-family house was modelled in TRNSYS where different system sizes of either ST or PVs was simulated for a year with three-minute intervals. The ST was connected in a parallel configuration thereby supplying the building's domestic hot water (DHW) through a separate storage tank. The modelled heat pump was a ground source heat pump (GSHP) which utilizes boreholes as the low temperature energy source.

The SPF increased for both the ST and PV integration from the reference scenario (no PV/ST integration) but to a varying degree depending on the analyzed system boundary. The economic results suggested that PVs are the more financially sound option over ST for the simulated MFH. The sensitivity analysis also showed the large impact of economic assumptions on the expected profitability for both the PV and ST systems. Based on the results would the simulated MFH with an existing GSHP benefit more from installing PV instead of ST from both a technical, economic and environmental perspective.

It is reasonable that PVs will most likely be an integral part for future buildings in Sweden with or without HPs because of its financial strength and versatility of demand supply, especially compared to ST.

Keywords: Solar Thermal, PV, Heat Pump, KPI, Multi-family houses, TRNSYS

Sammanfattning

Byggsektorn står för 40% av det globala energibehovet, och ett alltmer populärt sätt att leverera värme till ett hus är genom användning av värmepumpar. Solvärmefångare kan antingen användas som en lågtemperaturenergikälla i värmepumpen eller för att direkt leverera byggnadens värmebehov.

Den ökande marknaden för solceller har gjort den till en favorit för takmonterad solinstallation. Dess fysiska integration med byggnader är enklare än solvärmefångare och kan leverera el till hea byggnaden och inte bara värmepumpssystemet. Solceller kan också leverera till elnätet om produktionen överstiger byggnadens behov.

För att korrekt jämföra dessa två alternativ identifierades viktiga indikatorer för flera systemgränser inom byggnaden och värmepumpssystemet. Tekniska indikatorer som användes var årsvärmefaktor, solfraktion och självförbrukning, medan internränta, nuvärde, lönsamhetsindex och återbetalningstid användes för att utvärdera deras ekonomiska resultat.

För uppsatsen modellerades ett flerbostadshus med tillgänglig takyta i TRNSYS där olika systemstorlekar (i kvadratmeter) av antingen solvärmefångare eller solceller var simulerade i ett år med tre minuters intervall. Solvärmefångaren var ansluten i en parallell konfiguration med värmepumpen, varigenom byggnadens varmvatten levereras genom en separat lagertank. Den modellerade värmepumpen var en bergvärmepump som utnyttjar borrhål som lågtemperaturenergikälla.

Årsvärmefaktorn ökade för både solvärmefångar- och solcells-integrationen från referensscenariot (ingen solteknisk-integration) men i varierande grad, beroende på den analyserade systemgränsen. De ekonomiska resultaten visade att solceller är det mer ekonomiskt sunda alternativet över solvärmefångare för det simulerade flerbostadshuset. Känslighetsanalysen visade också på den stora effekten av ekonomiska antaganden på den förväntade lönsamheten för både solceller och solvärmefångare. Baserat på resultaten skulle det simulerade flerbostadshuset med en befintlig bergvärmepump dra nytta av att installera solceller istället för solvärmefångare från ett tekniskt, ekonomiskt och miljömässigt perspektiv.

Det är troligt att solceller kommer vara en del i framtida byggnader i Sverige med eller utan värmepumpar på grund av den ekonomiska styrkan och möjligheten att tillgodose både byggnaden och elnätet vid överproduktion.

Contents

Abbreviations

AC	Alternating Current
ASHP	Air Source Heat Pump
DC	Direct Current
DH	District Heating
DHW	Domestic Heat Water
FPC	Flat-Plate Collector
GSHP	Ground Source Heat Pump
HP	Heat Pump
IEA	International Energy Agency
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCOE	Levelized Cost of Energy
MFH	Multi Family House
NPV	Net Present Value
NZEB	Net Zero Energy Building
OEM	Original Equipment Manufacturer
PI	Profitability Index
PV	Photovoltaic
SHP	Solar Heat Pump
SGSHP	Solar Assisted Ground Source Heat Pump
SC	Solar Collector
SFH	Single Family House
SHC	Solar Heating and Cooling programme
SPB	Simple Payback Time
SPF	Solar Performance Factor
ST	Solar Thermal
UC	Uncovered/Unglazed Collector

1. Introduction

1.1 Background

Buildings account for 40 % of the global energy usage [1,2] and the residential sector is responsible for 30 % of the global energy usage [3]. A noticeable share of that usage is losses due to low efficiency technologies [4] and there is a need for sustainable solutions to be implemented [5]. Existing buildings in Europe have a replacement rate of 1 – 3% per year [2] resulting in a slow development of new low energy building developments, and highlights the need to retrofit existing buildings with sustainable solutions [5].

Heat pumps (HPs) have become common choice to supply a building's heating demand [6]. Designing and evaluating a HP system is complex due to the many configuration options available and specific building parameters [6,7] which can cause problems when evaluating and comparing different HP systems. However, Sweden is per capita one of the world's leading markets for HPs [8] and Europe's leading market for ground source heat pumps (GSHPs) [9].

Solar power is increasing exponentially in today's energy infrastructure [10], but some of the main problems with solar energy is the daily intermittency and seasonal differences. Solar irradiance is at its highest during the day, which means that the solar energy must be utilized during the time of irradiance. The differences of high solar irradiance during summer and lower solar irradiance during winter cause a seasonal delay between the high production during summer and high heating demand during winter.

Photovoltaics (PVs) produce electricity from solar irradiance which can be utilized in both large- and small-scale applications. This technology has gained attention through recent price reduction and is a viable option for use with HPs [6].

Another aspect of utilizing solar irradiance is through heat absorption. The technology of solar thermal (ST) applications is more mature than PV. However, both, or either solutions might prove beneficial when assisting HPs and GSHPs (also called Solar Assisted Heat Pumps, SHPs, and Solar Assisted Ground Source Heat Pumps, SGSHPs) in supplying heat and/or electricity loads in buildings. Therefore, the addition of solar technologies for the existing HP market in Sweden is of interest.

1.2 Problem Definition

Multi-family houses (MFHs) which seek to improve the building's energy performance through solar systems needs a way to compare the use of either ST or PV in combination with a HP. Up until now research in SHPs has mostly been done with ST [6], but now combinations with PV gain interest because of the growing PV market and PV price reduction. Even though PV and ST are technologies with different useful energy outputs (electricity and heat respectively) their performance compared with each other is relevant since they could compete for the same area and assist the same building and/or HP system. In this thesis, the area of interest is the rooftops of MFHs. To accurately compare these two solar technologies in combination with HPs, key performance indicators (KPIs) must be applied through clearly defined system boundaries of these systems.

1.3 Research Questions

The thesis aims to fill the knowledge gap in comparison between PV and ST for combination with a HP through identification and testing of KPIs. There is a need to adequately describe these complex systems such that the performance between them is comparable and relevant for the appropriate stakeholder. The research questions in order to achieve these results are formulated as;

"Which KPIs are of relevance for MFHs when comparing ST and PV for GSHPs, and why"
and;
"What is the performance of these SGSHP systems for a standard MFH in terms of these KPIs".

To accurately answer these research questions, a multi-level system perspective is necessary where different system boundaries are examined.

1.4 Methodology

During the first part of the thesis a literature review was done of HPs, the current technologies of ST and PV and their associations with HPs as well as used KPIs for these systems. From this literature review, a set of KPIs at multiple boundary levels was identified to accurately compare these two systems.

After the literature review, a quantitative analysis was done with a TRNSYS (TRaNsient SYStems) software model where a SGSHP system was analyzed for a MFH and compared through these identified KPIs. A preliminary TRNSYS model with a GSHP was developed before the start of thesis [11] but required further work to include ST and PV. Technical specifications of simulation components were either provided by original equipment manufacturers (OEMs) or assumed based on similar configurations from previous systems. An in-depth description of the TRNSYS model is done in chapter 4, the results are presented in chapter 5 and discussed in chapter 6. The evaluation of ST and PV through the KPIs was based on the results obtained from the model and discussed from the basis of the literature review.

The choice of sources was based on their relevance for the overall topic of KPIs applied for SHPs in MFHs. The bibliography consists primarily of published articles from different journals, conference proceedings, and books. A large part of the literature was based on the Task 44 Appendix 38 (T44A38) initiative of the International Energy Agency's (IEA) Solar Heating and Cooling programme (SHC) as well as books, journals and articles related to it. This included the book *Solar and Heat Pump Systems for Residential Buildings* [6] which contained much of the relevant information for this thesis.

Previous research done by N. Sommerfeldt, and H. Madani from the Royal Institute of Technology were also relevant, as the fundamental motivation for this thesis is derived from that research [11–22].

Other sources include those that are relevant for KPI identification [23], [24] which stem from the science of project management. However, KPI applications for project management have a relevance in that the definitions and theories of KPIs also can be applied for SHPs in MFHs. Even though several relevant KPIs are identified for SHP systems, a clear definition of system boundaries and stakeholder relevance had to be applied for accurate comparison of the same KPIs for the different technologies which is why the fundamental theory of KPIs are relevant.

1.5 Scope and Limitations

The thesis was aimed at MFHs in Sweden and their decision to add solar to their existing GSHPs. Therefore, the cost and technical performance of boreholes were considered outside of this thesis scope and were not examined. While the installation costs of the HP were not considered, its operational costs were, as well as its technical performance. This is due to the HP being central in the SHP system's performance while the borehole acts as the low temperature heat source, it was not relevant for the technical and economical comparison of ST and PV and their effect on the HP.

No standalone solar system was analyzed as the thesis evaluated these systems from the perspective of an existing HP, and specifically a GSHP, The weather data that was used is representative of what one would experience in Sweden, and more specifically mid-Sweden/Stockholm area. Therefore, the results of this thesis are limited to such locations of similar climate.

The building loads were from the Tabula database and is based on a MFH built 1976 – 1985. This data was used in the TRNSYS model to obtain realistic results applicable for the thesis target building.

1.6 Expected Results and Importance

The thesis resulted in relevant KPIs for Swedish MFHs based on the assumptions and scope outlined and a TRNSYS model for the SGSHP system. The usage of these KPIs will ultimately provide more informed decisions regarding ST or PV installations in terms of efficiency, cost and emissions. As discussed in the background, the sustainability goals of incorporating solar energy into the existing energy mix, and reducing emissions related to households is widespread.

The thesis targeted the market for further development and research of ST and PV for HP systems. It was therefore written with other researchers and MFH-related actors in mind. As these systems are complex in terms of relevant stakeholders, system boundaries, external markets and environments, a simplification of the perspective was applied in that it was focused on the performance of a SGSHP in a single MFH.

2. Literature Review

The literature review was done to identify relevant information and lack of research regarding HPs, GSHPs, ST, PV and KPIs to support assumptions when designing the TRNSYS model and KPI application as to properly answer the proposed research questions.

2.1 Solar Energy

At the very basic level, solar energy is the result of fusion reactions in the Sun. These reactions emit electromagnetic waves at different wavelengths which travel through space, and the solar irradiance reaching the Earth is about 1367 W/m^2. Further losses occur when the light travels through the Earth's atmosphere. Depending on cloud coverage and the suns position on the sky, the useful solar irradiance reaching a horizontal surface can vary from around 100 – 1000 W/m^2 [25]. For northern Europe the yearly average of global horizontal irradiation is about 970 kWh/m^2, compared to southern Europe which has a yearly average of about 1400 kWh/m^2 [25].

2.1.1 Solar Thermal Collectors

ST collectors absorb the solar irradiance as heat by circulating a fluid. That heat is either used directly as heating for the building, as evaporation heat in a heat pump, or stored separately for either type of use at a later time. One of the main advantages of ST is that the useful energy can be stored as hot water in any insulated volume. Therefore, the solar irradiance can be absorbed even when there is low demand at the time of heat production and used later when demand increases. Previous research by IEA indicates that a ST collector area between 15 - 30 m^2 with a storage of 1 – 3 m^3 could supply 20 – 60 % of single-family houses (SFHs) SH and DHW demand in countries like Sweden, Austria and Switzerland [26].

There are several types of solar collectors, with different designs and performances. Figure 1 shows the use of different collector technologies from a study of European SHP systems for residential buildings [6].

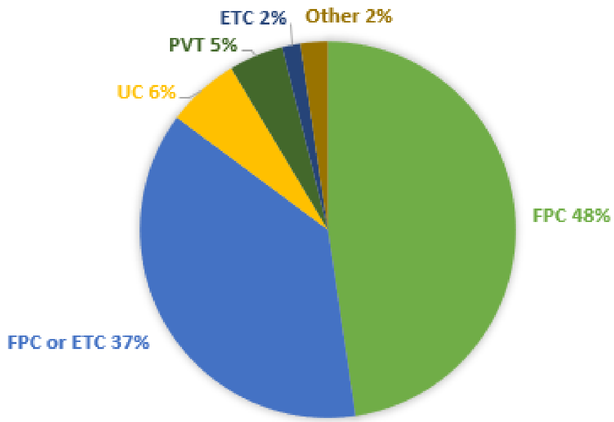

Figure 1. Use of different solar collector technologies; Flat plate collector (FPC), Evacuated Tube collector (ETC), Uncovered/Unglazed collector (UC), PV/Thermal (PVT). [6]

The flat-plate collector (FPC) design is shown in Figure 3, and its performance versus an evacuated tube collector (ETC) for different temperature differences is shown in Figure 2. A FPC consists of transparent cover, as to let solar irradiance in, but to also keep the heat in the absorber from convection losses. The insulation and housing further reduce heat losses through the back side of the panel. The absorber connected to a system of tubes in which the heat absorbing fluid is circulated.

The ETC design is shown in Figure 3. The collector consists of several glass tubes connected to a connection tube in which the heat absorbing fluid is circulated. Within the glass tubes is the absorber which has the same characteristics as the FPC absorber. The heat is transferred via convection between the heat exchanger connected to the absorber with an internal fluid mixture [25]. There are two main types of ETCs; Heat pipe tubes as seen in Figure 3, and direct flow tubes where the fluid is circulated through the absorber in the glass tube and back to the collection tube.

ETCs are more efficient for larger temperature differences than FPCs but as the collectors are used for DHW FPCs are viable. ECTs also cost twice as much more per collector [27]. FPC are also a more common choice of collector in Europe and Sweden [28].

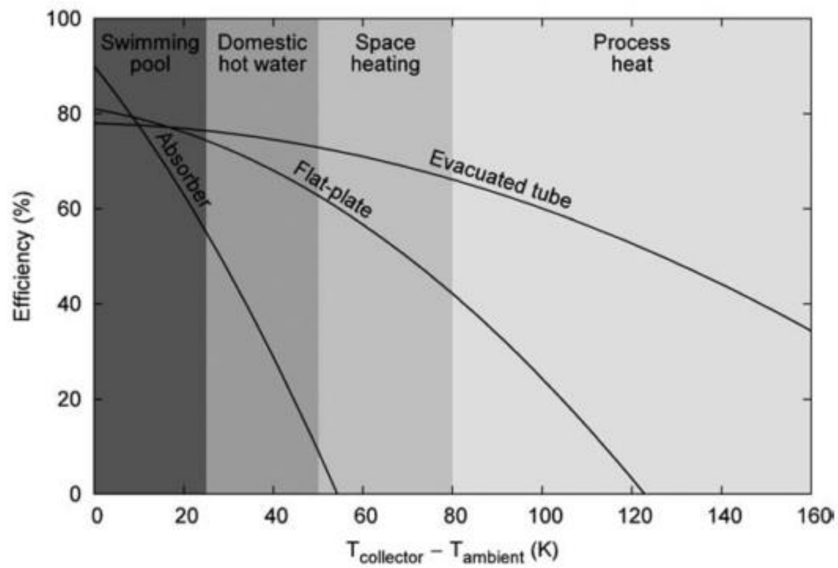

Figure 2. Efficiency difference between unglazed (absorber), Evacuated Tube Collector and Flat-Plate Collector. Different heating purposes is also displayed in the background at different temperature intervals. [25]

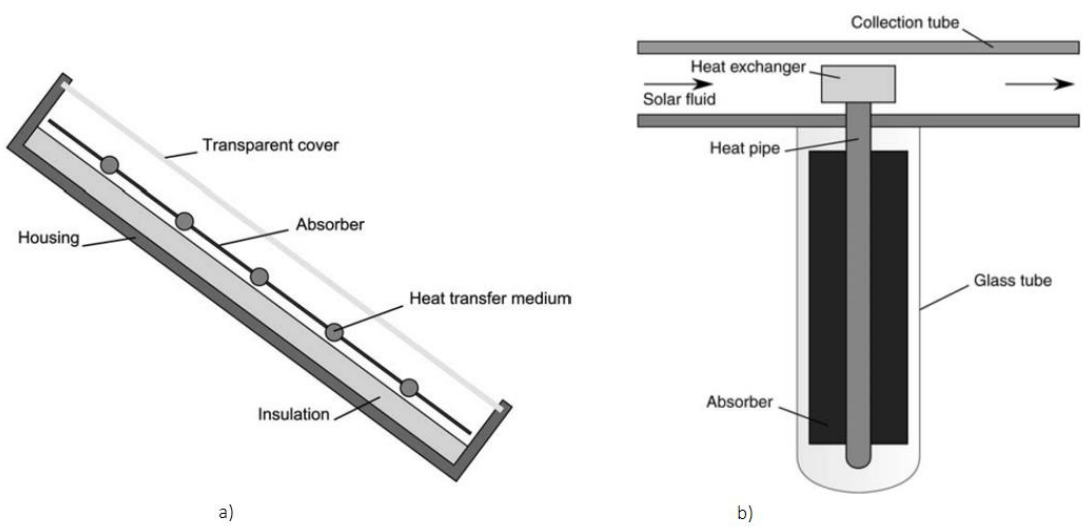

Figure 3. Designs of a) Flat-Plate Collector and b) Evacuated Tube Collector. [25]

As the thesis analyses the use of solar systems for rooftop areas of MFHs, FPCs and ETCs is the collector types of consideration as recommended by [6]. The final choice between the two depends on the specific location characteristics, application, and stakeholder preferences [6], [26].

Improvements have been made for FPC since 1983 [29] but the market for ST is mature and 81.4 % of the global ST market is located in China, compared to Europe's 9.3 % [26]. The primary focus of the thesis is for European applications, therefore there won't be an analysis and review of the Chinese market.

The costs related to ST is highly dependent on the specific configuration and building characteristics. Most of the cost is from the initial investment where the collector cost is around 50 – 80% of the total ST system cost [30]. Beyond that, storage tanks, design and planning, and installation/piping are notable costs. Total initial cost examples for smaller systems in Germany can range between 6 000 and 15 00 SEK/m^2 [27]. Other cited turnkey costs vary from 2 000 – 20 000 SEK/m^2 for high-performance ST collectors [31], [32], and a Danish study used a turnkey cost of 2 500 SEK/m^2 [33].

2.1.2 Photovoltaics

The process of electricity generation in PV cells is due to the physical properties of semiconducting materials, such as crystalline silicon, which is the most common material for PVs accounting for over 90 % of all installations [12]. Different types of silicon-based PV modules are presented in Figure 4. There are other PV technologies such as thin-film, perovskite, nanocrystal solar cells, and so on [10]. However, as silicon-based PV is by far the most common technology, this thesis will not examine the other PV technologies.

The technology of PV is not new, but with recent price reductions, the number of PV installations are increasing [12]. In Sweden, PVs have total installed power of 205 MW as of 2016 as shown in Figure 6 [34]. Estimates on current policy scenario from IEA points towards a 2 192 TWh production from PVs 2040 up from 303 TWh 2017 worldwide [35]. This estimate is the worst-case policy and the "sustainable policy" scenario estimates 5 265 TWh of electricity generation from PVs worldwide by 2040.

Figure 4. Common crystal silicon PV panels with different module backgrounds. [12]

The useful energy output of PVs is electricity, compared to heat for ST. This means that PVs can supply a HP system's electricity load as well as a buildings electricity load. Storage of the PV's power output can be done with an electric battery or by overproducing heat and storing it in a tank if coupled with a HP system, just like a ST-HP system. PVs converts solar irradiance directly to direct-current (DC) electricity. Electric appliances and the power grid run on alternating current (AC) which means that an inverter is necessary for a grid-connected PV system. This adds to the cost of the PV system, which other than electrical wiring and mounting is simple in design and installation compared to ST [27].

The efficiency of PVs depend to a large degree on the PVs cell temperature [36] and is shown in Figure 5. As seen, the efficiency lowers with increasing cell temperature. The figure represents the traditional linear equation of a PVs efficiency [36]. A PV system with an efficiency of 12 – 15% would expect to theoretically produce 117 – 145 kWh/m^2.yr in the Stockholm region.

While total system cost often are represented per collector or m^2 for ST, for PV a total system cost per peak power is often used [27]. For PV a module price reduction to 6.5 SEK/W$_{peak}$ as seen in Figure 7 has occurred in Sweden up until 2016. Total investment costs for larger rooftop mounted PV systems is estimated to 12 SEK/W$_{peak}$ [34]. PVs also receives subsidies from the Swedish Energy Agency for up to 30 % of the initial cost as of January 1st 2018. [37]

PV integration with HPs is an expanding topic in research [6], and proper comparison with ST is of relevance with the increasing popularity and module price reduction as seen in Figure 6 and Figure 7.

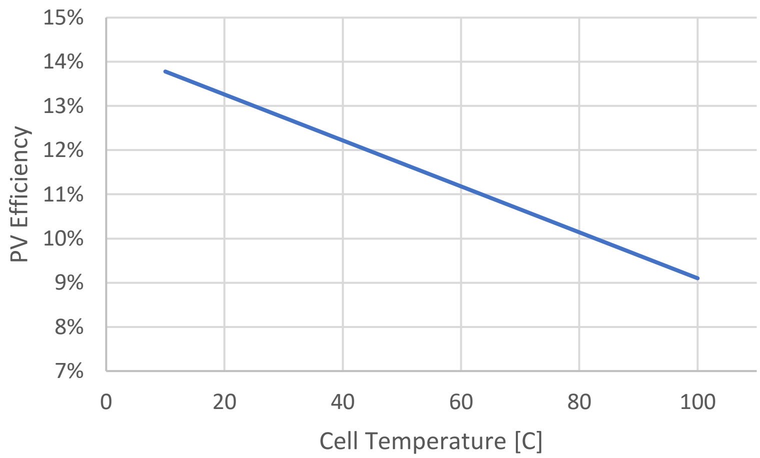

Figure 5. PV Efficiency for different cell temperatures $\eta = \eta_{ref}\,[1-\beta(T_C-T_{ref})]$ with $\eta_{ref} = 0.13$, $\beta = 0.004$, $T_{ref} = 25$ C [36].

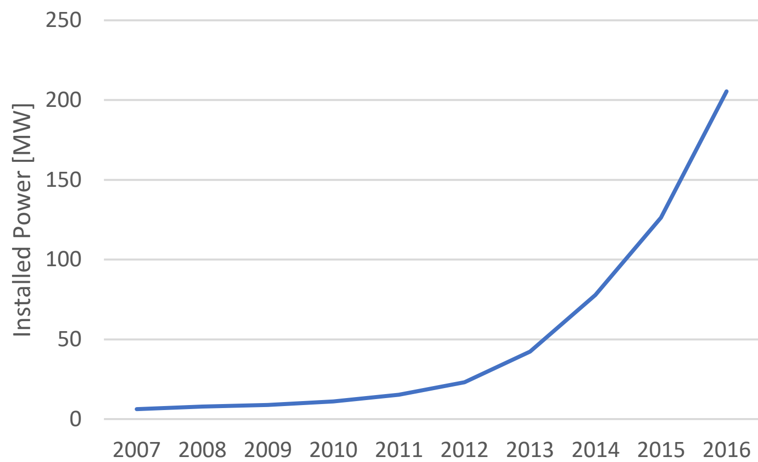

Figure 6. Total installed PV power in Sweden [34].

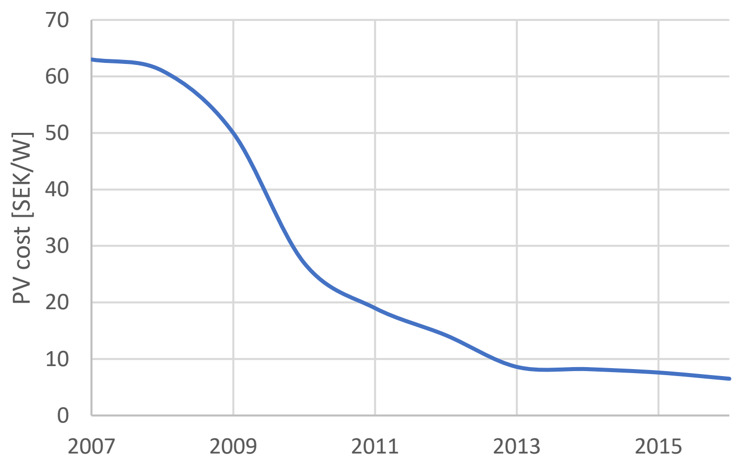

Figure 7. Cost of PV modules in SEK per peak power [34].

2.2 Heat Pumps

HPs utilizes heat at low temperatures to deliver heat at higher temperatures by a compression and expansion cycle. The basic principle of a HP is to circulate a fluid in a closed system which undergoes phase changes between liquid and vapor. When it's in the liquid phase, the fluid evaporates by the absorption of heat at a low fluid temperature (source). It is then compressed (which requires work input) to increase fluid temperature. The fluid is then condensed as heat is rejected at a high fluid temperature (sink). The liquid then goes through an expansion valve, lowering its temperature where it enters the evaporator again. This simple schematic is shown in Figure 8.

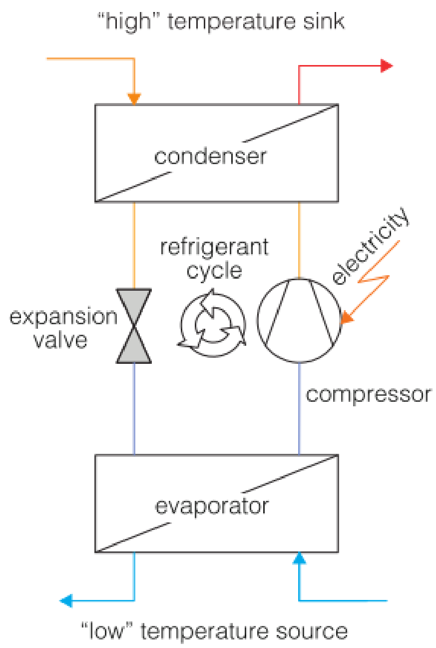

Figure 8. Simple schematic of a heat pump cycle. [6]

There are many solutions with different applications and characteristics to absorb solar irradiance and convert that energy for a specified purpose. But how to control and integrate different technologies to HP systems is still a challenging task [19], [38].

2.2.1 Solar and Ground Source Heat Pump Systems

The Solar Heating and Cooling programme (SHC) is a programme developed by the International Energy Agency (IEA) in 1977 to promote the diverse aspects and uses of solar thermal energy. SHC develops standardizations which enforces the global research and development within the sector. There has been research done using these standards and elaboration on defined system boundaries and categorization.

A parallel connection can be seen in Figure 9 where a solar collector is in parallel connection to the HP. A parallel connection means that the energy output from the collector is used at the HP system's sink side. A series connection means the energy output of the collector is used in the HP as a low temperature energy source. Regenerative connection is when the collectors produced heat is used to warm the HPs primary heat source, usually a ground source [6]. The notations in this case refers to a ST-HP combination and is not applicable for PV-HP applications.

As PVs generate electricity, its energy output cannot be used as the HP's low temperature energy source or at the sink side. However, the PV would supply the HP system and building load with electricity, and even if the PV production exceeds HP and building electricity demand at a certain time, excess power can be sold to the power grid. This is however at a lower economic value than if used in the system, as it costs more to buy electricity than one would get for selling it. Therefore, the primary usage of PV in this thesis is through integration with the building and not stand-alone systems selling only to the grid.

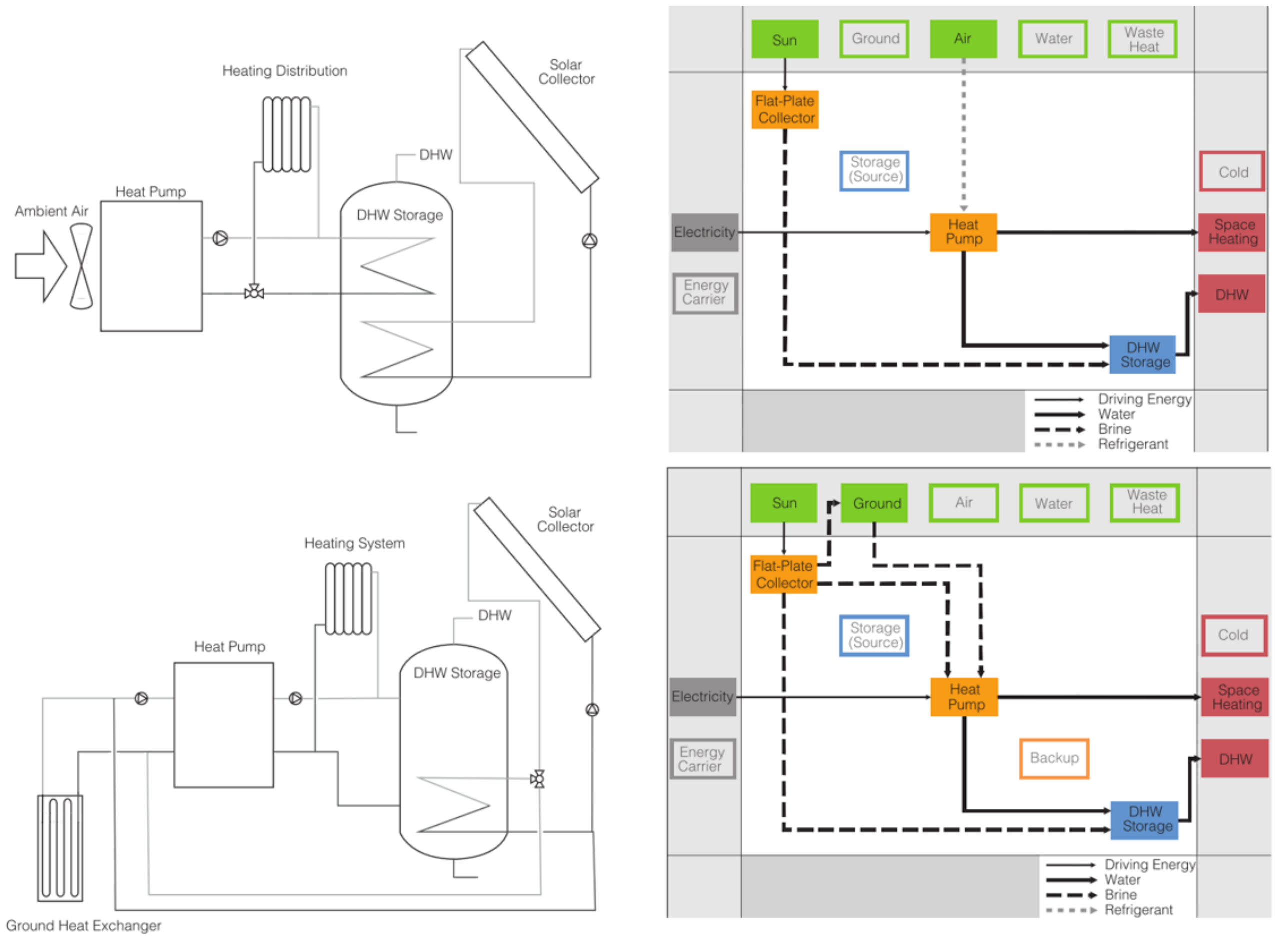

Figure 9. "Simplified hydraulic schemes (left) and corresponding visualizations (right) of different solar and heat pump systems." [6]

Figure 10 shows the most common system configurations for SHP (a) (P – Parallel, S – Series, R – Regenerative), and (b) the most common low temperature energy sources for HPs. The research study is based upon 128 SHP systems, provided by 72 companies from 11 countries [6].

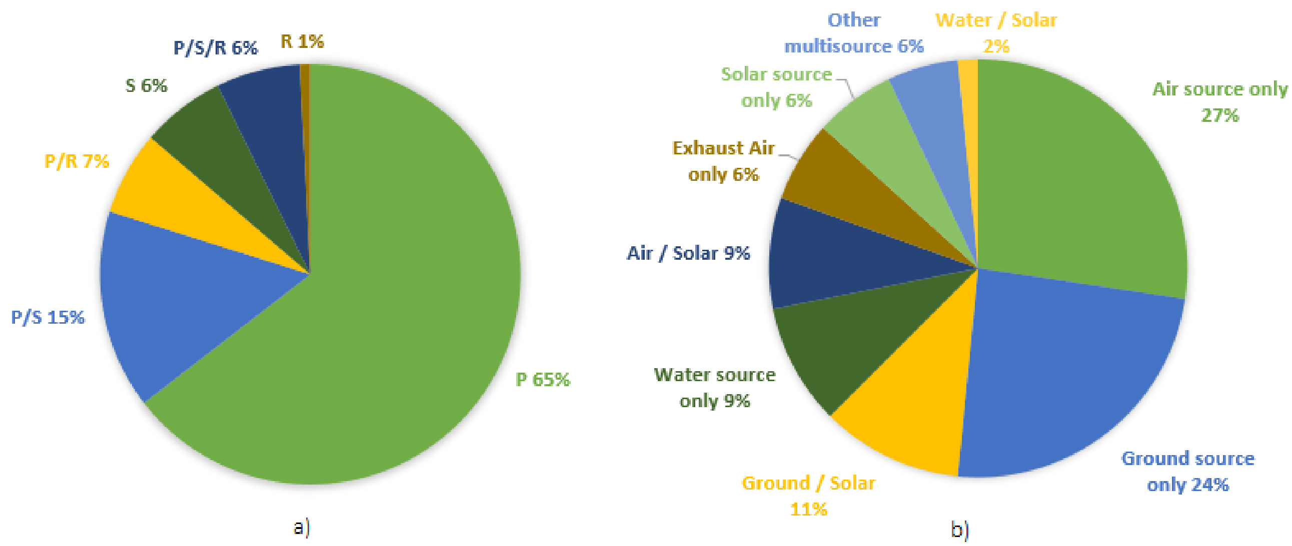

Figure 10. Surveyed HPs of a) SHP's system configurations and b) HP's low temperature source. [6]

Several low temperature energy sources displayed in Figure 10 are viable options for HPs. As seen is air and ground common low temperature energy sources. While only solar account for 6%, ground and solar account for 11% of heat pump configurations from the study [6]. The solar in question is ST and any comparison with PV was not done. The most common configuration for ST-HPs is the parallel connections for DHW alleviation.

Boreholes have the advantage of higher source temperatures in the winter when loads are higher (as the earth has an inherent thermal mass), which provides higher annual efficiencies as solar collectors have limited use during cold weather and winter months [39]. The further use of ST together with boreholes also show signs of reducing required borehole length, thus lowering initial costs of the borehole and increasing system performance [40].

Research has been done in the field of PV/Thermal (PVT) and GSHP combination [20]. PVT produces both electricity from the PV cells and heat by cooling the PV via a circulating a fluid much like a FPC. With the recent price reductions of PV, PVT+GSHP combination show promise [20].

The choice of system designs for SHPs depends on several factors. While several studies have been made on SHPs, the comparison of utilizing PV has been scarce. An improvement of system performance is expected with the integration of correctly designed ST collectors, however the initial cost related to ST is a bottleneck for future market expansion [6].

3. Identification of Relevant KPIs

"KPIs are commonly used by an organization to measure, quantify and evaluate its success or the success of a particular activity in which it is engaged." [41]

KPIs are commonly used for goal setting and performance measuring in project management [23,24]. There are plenty of suggestions how to formulate project specific KPIs, but no clear point by point methodology applicable for most cases. That is because KPIs are mostly developed and implemented by the ones who will handle them and communicate them to relevant shareholders for their own specified needs [23], but some general guidelines are outlined as follows;

- KPIs should be subject to change from its underlying parameters.
- KPIs should combine different metrics in to a single variable.
- KPIs should not be hard to understand for the respective shareholder.
- KPIs are always subject to variance and cannot be predicted precisely.

Indicators from a standardization point of view for SHPs are presented by [6] and are considered the most promising for use in this thesis. But as they are primarily used for ST-HP systems, some adaptation is required for an accurate comparison of the PV-HP KPIs. The key thing is to identify critical factors when being applied for the specific system boundaries.

The focus of this thesis is to apply KPIs relevant for SHP systems for comparison of PV and ST. The selected KPIs are further divided into the three categories; Technical, economic, and environmental due to the goal of an overall sustainable system perspective. The identification of multilayered (boundaries) and multiarea (stakeholder relevance) KPIs is of importance.

3.1 System boundaries

To properly compare and analyze any systems in terms of KPIs, clear boundaries and definitions must be applied and explained. Most of the current KPIs used to evaluate HP systems are defined through different system boundaries and defined for specific cases which makes them hard to compare. The choice of system boundaries for the HP system in this thesis is presented in Figure 11 and is based around the previous research regarding T44A38 which allows for a common ground which further research and applications can be built upon as seen in [6][14]. Also displayed are the electrical components and relevant heat outputs for each system boundary.

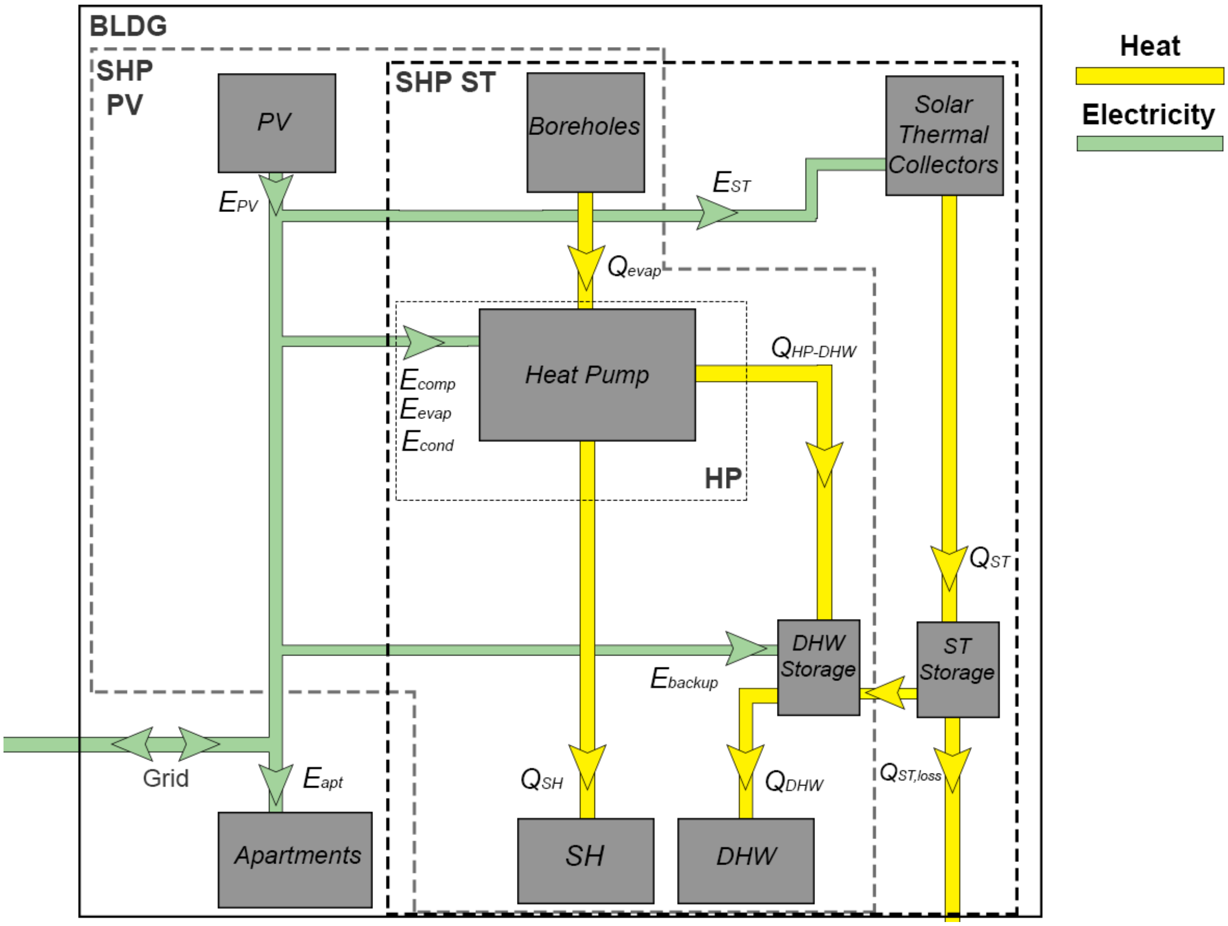

Figure 11. System Boundaries used for the SGSHP with specified electrical components and heat transfers.

3.2 Choice of key performance indicators

The overall goal for a SHP system is to capture solar energy and to supply an energy load. This could be identified as a critical factor for the success of a SHP system. Therefore, KPIs which measure and evaluate the process of supplying the domestic energy load (heat and electricity) is of importance as per the KPI definition previously mentioned.

The assumption of HP electricity demand as a prioritization in the case of PV is not always a correct one. As the system in this thesis is a PV-HP integration, it is a reasonable one from a technical standpoint due to the limiting system boundaries to not include its effect on power grids. It also depends on which stakeholders pay for what in a MFH. Even if the interaction of PVs and HPs are examined, PVs potential of supplying the grid is not ignored as to fully capture the real benefits of PV. The differences of these prioritizations are highlighted in the different KPIs.

3.2.1 Technical Indicators

The main problem and focus area of this report is the assessment of comparable technical performance indicators related to energy yield and demand supply. The availability of technical KPIs for ST-HP and PV-HP comparisons are limited due to irregular boundaries, different useful energy outputs and lack of research for PV-HPs. Assumptions resulting in KPIs used in one study might not be comparable with the same KPIs used in another study due to their different boundary assumptions. This becomes apparent when analyzing the most common system KPIs such as Seasonal Performance Factor (SPF) or Solar Fraction (SF) [5], [6], [42]. The system boundaries referred to in this chapter are those presented in Figure 11.

The proposed KPIs are within the identified critical factor for the HP system, which is to deliver heat to the building and for the SHP system which is to convert solar to useful energy via a HP system. The SF complements the SPF by that identification of the solar energy's share of the system which is a critical factor of the SHP system.

No consideration of the borehole performance is done. That is because both PV and ST are chosen to be integrated on the HP system's sink side, i.e. they supply a demand directly.

The electric components and heat transfers used are presented in Table 1 and visualized in Figure 11. The units for all electrical components and heat transfers are in kWh.

Table 1. Electric Components and Heat Transfers and their variable definition.

Electric Components	**Variable**
Compressor	E_{comp}
Evaporator pump	E_{evap}
Condenser pump	E_{cond}
Backup heating, electric	E_{backup}
Solar Thermal circuit pump	E_{ST}
Apartment's electric demand	E_{apt}
Heat Transfers	**Variable**
Domestic Hot Water	Q_{DHW}
Space Heating	Q_{SH}
Condenser Heat	Q_{cond}
Solar Heat	Q_{ST}
Solar Heat Losses	$Q_{ST,loss}$

To make the electricity demand clear for each system boundary, grouping of components for each system boundary are done to more easily understand the difference between the proposed KPIs. These are presented in Table 2.

Table 2. Definition of electric demand and components.

Electric Demand	Electric components
E_{HP}	$E_{comp} + E_{evap} + E_{cond}$
$E_{SHP,PV/ST}$	$E_{comp} + E_{evap} + E_{cond} + E_{backup}$ $(+ E_{ST})$
E_{BLDG}	$E_{comp} + E_{evap} + E_{cond} + E_{backup} + E_{apt}$

3.2.1.1 PV Self-Consumption

Self-consumption (SC) is a measure of how much of the PVs power production is used to supply the domestic electricity demand. The SC for PV is studied in this thesis to measure its effect on the SGSHP system. This is because the PV in and of itself does not directly affect the operations of the HP like ST. Therefore, clear definitions of how PV power is used in the system and why is needed. The SC is not itself a used KPI in this thesis as it only relates to the PV, but it is used in order to properly compare PV-HP systems with ST-HP systems. Therefore, the first customer of the PV generation is the HP system in this thesis.

As this thesis focus on MFHs, the electricity load of the building as a whole is also of interest and not only the HP system. When calculating the PV's SPF and SF, the definition of SC becomes relevant as the included electric components change depending on system boundary. While electricity cannot be earmarked for certain loads, the possibility of PV supplying these components is analyzed, i.e. when PV production and the component's load coincide. The components included for the SC are presented in Table 3.

Table 3. Self-Consumption definitions of included components for PV.

SC definition	Components
$E_{PV \cap comp}$	E_{comp}
$E_{PV \cap SHP,PV}$	$E_{comp} + E_{evap} + E_{cond} + E_{backup}$
$E_{PV \cap BLDG}$	$E_{comp} + E_{evap} + E_{cond} + E_{backup} + E_{apt}$

3.2.1.2 Season Performance Factor

SPF is a common choice for HP performance analysis [6]. In the application for PV and ST comparison, the indicator is of importance since it shows how much useful heat is delivered for the required input electricity [6], [42], [43]. For comparison between PV and ST, the system boundaries will follow the respective boundary notation as specified in Figure 11.

The SPF for each system boundary is done in eq. (1)-(4) and uses the variables presented in Table 1-3.

$$SPF_{HP,ST} = \frac{Q_{cond}}{E_{comp}} \tag{1}$$

$$SPF_{SHP\ ST} = \frac{Q_{SH} + Q_{DHW}}{E_{SHP,ST}} \tag{2}$$

$$SPF_{HP,PV} = \frac{Q_{cond}}{E_{comp} - E_{PV \cap comp}} \tag{3}$$

$$SPF_{SHP\ PV} = \frac{Q_{SH} + Q_{DHW}}{E_{SHP,PV} - E_{PV \cap SHP,PV}} \tag{4}$$

Q_{SH} and Q_{DHW} is the space heating and domestic hot water output respectively. Q_{cond} is the condenser heat output. The boundaries entail the same critical factor of supplying heat with an as low as possible electrical input. While PV SC is argued throughout the thesis, for the calculation of SPF it is considered to primarily supply the HP/SHP system for the purpose of the critical factors.

3.2.1.3 Solar Fraction

SF measures the useful (solar) energy supplied by the PV or ST system divided by total heat or electricity demand for each respective system boundary. In other words, how much of the total energy demand is supplied by the solar system. The SF calculations are done in eq. (5)-(8) and uses the variables presented in Table 1-3.

$$SF_{SHP\ ST,1} = \frac{Q_{ST}}{Q_{DHW} + Q_{SH}} \tag{5}$$

$$SF_{SHP\ ST,2} = \frac{Q_{ST} - Q_{ST,loss}}{Q_{DHW} + Q_{SH}} \tag{6}$$

$$SF_{SHP\ PV} = \frac{E_{PV \cap SHP,PV}}{E_{SHP,PV}} \tag{7}$$

$$SF_{PV,BLDG} = \frac{E_{PV \cap BLDG}}{E_{BLDG}} \tag{8}$$

The SF for PV changes depending on the assumption of where the PV production should be utilized, as mentioned earlier.

The ST storage losses will indicate how much useful heat is lost between production and usage and is included in eq. (6). The reason this KPI is important is to accurately compare how larger systems and storages might be prone to more losses.

3.2.2 Economic Indicators

Several economic indicators are used to evaluate the economic performance of PVs [21] and ST systems. In this case compared to technical KPIs, the comparison of ST and PV are straight forward because both system's KPIs are being quantified by a monetary value. Both systems require an initial investment, with yearly benefits and expected payback periods.

Discounted cash flow analysis serve as a basis for many of the investment based indicators in order to assess an investments present value, and estimated return [21]. The reason it is important to use a discounted cash flow analysis is that money is worth more now than in the future. Using a discount rate, we can determine how much more one would value money in the future. A common way to define the discount rate is to consider interest rates of bank loans, average stock market return, inflation or similar studies.

The calculation of net cash flows for the different systems is based around the savings of electricity during operations, seen in eq. (9). This is done by calculating the electricity demand ($E_{el,i}$) for the respective system compared to the reference scenario ($E_{el,ref}$) where neither PV or ST are present. This reduction of electricity consumption then corresponds to a monetary value based on grid electric retail prices calculated in eq. (10). For PV, other benefits which are included are grid sales and green certificates which are awarded to producers of electricity from renewable sources as seen in eq. (11).

$$E_{save,el} = E_{el,ref} - E_{el,i} \tag{9}$$

$$Benefits\ ST = E_{save,el} \cdot P_{buy,el} \tag{10}$$

$$Benefits\ PV = E_{SC,el} \cdot P_{buy,el} + E_{sold,el} \cdot P_{sold,el} + E_{PV} \cdot P_{Cert,el} \tag{11}$$

Costs associated with PV and ST are assumed to an average fixed yearly sum which represents the cost of maintenance and other related costs to the upkeep of ST and PV. A more detailed explanation of used values for costs and benefits used for the results are done in the TRNSYS simulation section. Because the HP systems are identical between the ST and PV cases, no economic analysis of either boreholes or heat pump installations are included.

The calculation of the Internal Rate of Return (IRR) includes expected net cash flow (benefits minus costs, $B_t - C_t$) and initial investment cost I_0. IRR is the rate d that solves eq. (12). The IRR indicator results in a return rate that can be compared to other similar investment options of similar initial cost. As PV and ST cost comparison are one of the key aspects of the thesis the IRR is considered relevant for the overall comparison of ST and PV as it is one of the most commonly used KPI in economic analyses and it helps describe an investment's profitability.

$$IRR = d \text{ when} \sum_{t=1}^{T} \frac{(B_t - C_t)}{(1+d)^t} - I_0 = 0 \tag{12}$$

The payback time (PB) shows in how many years it takes for an investment to generate enough cash flow to repay the initial investment and is calculated in eq. (13).

$$PB = T \text{ when} \sum_{t=1}^{T} (B_t - C_t) - I_0 = 0 \tag{13}$$

The analysis of expected cash flow and initial investment cost is relevant for comparison of the two different options. The Net Present Value (NPV) presented in eq. (14) calculates the current value of the system in terms of discounted net profit. Therefore, an investment with a NPV above zero is defined as profitable.

$$NPV = \sum_{t=1}^{T} \frac{(B_t - C_t)}{(1+d)^t} - I_0 \tag{14}$$

The motivation for the Profitability Index (PI) as a KPI is that while the NPV shows the current value of an investment, it does not highlight the potential differences in initial investments while two options results in similar NPVs. The calculation for the PI is presented in eq. (15).

$$PI = \frac{NPV}{I_0} + 1 \tag{15}$$

The profitability index should exceed 1 for an investment to be profitable. Otherwise (if PI < 1) the initial investment is larger than the present value and should therefore not be considered. NPV holds the same reasoning (NPV should be positive). However, the PI is used to compare ST and PV's economic performance.

3.2.3 Environmental Indicators

Emissions vary depending on what is taken in to consideration for each system. Therefore, comparisons can be misleading when a LCA for example is taken in to consideration in some cases, and only operation related emissions in other cases. Neither ST or PV produce any carbon emissions during operation in and of itself. The indicator presented in eq. (16) shows the total CO_2 emissions. It is calculated by CO_2 conversion of the replaced energy (R_{CO2} [$kg_{CO2\text{-}eq}$/kWh]), now supplied by the carbon emission free solar systems. The reduced CO_2 for each system is calculated in eq. (17).

$$Total\ CO_2 = (E_{el,ref} - E_{save,el}) \cdot R_{CO2} \tag{16}$$

$$Reduced\ CO_2 = E_{save,el} \cdot R_{CO2} \tag{17}$$

As ST and PV have close to the same embedded/embodied emissions and energy payback time [44]–[48], the difference in associated emissions is therefore based on the different usage of grid electricity, which have associated CO_2 emissions per kWh. The CO_2 reduced KPI for ST-HP and PV-HP's operation should therefore be a relevant comparison.

The Swedish grid electricity related emissions are lower than the European and global average due to Sweden's low emission related power production (mainly hydro and nuclear). Common values around 50 g $CO_{2\text{-}eq}$/kWh are associated with Sweden's power grid [49]–[51] while European average is about 440 g $CO_{2\text{-}eq}$/kWh [51]. These values include lifetime emissions related to the power production.

4. TRNSYS simulation

TRNSYS is a graphically based software environment used to simulate the behavior of transient systems calculated in a Fortran compiler. The choice of using TRNSYS is due to the previous research of N. Sommerfeldt who has developed a TRNSYS model of a GSHP system with a MFH and appropriate loads. The simulation runs calculations with three-minute time-steps for one year.

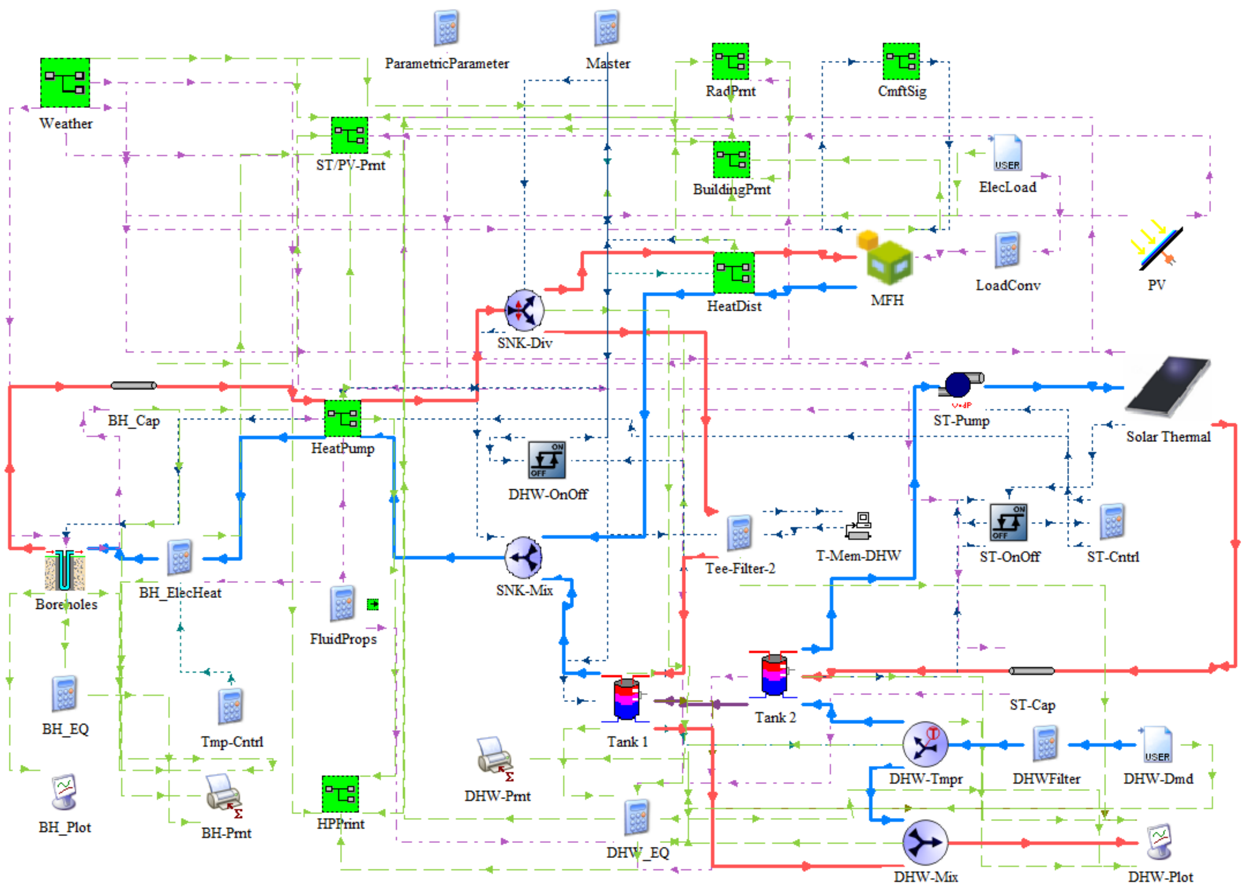

Figure 12. Screenshot of the TRNSYS model.

Figure 12 shows a screenshot of the TRNSYS model used to simulate the SGSHP system. The model is further described in this chapter with focus on the key concepts of this model.

4.1 Weather Data

The model uses weather data based on mid Swedish climate, i.e. Stockholm. Weather data is generated with "Meteonorm" software [52] which uses data from several weather stations in the nearby area. A stochastic model is used to generate the solar radiation data by creating one-minute values from hourly averages [53]. The use of small time steps for solar radiation is important as to not overlook irregular weather behavior which might happen when using up to hourly time steps [11], [54]. The one-minute time steps are then averaged for the tree-minute time step used in TRNSYS. Other weather data uses hourly time steps and are processed in TRNSYS by Type 16a.

This resulted in the data presented in Figure 13, and with a yearly average global horizontal solar radiation of 975 kWh/m^2. Which is what one would expect from a Swedish climate around Stockholm [55]. Figure 13 shows the average ambient air temperatures, as well as the average global horizontal solar radiation for each month.

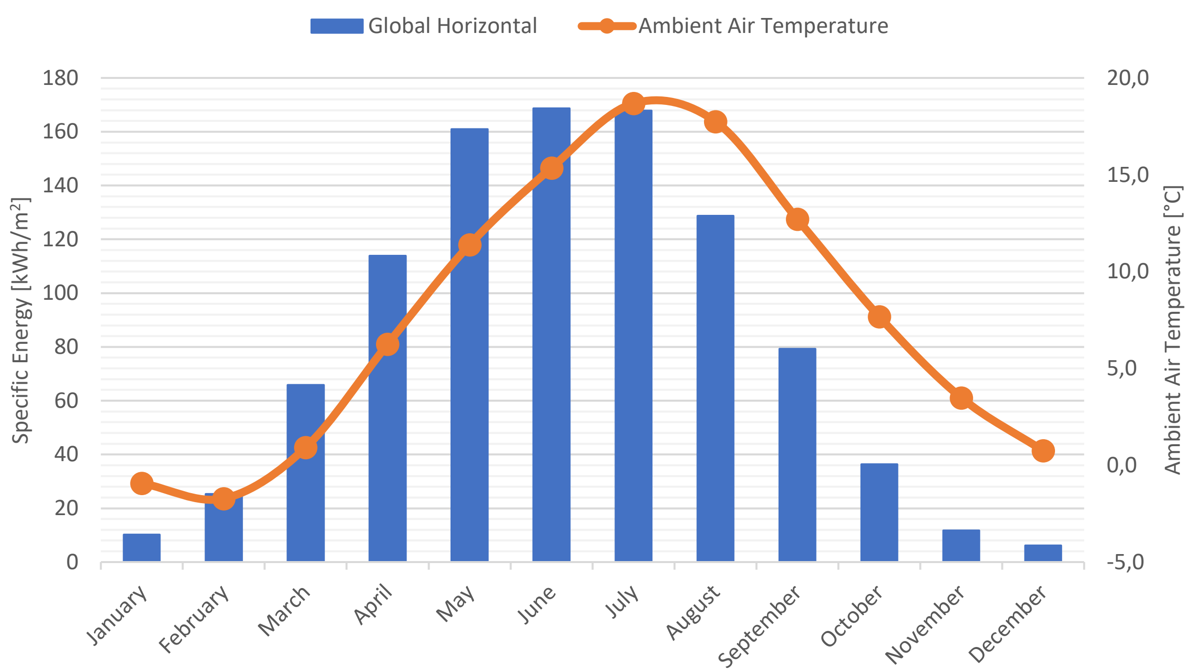

Figure 13. Weather data used in the TRNSYS model over a year. Presented is the global horizontal solar radiation and the ambient air temperature.

4.2 Building Loads

The modelled building is to represent a realistic MFH in Sweden. For the building parameters the Tabula database [56] is used for a 1976-1985 MFH in Sweden and is used in the TRNSYS Type 56. The building also has a limiting roof area of 250 m^2 with a tilt angle of 20°. The building's total heating area is 2 000 m^2.

The heating demand of the MFH in terms of SH and DHW amounts to a total of 133 kWh/m^2.yr and with an electricity demand of 60 kWh/m^2.yr, which is what one would expect from a MFH [57]. These loads are presented in Table 4 and visualized monthly in Figure 14.

Table 4. The Building's heating characteristics.

Parameter	Value	Units
Space Heating Demand	95.9	kWh/m2.yr
Domestic Hot Water Demand	37.6	kWh/m2.yr
Electricity Demand	59.7	kWh/m2.yr

The heating distribution in the TRNSYS model is done via wall-mounted radiators in eight zones with no air flow between the spaces. A heating curve sets the supply temperature and is done at the heat pump. The TRNSYS model layout for the heating in the eight different zones is presented in Figure 15. DHW and internal heat gains are generated by a stochastics model [55-56] in one minute intervals and averaged to a three minute interval which was used for the TRNSYS simulation. One assumption was that the buildings internal energy gains consisted of both human heat and the use of electrical appliances. These internal gains are added to the building zones as 80% radiative and 20% convective, while latent energy is not modeled.

The DHW demand is supplied by the HP, backup heating, or ST. It utilizes two storage tanks of 1 m^3 each in the case of no ST, but in which case further storage is added and is discussed in the Solar Thermal Collector part of this chapter.

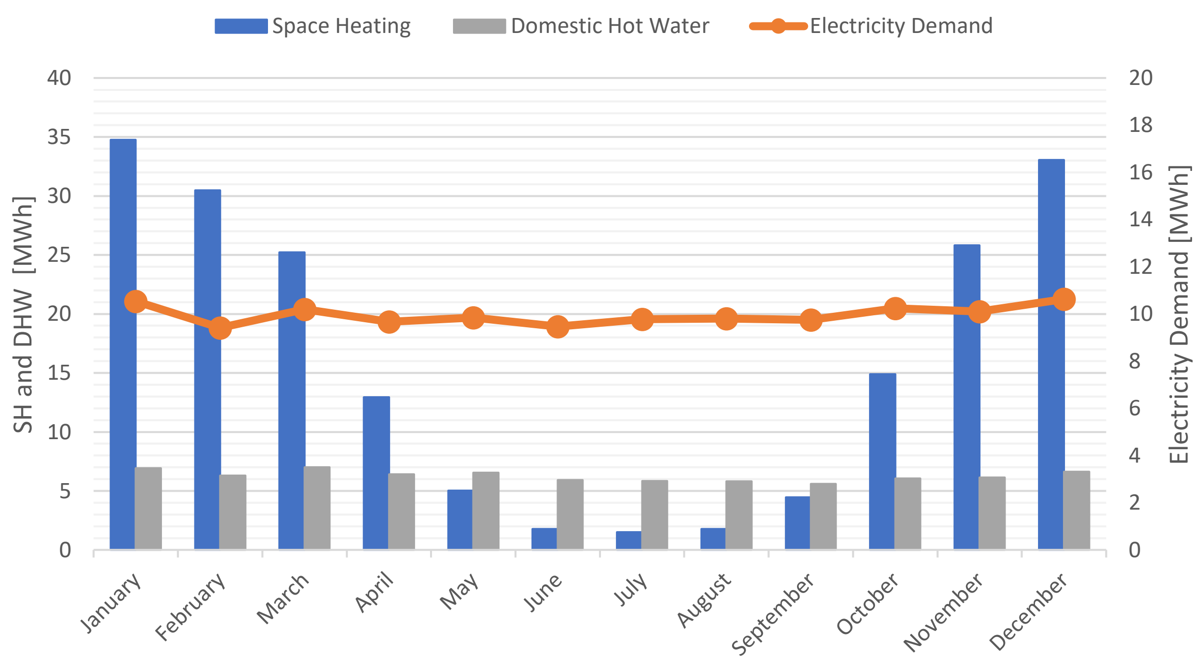

Figure 14. The building's total space heating, domestic hot water, and electricity demand per month.

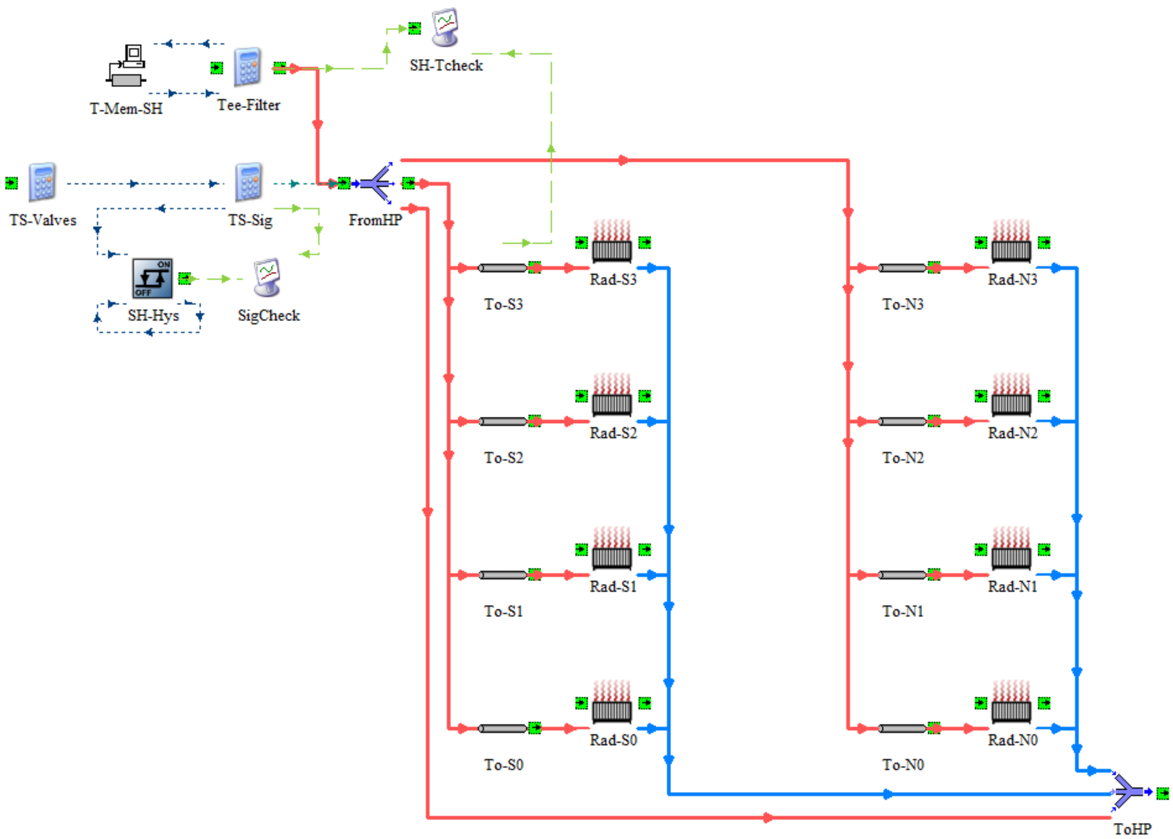

Figure 15. Screenshot of the heating distribution by radiators in the buildings eight zones.

4.3 Heat Pump

The HP modelling is based on an existing HP which has a rated peak power of 88 kW_{th} and uses a variable speed scroll compressor in the range of 1 500 – 6 000 rpm [60]. The HP is modeled in TRNSYS by using a multi-dimensional interpolated performance map [11] [61]. The HP model in TRNSYS is shown in Figure 16. The performance map uses the Type 581 which is a multi-dimensional data interpolator and is used as a three-dimensional data interpolator in the model. These three parameters are; the source fluid temperature; supply return temperature; and compressor speed. The component then returns the compressor electricity load ($\dot{E}_{Comp}$) and the condenser heat rate ($\dot{Q}_{Cond}$). These two variables are then used to calculate evaporator heat rate ($\dot{Q}_{Evap}$) from the relation of eq. (18).

$$\dot{Q}_{Evap} = \dot{Q}_{Cond} - \dot{E}_{Comp} \tag{18}$$

From these heating rates the outlet temperatures of both the evaporator and condenser can be calculated from eq. (19) - (20) where T_{in} is the inlet temperature, $\dot{m}$ the mass flow rate and c_p is the specific heat capacity. The results of these equations are used in the “EvapHEX” and “CondHEX” units presented in Figure 16.

Evaporator: $$T_{out,evap} = T_{in,evap} - \frac{\dot{Q}_{Evap}}{\dot{m}_{BRN} c_{p,BRN}} \tag{19}$$

Condenser: $$T_{out,cond} = T_{in,cond} + \frac{\dot{Q}_{Cond}}{\dot{m}_{H20} c_{p,H20}} \tag{20}$$

A proportional/integral controller is used to control the compressor speed and is modelled by Type 23. The controller compares the supply temperatures with the heating curve’s target temperatures and adjust the compressor speed accordingly. As the HP supplies both SH and DHW loads, a control system to shift between the two are used. The DHW switch turns On when the temperature in the DHW storage drops below 50 °C and Off when it increases above 55 °C. The ST collectors are coupled with a separate storage tank, with which the HP-DHW storage is connected in series with. Therefore, the HP-DHW storage could reach temperatures well above 55 °C and thereby not require any heat from the HP. Once the HP switches between On and Off, it will remain in either state for a minimum duration of 15 minutes.

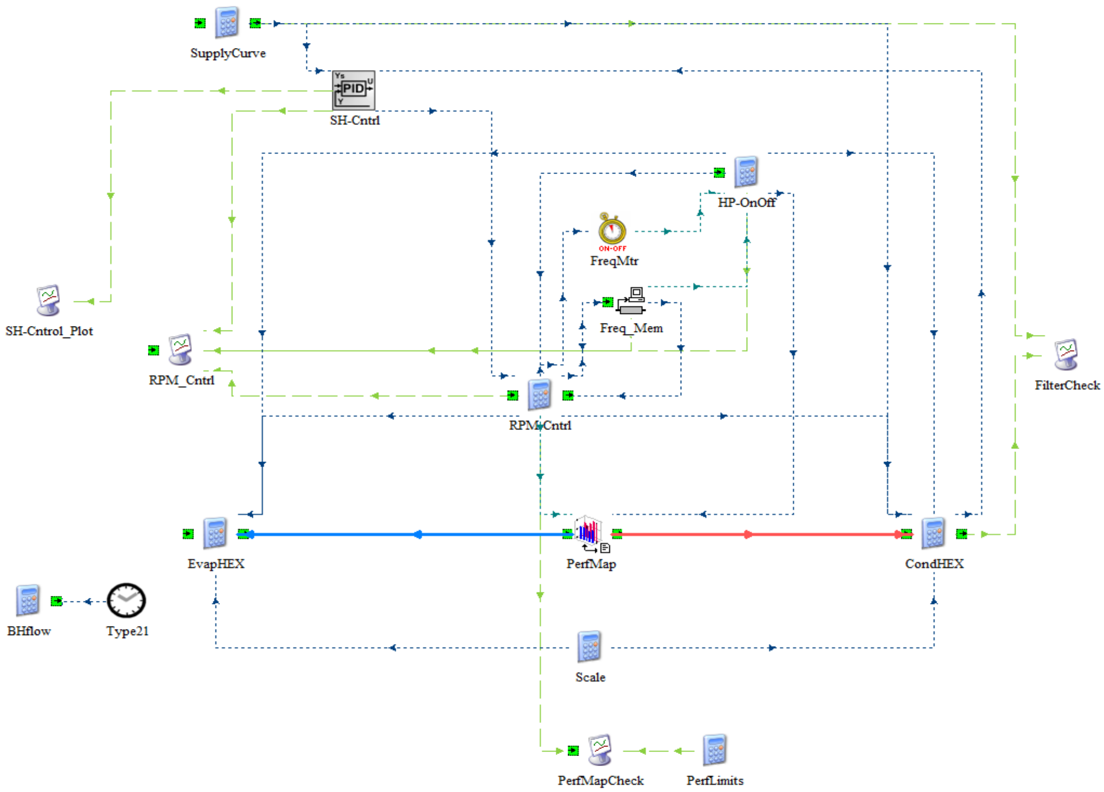

Figure 16. Screenshot of the heat pump macro in the TRNSYS model.

4.4 Solar Thermal Collector

In the literature review different collector technologies were discussed. However, different types of ST collectors are not compared in the model for performance evaluation through identified KPIs and will instead focus on FPCs as the collector of choice in the TRNSYS simulation.

The FPCs are connected to a separate storage tank on the HP sink side, representing a parallel SHP connection as described in Figure 9. A pump, connection pipes and an internal heat exchanger in the storage tank are included in the model. The ST is modelled with Type 539 and the pump used is a constant speed pump with a predefined pressure drop of 50 kPa and is modelled with Type 740.

Flow rates for ST collectors are suggested for a range between 20 – 100 l/hr.m^2 and a flow rate of 30 l/hr.m^2 are chosen as is a common flow rate for similar cases [11][33][62]. The fluid is a propylene glycol-water mix, of 40 % propylene glycol. Further studies of different flow rates are not done.

Data for solar collectors are estimated based on common values from similar studies which also utilizes Type 539 to model FPCs [32]. Some of the key parameters are presented in Table 5, and the FPC 2nd order efficiency equation is presented in eq. (21). T_{coll} [K] is the collector temperature, T_{air} [K] is the ambient air temperature and I_T [W/m^2] is the total irradiance on the collector surface.

Table 5. Input variables used for Type 539 to model a ST FPC.

Parameter	Value	Units
Intercept Efficiency (a_0)	0.84	-
1st Order Efficiency Coefficient (a_1)	3.1	W/m^2.K
2nd Order Efficiency Coefficient (a_2)	0.015	W/m^2.K^2

$$\eta = a_0 - a_1 \frac{(T_{coll} - T_{air})}{I_T} - a_2 \frac{(T_{coll} - T_{air})^2}{I_T} \tag{21}$$

The collectors are connected in parallel, and no testing of different system layouts are done. The tilt angle of the collector is the same as the building’s roof of 20°.

The choice of storage is based on an average recommended storage of 70 - 100 liters per m^2 collector area [63]. For the utilization of ST, a storage size of 80 l/m^2 is used with a total maximum storage capacity of 6 m^3 (for a collector size of >75m^2) due to limited space to accommodate for any larger storage sizes.

4.5 Photovoltaic

For the PV integration with the HP system, no real configuration specification is necessary in the TRNSYS model. However, an analysis of system performance depending on supply prioritization and SC is relevant to properly compare the impact of PV on the HP system. The tilt angle of the PV is the same as the building's roof of 20°.

The TRNSYS type 562 is used to model the PV which simulates a glazed PV panel based on a temperature and radiation dependent efficiency. The calculation is presented in eq. (22) where T_{PV} is the PV cell temperature and I_T the total irradiance on the PV surface. Other input parameters are presented in Table 6.

$$\eta = \eta_{ref}\left(1 + \eta_{T,coef}\left(T_{PV} - T_{ref}\right)\right)\left(1 + \eta_{I,coef}\left(I_T - I_{T,ref}\right)\right) \tag{22}$$

Table 6. PV efficiency input data used in TRNSYS Type 562.

Parameter	**Value**	**Units**
Reference efficiency (η_{ref})	0.15	-
Efficiency modifier – temperature ($\eta_{T,coef}$)	-0.004	1/°C
Efficiency modifier – radiation ($\eta_{I,coef}$)	0.00009	m^2/W
Reference radiation ($I_{T,ref}$)	1000	W/m^2
Reference temperature (T_{ref})	25	°C

4.6 Borehole

The model uses vertical boreholes for the HP's evaporator. The borehole uses type 557 which is based on mathematical research from University of Lund 1989 [64]. Presented in Table 7 are the key borehole parameters used in the TRNSYS model [11]. The heat transfer fluid used in the boreholes is an ethanol-water mix of 30 % ethanol.

As the borehole circuit in and of itself is not a key part of this thesis, the literature review and analysis of it is limited. The used parameters and data are from the previous study of [11].

Table 7. Borehole parameters used in TRNSYS Type 557.

Parameter	Value	Units
BH Depth	225	m
BH numbers	8	-
Ground Conductivity	2.8	W/m.K
Ground Thermal Capacity	2016	kJ/m^3.K
U-tube Inner Diameter	0.018	m
U-Tube Outer Diameter	0.02	m
Shank Spacing	0.080	m
BH Fill Conductivity	1	W/m.K
Pipe Conductivity	1.5	W/m.K

4.7 Economic assumptions

The cost of buying electricity is assumed at 1 SEK/kWh. Power sold to the grid are valued lower and assumed at 0.3 SEK/kWh. The operational costs for both PV and ST are estimated to 500 SEK annually on average.

Initial cost of PV is estimated to around 12 SEK/W without VAT for large roof-top systems [34] and was used for this thesis. PV also receives a 30 % subsidy on the total initial cost, as well as increased benefits from green certificates of 0.15 SEK/kWh on average for 15 years after installation [65].

The initial cost related to ST varies a lot depending on building layout, collector prices, design/planning, and installation. The result of similar studies and their used turnkey costs were presented in the literature review with example turnkey costs of over 10 000 SEK/m^2, while others were as low as 2 000 SEK/m^2 [11], [31], [33]. Based on this, an initial turnkey cost of 5 000 SEK/m^2 excluding VAT is used.

5. Results

The results presented are those from the TRNSYS model of ST or PV integration for a GSHP in a MFH. The results are primarily presented for different system sizes as it is a relevant parameter for both technologies. It is also an important parameter for the stakeholders associated with MFHs and the limiting roof top area in this thesis focus. The range of size is between 37 and 204 m^2 for both ST and PV based on the number of modules and sizes. No systems using combinations of PV and ST was done.

The total produced useful energy produced is presented in Figure 17, where the PV electricity production and ST heat production is presented for different system sizes. The production of ST decreased with increasing size due to the limited demand, storage capacity and losses.

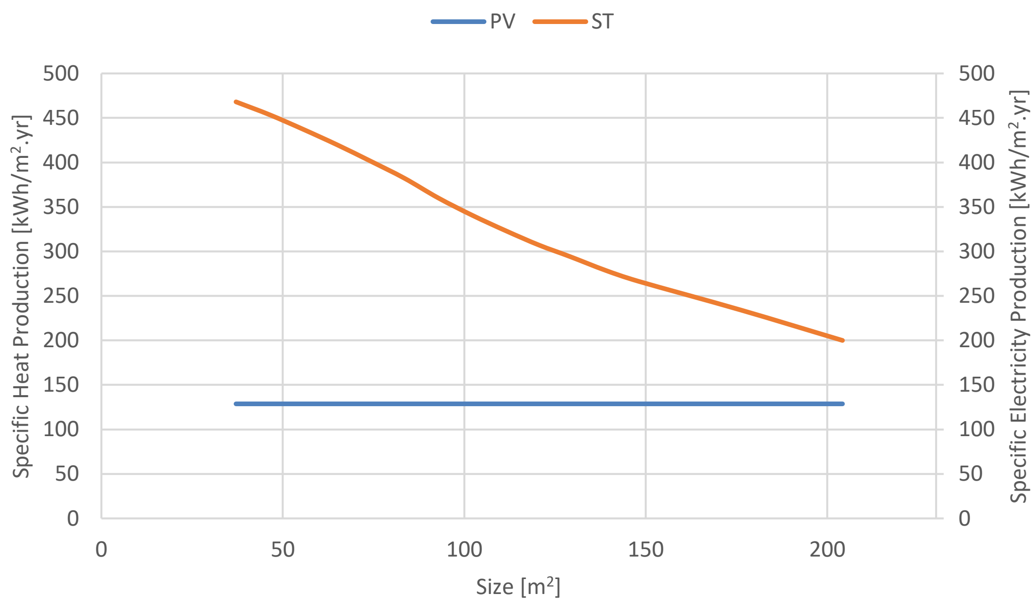

Figure 17. Specific Energy Production of the ST and PV for different system sizes.

The basis for comparison of ST and PV is their impact on the electricity consumption of the GSHP. While ST lowers electricity consumption by directly reducing the demand of DHW production by the GSHP, the PV power production does not directly affect the power consumption of the GSHP. Therefore, the results presented in Figure 18 account for PV SC for each system boundary. The figure shows the electricity consumption for each system boundary and solar system. For the case of PV, the electricity consumption is lowered by the definition of SC presented earlier for each system boundary.

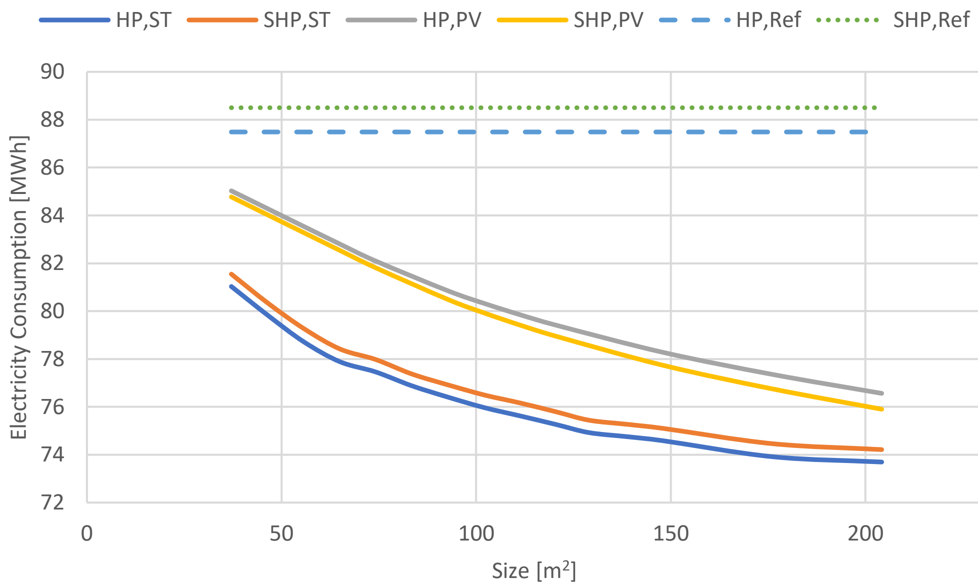

Figure 18. Total electricity consumption for different system boundaries and system.

5.1 Technical performance

Presented in Figure 19 is the SC for the different system boundaries and PV sizes. The PV self-consumption is defined as electricity used by the electrical components within each specified system boundary at the same time step where PV generates electricity. For these results, the PV "prioritize" the SGSHP system, but the case of apartment prioritization is also presented. This SC definition (presented as SHP-Apt) means that apartments are prioritized over the SGSHP system which are only supplied if PV generation is larger than apartment demand. The energy production of PV presented earlier shows the total energy production. However, from Figure 19 it is seen that only a part of that power can be used exclusively for the SGSHP (system boundary SHP,PV and HP). The apartment load however allows further usage of the PV production, and while the total SC starts to decrease above 145 m^2, it can still supply the grid.

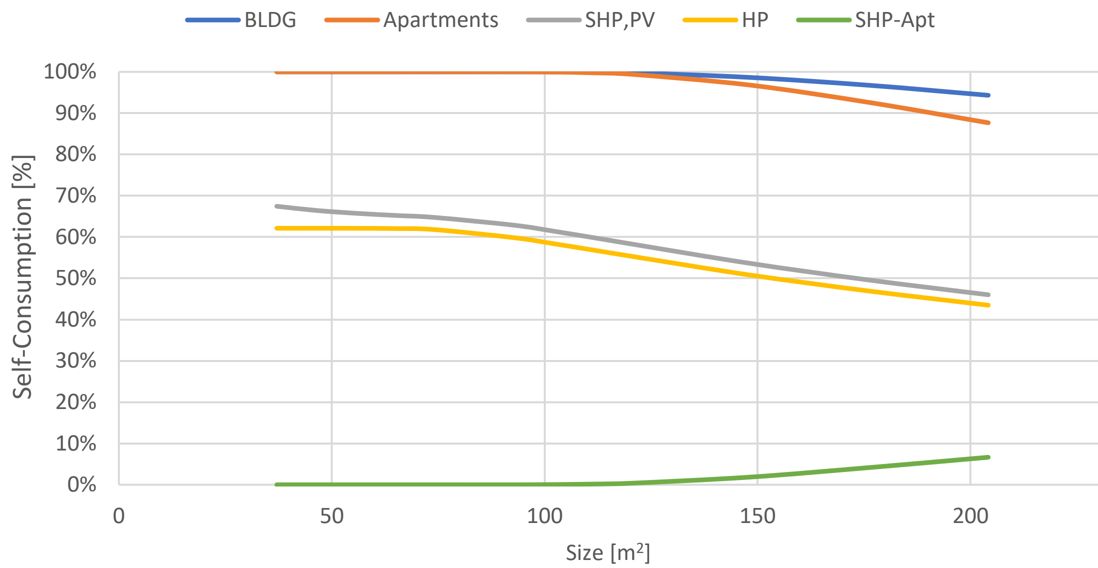

Figure 19. Total Self-Consumption of PV for different sizes and system boundaries.

For the SPF, the different system boundaries (HP and SHP-PV/ST) are defined according to the equations (1(4). The results for the SPF are presented in Figure 20. The reference scenario of no ST or PV for each of the system boundary are presented as flat dotted lines.

The performance of the SGSHP in terms of SPFs increase with increasing ST/PV size for both system boundary. As seen from the PV's SC, a lower percentage of total production can be utilized for the SGSHP with increasing size. However, the total production (in kWh) increase linearly with size as seen in Figure 17. This means that even though SC (in %) decrease, the used power (in kWh) from the PV in each system boundary increases (not linearly) due to the larger total production of PV. This cause the increasing SPF for the PV-GSHP to diminish, however, not as fast as ST.

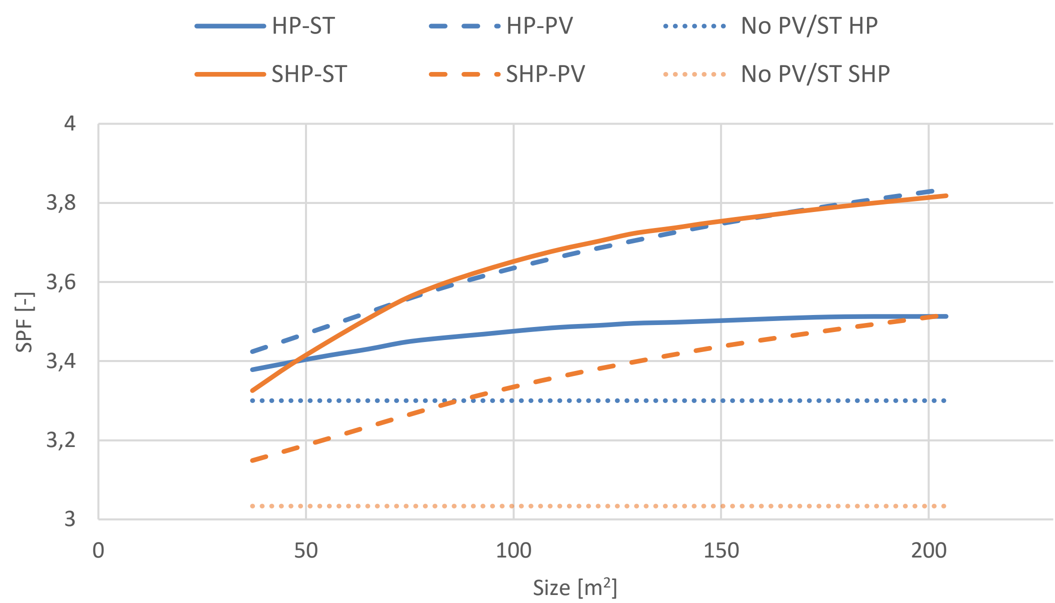

Figure 20. SPF for ST and PV at different system boundaries.

The SF presented are defined after the specific system boundaries. The SF for ST and PV shows how much of the total heat or electricity is supplied by the ST and PV and is presented in Figure 21. The inclusion of SHP-ST_{loss} is to properly highlight the fact that storage losses for larger sizes has a notable impact on the results.

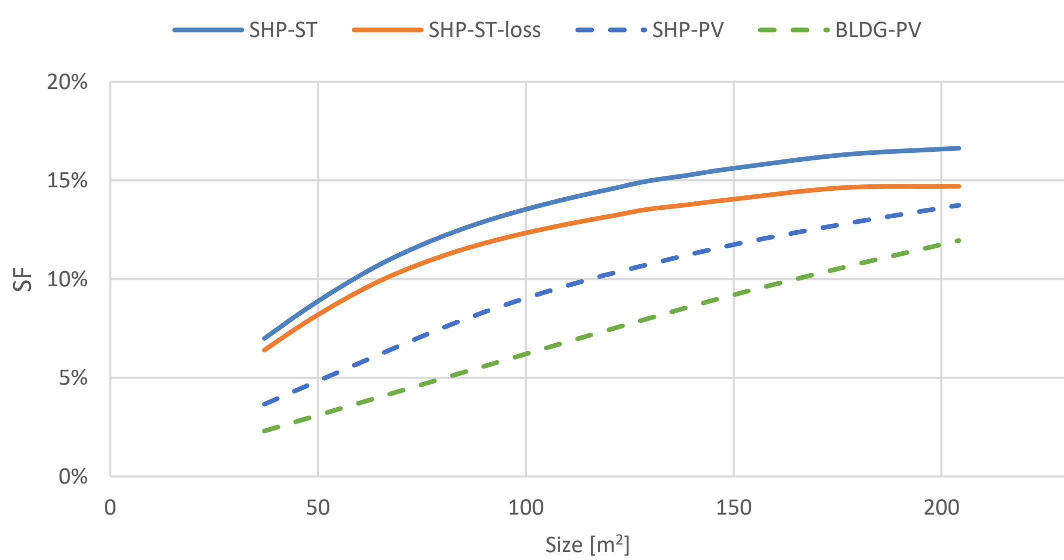

Figure 21. SF for ST and PV at different system boundaries

5.2 Economic performance

As presented earlier, the ST yield decrease with increasing system size due to the limited use of the larger total production of heat. PV production however remains constant as it always can supply either the building or the grid. However, grid supply is valued lower than when electricity is used in the building itself. But as seen previously, the total SC of PV remains at 100 % up until system sizes of 145 m^2 and reaches 94 % at a size of 204 m^2. Therefore, the impact of grid sales is minimal.

The benefits and costs associated with ST and PV are essential to their comparison. As seen in Figure 22 ST provides a larger net cash flow per year for sizes less than 65 m^2. But due to the stagnating energy yield presented earlier, so follows the associated benefits. The net cash flows presented are the cost savings from the reduced net electricity demand for the SGSHP system as explained earlier. The net cash flow associated with PV remains constant due to the high total SC.

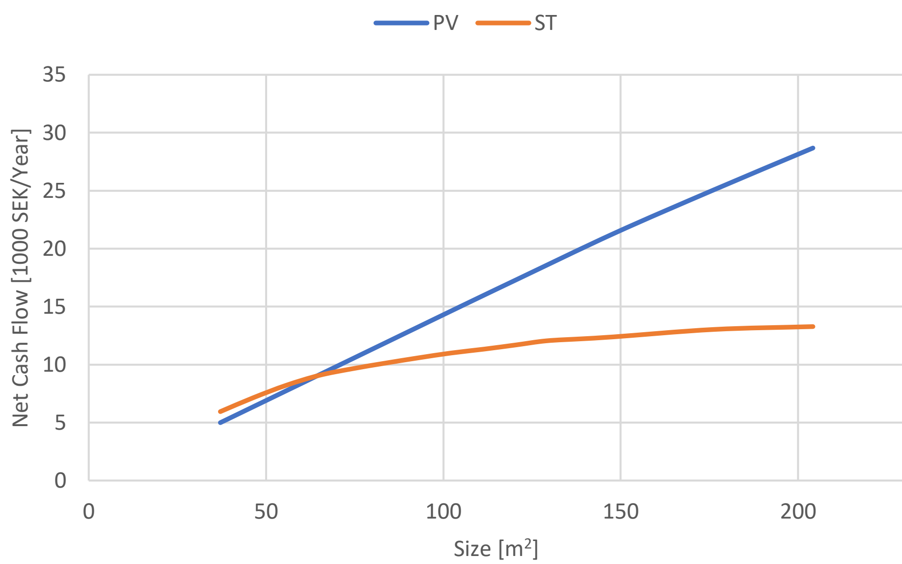

Figure 22. Net Cash Flow from ST and PV for different sizes.

For the calculation of the NPV, a 3% real discount rate was used. As seen in Figure 23 and Figure 24, the NPV and the payback time for the PV is favorable over the ST. This is primarily due to the larger initial cost for ST and diminishing returns compared to PV.

The expected lifetime of ST is 20 years and 25 years for PV.

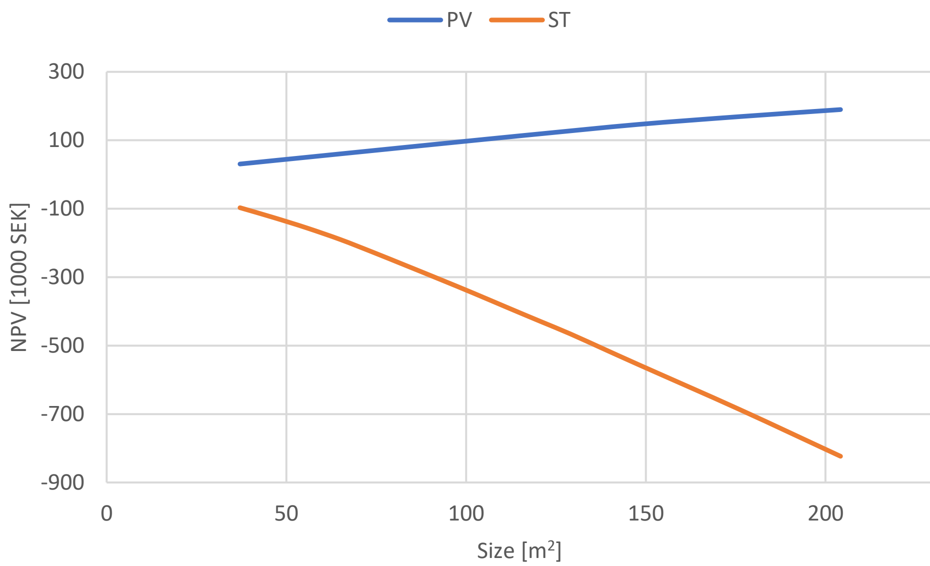

Figure 23. NPV for ST and PV at different sizes.

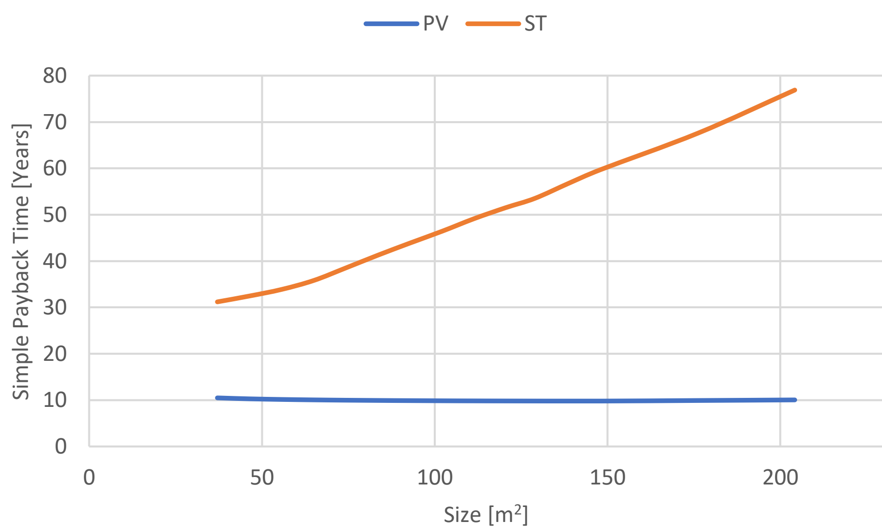

Figure 24. Payback time for ST and PV at different sizes.

The NPV of PV is in this case larger than zero which means that an IRR is applicable. However, as ST has a negative NPV for all sizes, IRR is not applicable. Therefore, only the IRR relating to PV is presented in Figure 25. As seen, it peaks around 9% at 148 m^2.

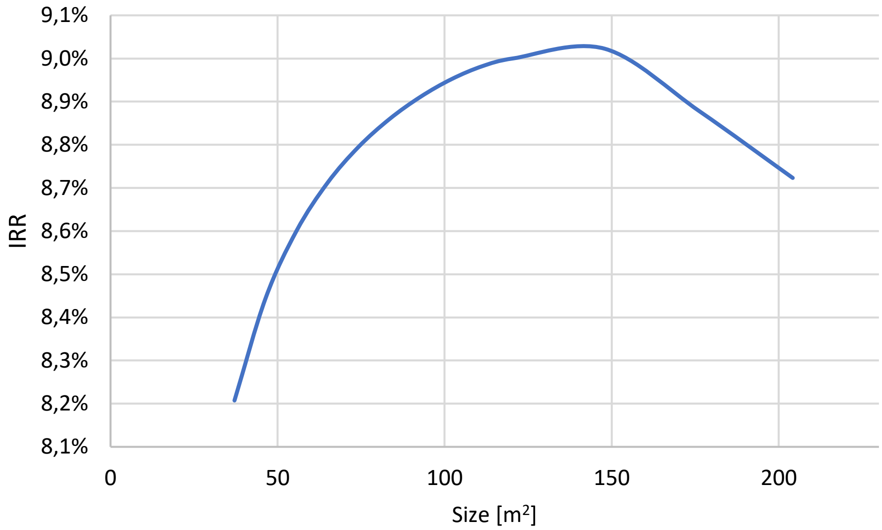

Figure 25. IRR for PV.

The PI is presented in Figure 26. As seen, the PI for PV is favorable for all sizes and larger than 1. It is also observed to peak around 1.7 at 148 m^2. However, the financial performance for ST is lower and in the range of 0.2 to 0.5.

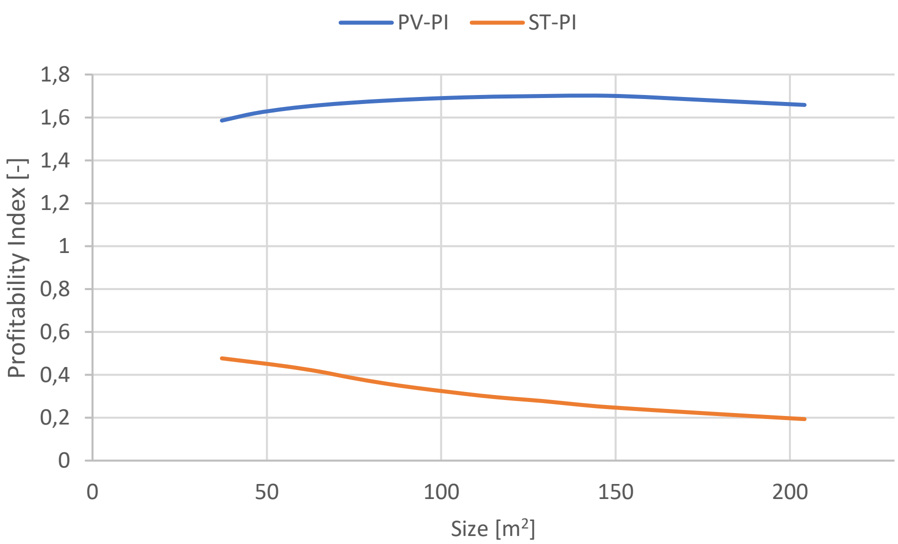

Figure 26. PI for ST and PV.

5.3 Environmental Impact

The environmental benefits of reducing the GSHP's electricity demand by these solar systems are presented in Figure 27 for different sizes. The total and reduced emissions are presented in $CO_{2\text{-eq}}$ for the systems operations i.e. the emissions associated with the reduced electricity consumption. As grid electricity has associated emissions [kg $CO_{2\text{-eq}}$/kWh], a domestic production of electricity from PV or electricity demand reduction from ST would then result in lower $CO_{2\text{-eq}}$ emissions for the SGSHP system compared to a HP system not utilizing solar technologies.

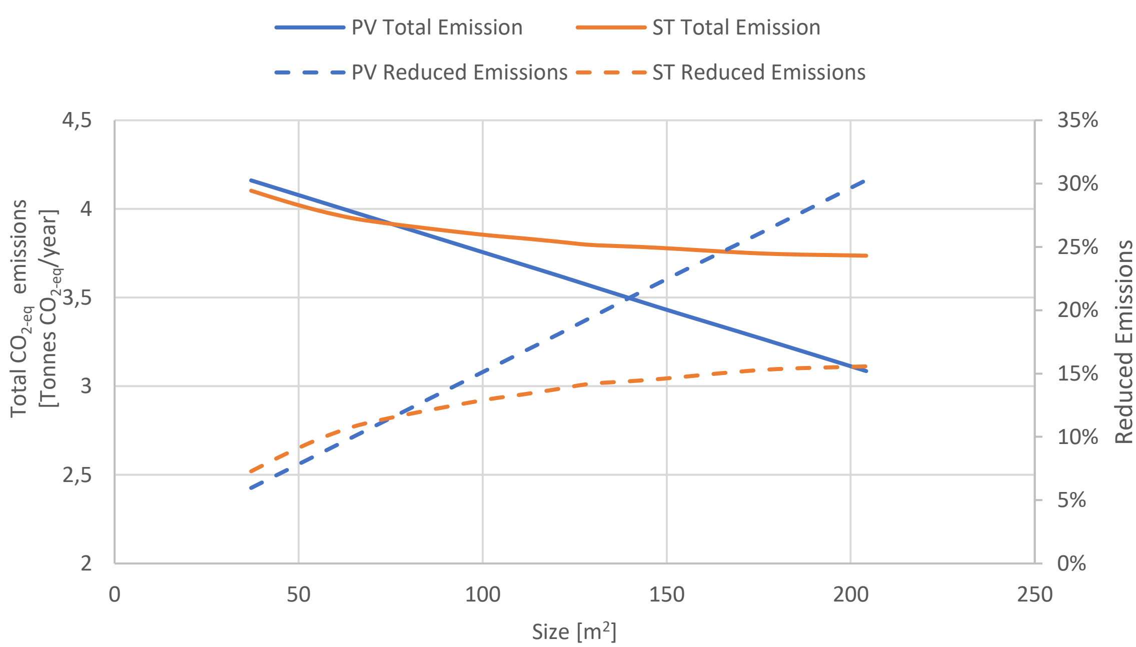

Figure 27. Total Emissions and Reduced Emissions for the two SGSHP systems.

While ST only affects the SGSHP's electricity demand, the power from the installed PV can be sold to the grid. In this result, the total PV production is assumed to lower emissions, even when sold to the grid.

5.4 Sensitivity Analysis

To properly compare the system's viability for MFHs, a sensitivity analysis is done for the systems economic performance which is a key decision point. The parameters of change are the initial costs, expected electricity prices, discount rate. The results are presented in payback time and PI.

PV installations obtain a 30 % discount of the total cost and green certificates per produced kWh while ST does not. Therefore, the case of no benefits is included, meaning no green certificates or initial cost reduction. This was done to highlight the impact of these incentives on PV's profitability.

5.4.1 Initial Costs

The initial cost analyzed are in the range of previously seen studies. While ST is calculated and commonly reported using a specific turnkey cost in [SEK/m^2] the PV uses [SEK/W] as specific turnkey cost. The impact of initial costs is also applied to the PV case which excludes benefits. As specified earlier, the initial cost analyzed is the total turnkey initial cost, meaning it includes modules, shipping, planning/design and complete installation.

The initial cost of both PV and ST is important in the decision making of investment choice. As seen previously, the initial turnkey cost of ST varies widely depending on several parameters. The range of tested initial costs for ST is therefore between 2 000 – 8 000 SEK/m^2 as is the common range presented earlier. For PV, a cost range between 4 – 20 SEK/W is used. The reference cases are presented in grey dotted lines.

The results presented in Figure 28 shows that the initial cost of ST has a large effect on expected payback time. The lines show the payback time at different costs in [SEK/m^2]. In the range between 2000 – 8000 SEK/m^2 (with 5000 SEK/m^2 as reference) we see a large range of payback time from as low as 12 years for 2000 SEK/m^2 at 37 m^2 and up towards 123 years for 8000 SEK/m^2 at 204 m^2.

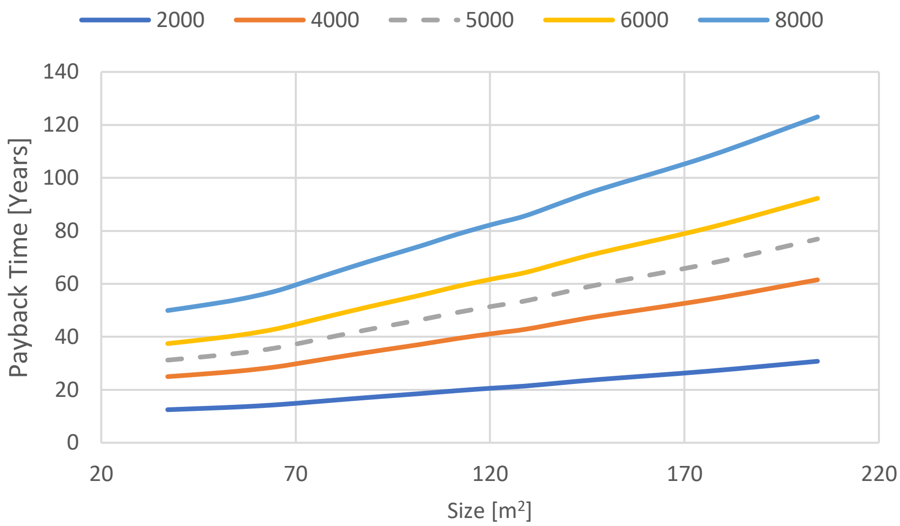

Figure 28. Payback Time [Years] of ST for different initial costs [SEK/m²] and sizes [m²].

For the profitability of ST, the PI is presented in Figure 29. As previously mentioned, a PI larger than 1 means that the investment is expected to be profitable. This is achieved for the lower cost of 2000 SEK/m² at sizes lower than 70 m². For the calculation of the PI a discount rate of 3 % is used, as in the result, for the NPV.

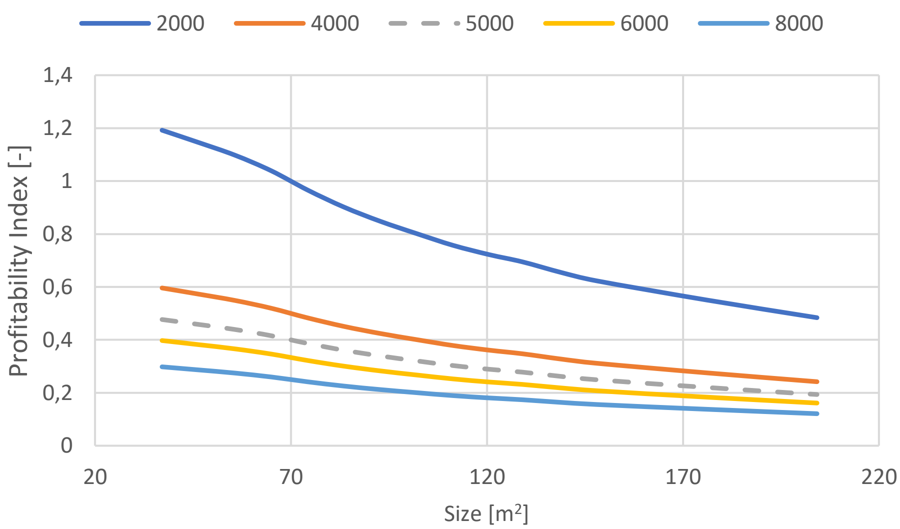

Figure 29. Profitability Index [-] of ST for different initial costs [SEK/m²] and sizes [m²].

The results for PV show a smaller range of payback time over different initial costs varying from around 3 to 18 years. The initial turnkey costs are presented in [SEK/W] with the reference value of 12 SEK/W is represented by the grey dotted line and a range between 4 and 20 SEK/W. The results for the payback time are presented in Figure 30.

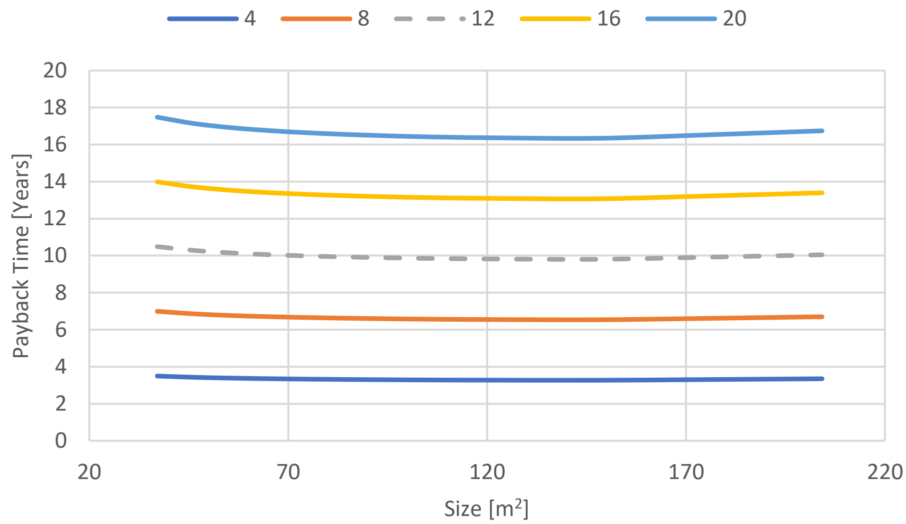

Figure 30. Payback Time [Years] of PV for different initial costs [SEK/W] and sizes [m^2].

For the highest initial cost of 20 SEK/W a PI slightly lower than 1 is obtained. It is seen that at that cost, the PV system can still be profitable. The results for the PI are presented in Figure 31.

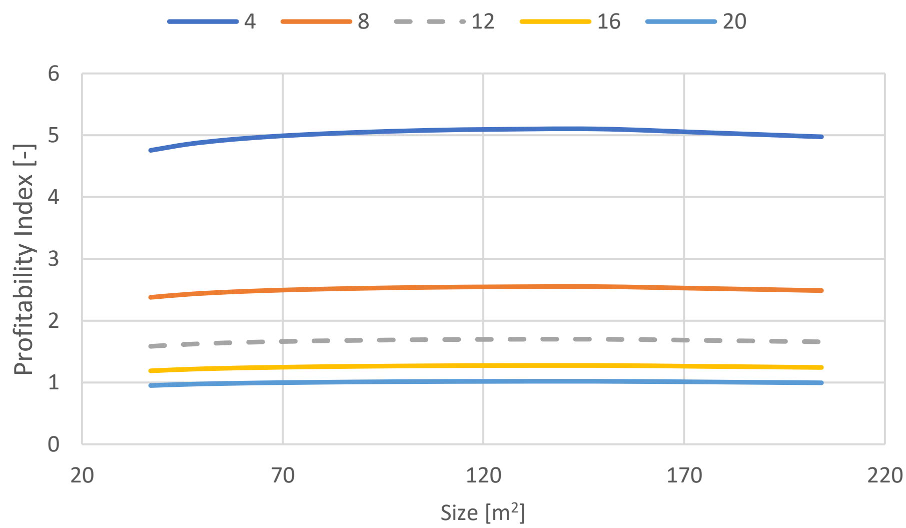

Figure 31. Profitability Index [-] of PV for different initial costs [SEK/W] and sizes [m^2].

For the case of PV excluding benefits, a payback time in the range of around 5 to 30 years are observed. The results for payback time are presented in Figure 32. For the case of initial costs of 20 SEK/W a larger payback time than the expected lifetime of 25 years is obtained.

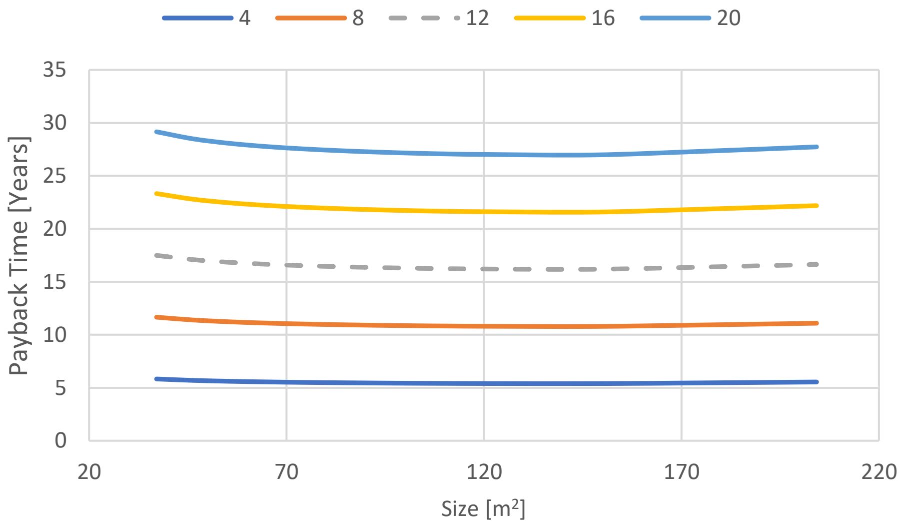

Figure 32. Payback Time [Years] of PV (excluding benefits) for different initial costs [SEK/W] and sizes [m²].

As seen in Figure 33 the PI ranges widely and show that for costs higher than 12 SEK/W results in non-profitable investments.

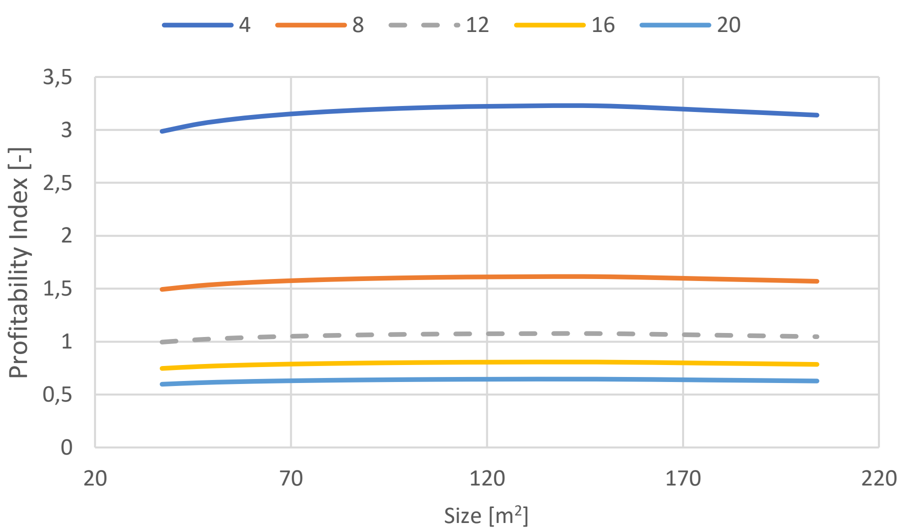

Figure 33. Profitability Index [-] of PV (excluding benefits) for different initial costs [SEK/W] and sizes [m²].

5.4.2 Cost of electricity

For the cost of electricity, a standard value of 1 SEK/kWh was used in the results. Here, a range between 0.6 and 1.4 SEK/kWh is used. The value of electricity varies depending on what to include (spot price, tariffs, taxes and so on), and seasonal and intraday spot price variance. In these results the cost, or value, of electricity is changed to determine the financial performance of each system, also including the case for PV without any of the existing financial benefits mentioned previously.

As these systems primary benefit is the reduction of electricity consumption of the existing GSHP, a higher cost of electricity is more beneficial for both solar systems since it saves more money.

The payback time for the ST is presented in Figure 34 for different costs of electricity [SEK/kWh] and sizes [m^2]. The reference case of 1 SEK/kWh is marked as a grey dotted line. It is seen, as mentioned previously, that the higher cost of electricity results in more savings and thereby a better financial performance.

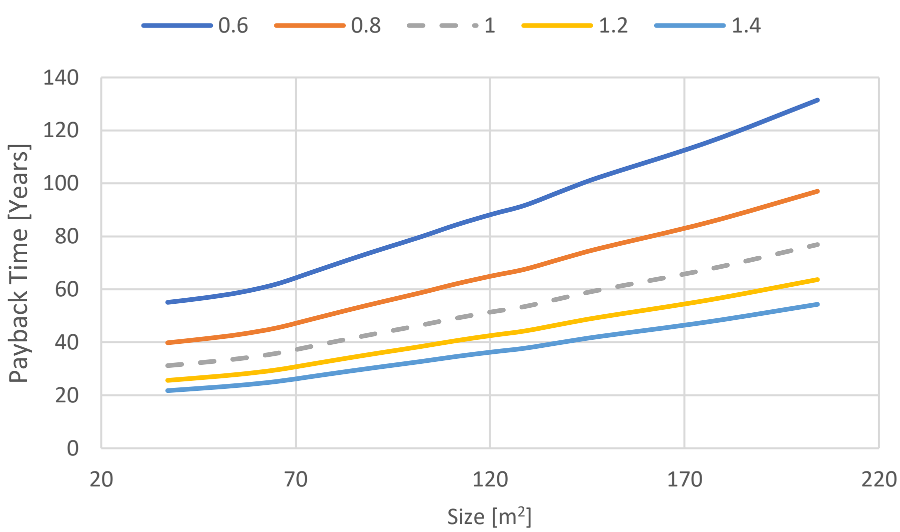

Figure 34. Payback Time [Years] of ST for different costs of electricity [SEK/kWh] and sizes [m^2].

This is also observed in Figure 35 for the PI. However, a PI above 1 is not reached for any value for ST, meaning the investment is not profitable.

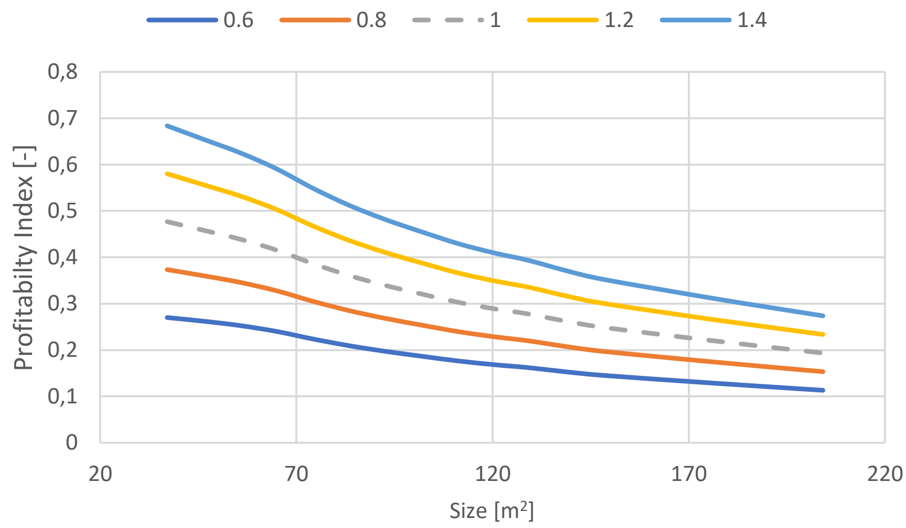

Figure 35. Profitability Index [-] of ST for different costs of electricity [SEK/kWh] and sizes [m^2].

PV still shows sign of being profitable over the range of different electricity costs. The payback time is presented in Figure 36 and the PI in Figure 37 for the PV system.

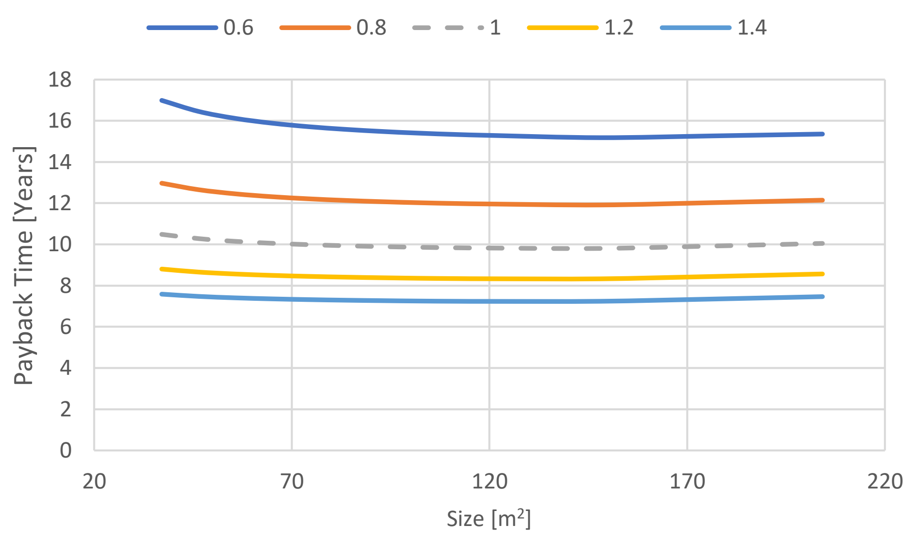

Figure 36. Payback Time [Years] of PV for different costs of electricity [SEK/kWh] and sizes [m^2].

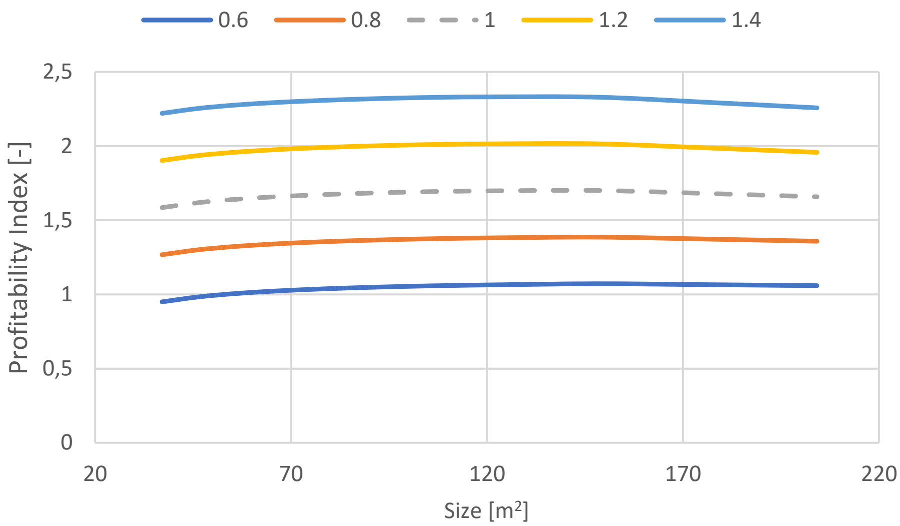

Figure 37. Profitability Index [-] of PV for different costs of electricity [SEK/kWh] and sizes [m^2].

When the benefits of green certificates and initial cost subsidy are removed, the payback time of PV increases, and PI reduces. The payback time is presented in Figure 38 and the PI in Figure 39 for PV.

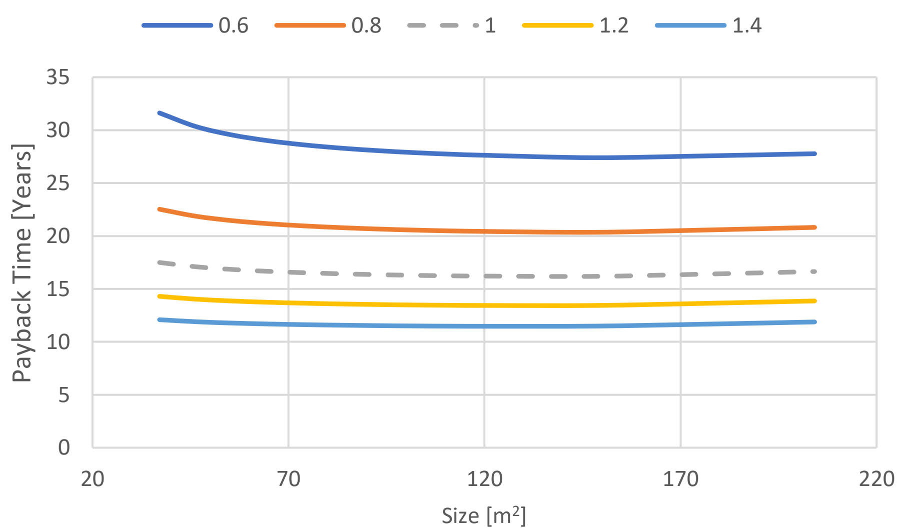

Figure 38. Payback Time [Years] of PV (excluding benefits) for different costs of electricity [SEK/kWh] and sizes [m^2].

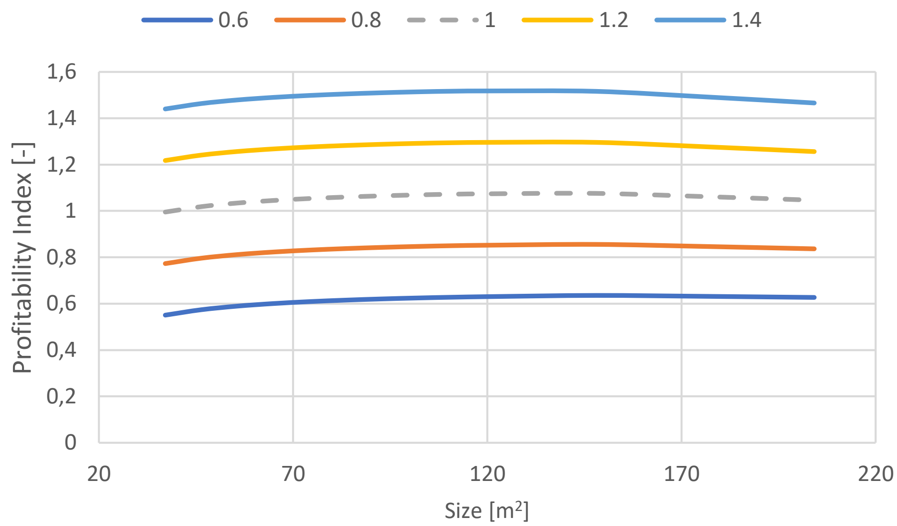

Figure 39. Profitability Index [-] of PV (excluding benefits) for different costs of electricity [SEK/kWh] and sizes [m^2].

These results show that without these benefits, and at low enough electricity costs, the investment in to PVs is not profitable.

5.4.3 Discount Rate

The discount rate shows how much one value money in the future. A discount rate of 0% would mean that future cash flow is valued as if they were acquired today. The choice of assumed discount rate has an effect on the present value of an investment. Therefore, the results of this sensitivity analysis are presented as NPV and PI, as the discount rate has no effect on payback time.

As seen in Figure 40 the ST systems NPV does not change significantly depending on the discount rate and still shows non-profitable outcomes.

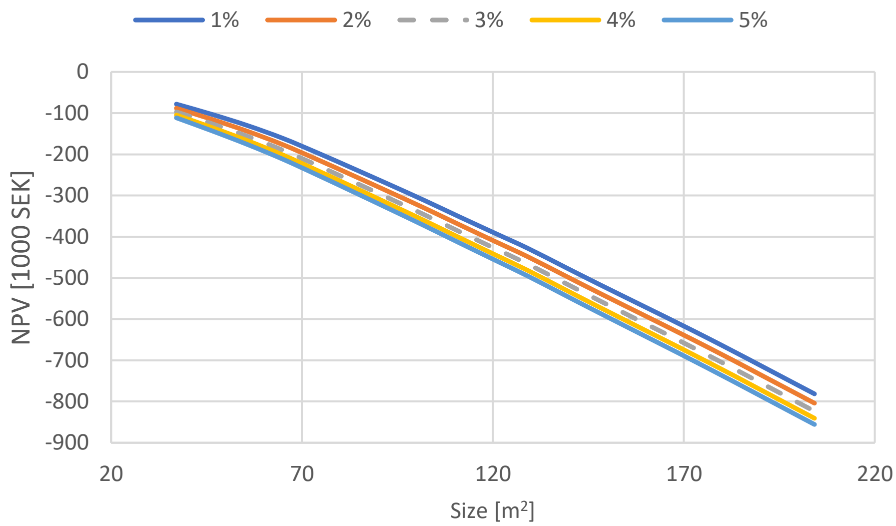

Figure 40. NPV [1000 SEK] of ST for different discount rates [%] and sizes [m^2].

This is also observed in Figure 41 that the ST system is not profitable at any presented size and discount rate.

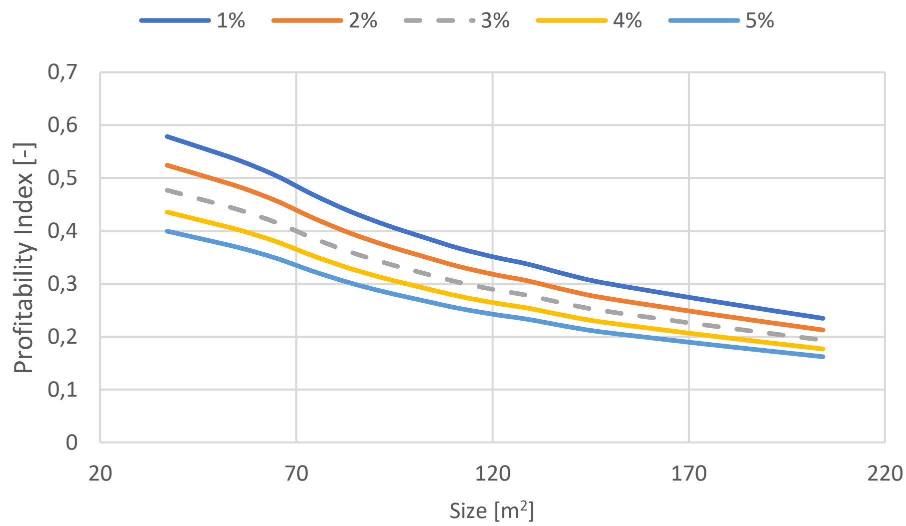

Figure 41. Profitability Index [-] of ST for different discount rates [%] and sizes [m^2].

For PV, an analysis was done for both the case of benefits and no benefits. The sensitivity analysis shows that PV, including benefits, are profitable over the range of presented discount rates. The NPV is presented in Figure 42 and the PI in Figure 43.

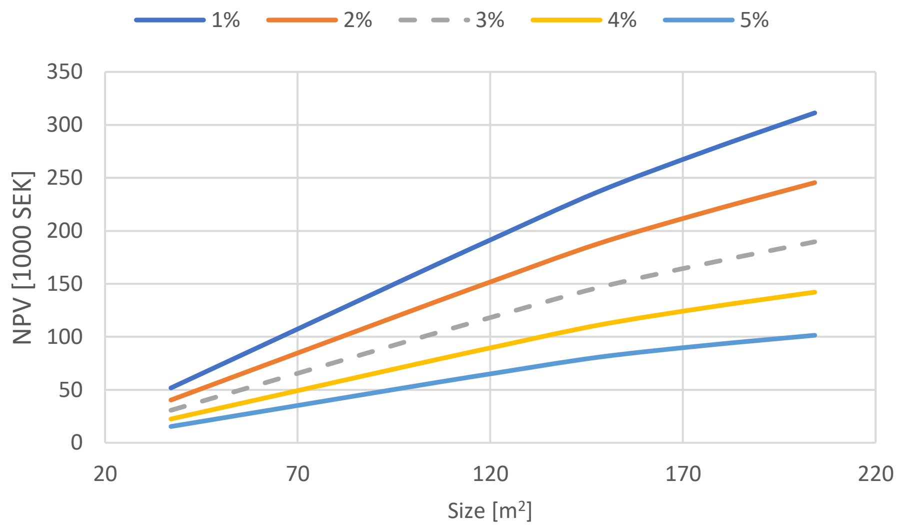

Figure 42. NPV [1000 SEK] of PV for different discount rates [%] and sizes [m^2].

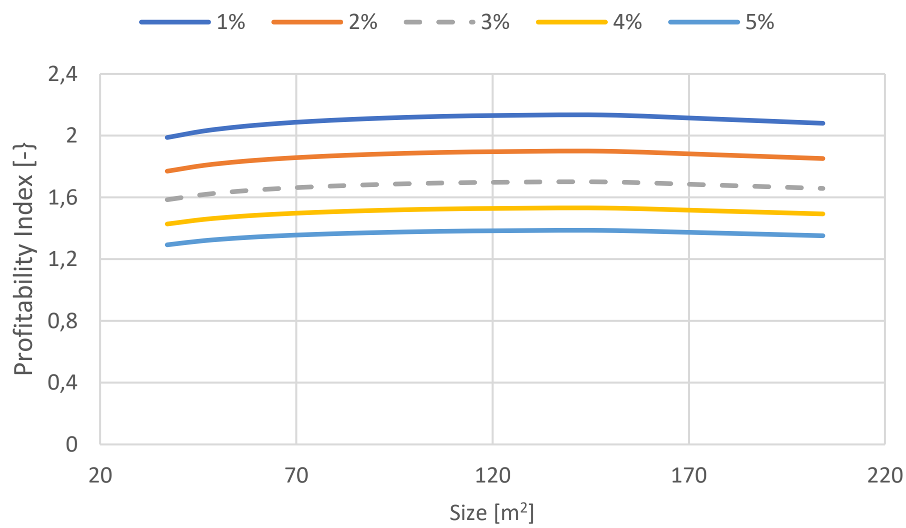

Figure 43. Profitability Index [-] of PV for different discount rates [%] and sizes [m^2].

However, when the benefits of green certificates and initial cost rebate are excluded, the PV system is not always profitable. The choice of discount rate can now result in either profitable or non-profitable systems. These results are presented as NPV in Figure 44 and PI in Figure 45.

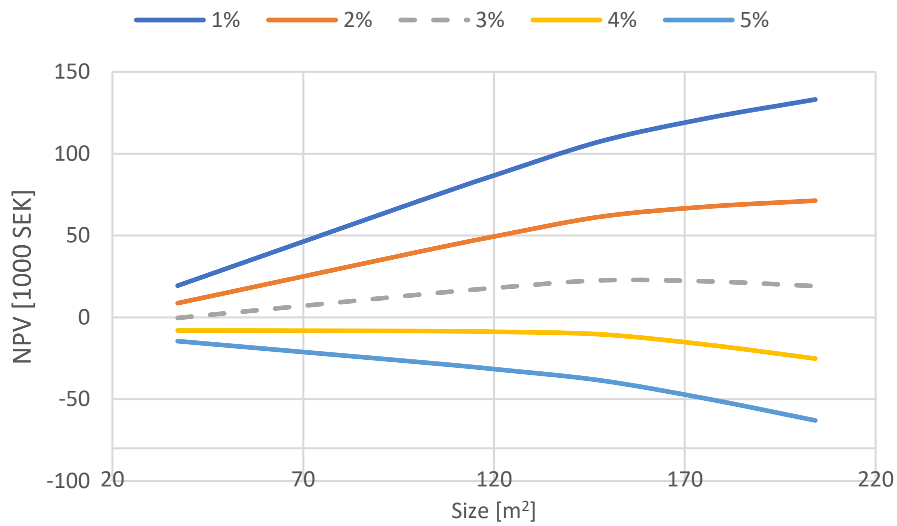

Figure 44. NPV [1000 SEK] of PV (excluding benefits) for different discount rates [%] and sizes [m^2].

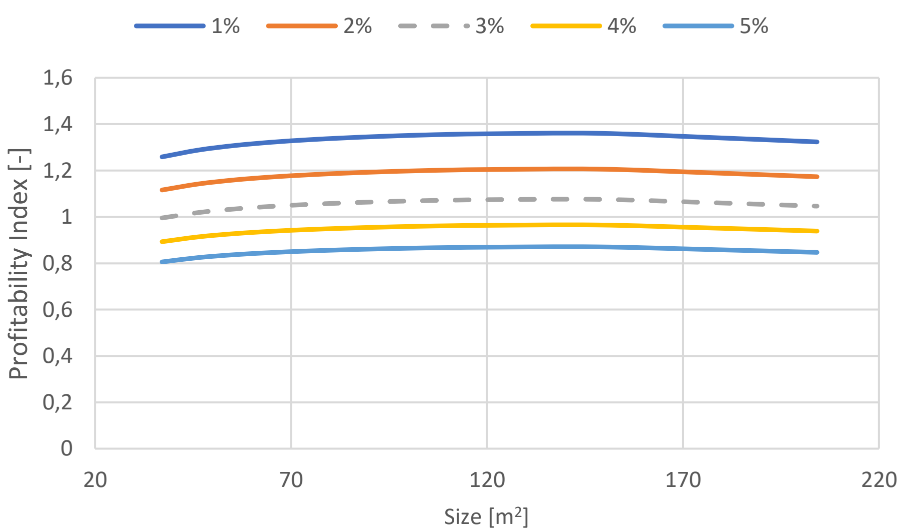

Figure 45. Profitability Index [-] of PV (excluding benefits) for different discount rates [%] and sizes [m^2].

6. Discussion

The discussion is based on the results in relation to the stated research questions;

“Which KPIs are of relevance for MFHs when comparing ST and PV for GSHPs, and why”
and;
“What is the performance of these SGSHP systems for a standard MFH in terms of these KPIs”.

The key focus of this thesis was to compare the addition of either solar thermal (ST) or Photovoltaic (PV) to an existing ground-source heat pump (GSHP) in a multi-family house (MFH). This was done by first identifying the commonly used key performance indicators (KPIs) in today’s heat pump, ST, and PV research and market. Some of these KPIs were redefined for use with PV. In order to do this, the definition of self-consumption (SC) at different boundary levels were applied in the case of PV. SC shows how much of the PVs produced power could be utilized within each system boundary. By integrating ST, as done in the model, the HP’s required DHW energy output is reduced and thereby lowering electricity consumption in the compressor and related pumps. This means that even if the PV integration/combination with a HP system doesn’t directly affect its component’s operations like ST, it could still be compared to the ST system. It is with this definition of the added value from ST (reduced electricity demand) that PV’s SC could be used for proper performance comparison between ST and PV.

The results showed that PV could be fully utilized in the BLDG system boundary, and even to be sold to a grid in the case of surplus production for sizes over 148 m^2. The system boundaries HP, SHP-PV however reached a SC of 70% – 40% between 38 – 204 m^2. Since the PV is able to supply either the HP, apartments, and ultimately the grid, it resulted in that the PV could still supply much of domestic electricity load when maximizing roof area utilization.

As the thesis compares ST and PV integration with HPs, it was assumed that the PV power production primarily supplied the building’s HP. However, the primary PV customer could also be the apartments within the building, or even grid sales. Providing the apartments first and the HP system second would show technical results similar to that of the reference scenario of no PV for the HP performance due to the low $SC_{SHP\text{-}Apt}$. The $SC_{SHP\text{-}Apt}$ which shows the SC of PV if it were to supply apartments first was presented in the results and showed that the HP system would only start receiving PV power for sizes above 148 m^2. As the thesis sought to compare ST’s and PV’s impact on a HP system, no further analysis of this case was done.

The SPF increased for both the ST and PV integration from the reference scenario (no PV/ST integration) but to a varying degree depending on the analyzed system boundary. SF was used to determine how much of the building’s heat or electricity demand was supplied by the ST or PV. The SF for ST and PV would be trivial to compare with each other as the useful energy analyzed in each case is different (heat and electricity respectively). However, as a critical factor of a solar-assisted HP is to utilize solar to supply a heat demand, the SF is a relevant KPI for the HP system rather than as a measure of the single ST or PV system's performance.

The economic performance of the system is a key decision point for building owners. Investments are to some degree expected to make a profit. For the case of this thesis, the investment options are those of either PV or ST for integration with an existing GSHP. The economic performance was evaluated by applying commonly used KPIs associated with investments of these types. The results showed that PV was a better investment option than ST for the modelled building. It was however showed by the sensitivity analysis that PV was not a profitable investment for some cases. In the sensitivity analysis, the case of PV excluding incentives (30% initial cost reduction) were analyzed. This was done to highlight the effect these benefits have on PV and compare those results with ST which does not receive any of these benefits.

The emissions associated with each system were calculated and presented in the results. This was done to also compare the environmental impact each system had. As the electricity from the grid has an associated $CO_{2\text{-eq}}$ emission per kWh, the reduced external electricity demand (by installing PV or ST) would then result in overall lower $CO_{2\text{-eq}}$ emissions associated to the HP. It was observed that PV reduced the systems indirect emissions further than ST for sizes larger than 74 m^2. As electricity produced by PV can be used either in the building (HP and apartments) or sold to the grid, the environmental benefits are not limited to any specific system boundary.

The TRNSYS simulation was conducted in order to compare ST and PV in terms of the proposed KPIs for clarification purposes rather than proof of concept. The sensitivity analysis also showed the large impact of economic assumptions on the expected profitability. However, based on the results, the simulated MFH with an existing GSHP would benefit more from installing PV instead of ST from both a technical, economic and environmental perspective.

7. Conclusion

The topic of the thesis was to compare ST and PV addition to an existing GSHP system through commonly used KPIs for these systems. This was done to further expand on the previous research on PV's combination and integration with a HP and how it compares to ST which to this day is limited. The literature review showed that through identification of the SHP's critical factors, SC for PV was identified as the common ground on which comparison of technical KPIs such as SPF and SF were relevant. In that sense PV "lowers" the electricity consumption of the SHP system just like the ST ultimately does. However, as the choice between ST and PV was of focus, the results showed that PV performed better economically and environmentally. PVs are also subject to several subsidies in Sweden which ST is not.

The conclusion of the thesis is that while ST is more established in both research and HP integrations compared to PV, its performance compared with the initial cost shows why it is not commonly used in Swedish MFHs for heating. PV's strength when integrated with a building is its versatility as shown via the different system boundaries self-consumption and possibility for grid connection. This together with the economic viability and installation simplicity makes it a clear contender for future building integration (with or without heat pumps) in Sweden.

7.1 Future Research

Future research is suggested to expand on the definition and standardization of PV SC as a key concept for SHPs utilizing PV.

- The inclusion of battery storage for PV in the case of larger differences between demand and production in order to improve SC for the SHP and HP system boundary.
- In this model, only PV and only ST were tested, therefore, different combinations of ST and PV could prove beneficial.
- Tests regarding other types of HP configurations such as ASHPs which is the most common HP configuration would also be relevant.
- Test the effect of district heating, which is common in Stockholm, with PV-HP combinations.

References

[1] E. Asadi, M. G. Da Silva, C. H. Antunes, and L. Dias, “Multi-objective optimization for building retrofit strategies: A model and an application,” *Energy Build.*, vol. 44, no. 1, pp. 81–87, 2012.

[2] Z. Ma, P. Cooper, D. Daly, and L. Ledo, “Existing building retrofits: Methodology and state-of-the-art,” *Energy Build.*, vol. 55, pp. 889–902, 2012.

[3] N. Fumo, “A review on the basics of building energy estimation,” *Renew. Sustain. Energy Rev.*, vol. 31, pp. 53–60, 2014.

[4] S. Wang, C. Yan, and F. Xiao, “Quantitative energy performance assessment methods for existing buildings,” *Energy Build.*, vol. 55, pp. 873–888, 2012.

[5] S.-N. Boemi, O. Irulegi, and M. Santamouris, *Energy performance of buildings: Energy efficiency and built environment in temperate climates*. 2015.

[6] J. Hadorn, *Solar and Heat Pump Systems for Residential Buildings*. Berlin: Ernst & Sohn, 2015.

[7] W. Grassi, *Heat Pumps: Fundamentals and Applications*. Pisa: Springer Nature, 2018.

[8] EHPA, “European Heat Pump Market and Statistics Report 2015,” 2015.

[9] C. Karytsas, “Current state of the art of geothermal heat pumps as applied to buildings,” *Adv. Build. Energy Res.*, vol. 6, no. 1, pp. 119–140, May 2012.

[10] N. Sommerfeldt and H. Muyingo, “Lessons in community owned PV from swedish multi-family housing cooperatives,” in *31st European Photovoltaic Solar Energy Conference and Exhibition*, 2015, pp. 2745–2750.

[11] N. Sommerfeldt and H. Madani, “Ground Source Heat Pumps for Swedish Multi-Family Houses - Innovative Co-Generation and Thermal Storage Strategies. EFFSYS Expand Final Report.,” 2018.

[12] N. Sommerfeldt and H. Muyingo, “Photovoltaic Systems for Swedish Prosumers A technical and economic analysis focused on cooperative multi-family housing,” 2016.

[13] H. Madani and E. Roccatello, “A comprehensive study on the important faults in heat pump system during the warranty period,” *Int. J. Refrig.*, vol. 48, pp. 19–25, Dec. 2014.

[14] S. Poppi, N. Sommerfeldt, C. Bales, H. Madani, and P. Lundqvist, “Techno-economic review of solar heat pump systems for residential heating applications,” *Renew. Sustain. Energy Rev.*, vol. 81, no. July 2017, pp. 22–32, 2018.

[15] D. Fischer, K. B. Lindberg, H. Madani, and C. Wittwer, “Impact of PV and variable prices on optimal system sizing for heat pumps and thermal storage,” *Energy Build.*, vol. 128, pp. 723–733, Sep. 2016.

[16] D. Fischer, J. Bernhardt, H. Madani, and C. Wittwer, “Comparison of control approaches for variable speed air source heat pumps considering time variable electricity prices and PV,” *Appl. Energy*, vol. 204, pp. 93–105, Oct. 2017.

[17] G. Mader and H. Madani, “Capacity control in air–water heat pumps: Total cost of ownership analysis,” *Energy Build.*, vol. 81, pp. 296–304, Oct. 2014.

[18] H. Madani, J. Claesson, and P. Lundqvist, “A descriptive and comparative analysis of three common control techniques for an on/off controlled Ground Source Heat Pump (GSHP) system,” *Energy Build.*, vol. 65, pp. 1–9, Oct. 2013.

[19] H. Madani, J. Claesson, and P. Lundqvist, “Capacity control in ground source heat pump systems part II: Comparative analysis between on/off controlled and variable capacity systems,” *Int. J. Refrig.*, vol. 34, no. 8, pp. 1934–1942, Dec. 2011.

[20] N. Sommerfeldt and H. Madani, “Review of Solar PV/Thermal Plus Ground Source Heat Pump Systems for European Multi-Family Houses,” in *11th ISES Eurosun Conference*, 2016.
[21] N. Sommerfeldt and H. Madani, “Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: Part one – Review,” *Renew. Sustain. Energy Rev.*, vol. 74, no. November 2016, pp. 1379–1393, 2017.
[22] H. Madani, J. Claesson, and P. Lundqvist, “Capacity control in ground source heat pump systems: Part I: modeling and simulation,” *Int. J. Refrig.*, vol. 34, no. 6, pp. 1338–1347, Sep. 2011.
[23] G. Indelicato, *Project Management Metrics, KPIs, and Dashboards: A Guide to Measuring and Monitoring Project Performance*, vol. 43, no. 2. 2012.
[24] D. Parmenter, *Key Performance Indicators*. 2007.
[25] M. Köhl, M. G. Meir, P. Papillon, and G. M. Wallner, *Polymeric Materials for Solar Thermal Applications Engineering*. Wiley-VCH, 2012.
[26] International Energy Agency, *Transition to Sustainable Buildings*. 2013.
[27] G. Resources, *Energy Effi cient Buildings with Solar and Geothermal Resources 587*. .
[28] F. Mauthner and W. Weiss, “Solar Heat Worldwide - Markets and Contribution to the Energy Supply 2013,” 2015.
[29] J. Fan, Z. Chen, S. Furbo, B. Perers, and B. Karlsson, “EFFICIENCY AND LIFETIME OF SOLAR COLLECTORS FOR SOLAR HEATING PLANTS,” in *ISES Solar World Congress 2009: Renewable Energy Shaping Out Future*, 2009, p. 10.
[30] A. Ghafoor and G. V. Fracastoro, “Cost-effectiveness of multi-purpose solar thermal systems and comparison with PV-based heat pumps,” *Sol. Energy*, vol. 113, pp. 272–280, 2015.
[31] R. Aldrich and J. Williamson, “NREL: Role of Solar Water Heating in Multifamily Zero Energy Homes Consortium for Advanced Residential Buildings,” 2016.
[32] NREL *et al.*, “High Performance Flat Plate Solar Thermal Collector Evaluation,” 2018.
[33] F. ; Bava, S. ; Furbo, and B. Perers, “Simulation of a solar collector array consisting of two types of solar collectors, with and without convection barrier,” *Energy Procedia*, vol. 70, pp. 4–12, 2015.
[34] Energimyndigheten, “National Survey Report of PV Power Applications in Sweden 2016,” *IEA Int. Energy Agency*, p. 69, 2016.
[35] IEA, *World Energy Outlook 2017*. 2017.
[36] S. Dubey, J. N. Sarvaiya, and B. Seshadri, “Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review,” *Energy Procedia*, vol. 33, pp. 311–321, Jan. 2013.
[37] Miljö- och energidepartementet, “Förordning (2009:689) om statligt stöd till solceller,” 2009. [Online]. Available: https://www.lagboken.se/Lagboken/lagar-och-forordningar/lagar-och-forordningar/naringsliv/Statligt-stod/d_432161-forordning-2009_689-om-statligt-stod-till-solceller. [Accessed: 21-Jul-2018].
[38] H. Madani, J. Claesson, and P. Lundqvist, “Capacity control in ground source heat pump systems Part I : modeling and simulation ´ gulation de la puissance des syste ` mes a ` pompe a ` chaleur Re ´ lisation et simulation sol-eau . Partie I e mode,” *Int. J. Refrig.*, vol. 34, no. 6, pp. 1338–1347, 2011.
[39] G. Emmi, A. Zarrella, M. De Carli, and A. Galgaro, “An analysis of solar assisted ground source heat pumps in cold climates,” *Energy Convers. Manag.*, vol. 106, pp. 660–675, 2015.

[40] G. Emmi, A. Zarrella, M. De Carli, and A. Galgaro, “Solar assisted ground source heat pump in cold climates,” *Energy Procedia*, vol. 82, pp. 623–629, 2015.
[41] A. Dada and K. Stanoevska, *Organizations’ Environmental Performance Indicators*. 2013.
[42] D. Carbonell, M. Y. Haller, and E. Frank, “Potential benefit of combining heat pumps with solar thermal for heating and domestic hot water preparation,” *Energy Procedia*, vol. 57, pp. 2656–2665, 2014.
[43] D. Carbonell, M. Y. Haller, D. Philippen, and E. Frank, “Simulations of combined solar thermal and heat pump systems for domestic hot water and space heating,” *Energy Procedia*, vol. 48, pp. 524–534, 2014.
[44] F. Ardente, G. Beccali, M. Cellura, and V. Lo Brano, “Life cycle assessment of a solar thermal collector,” *Renew. Energy*, vol. 30, no. 7, pp. 1031–1054, Jun. 2005.
[45] F. Ardente, G. Beccali, M. Cellura, and V. Lo Brano, “Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances,” *Renew. Energy*, vol. 30, no. 2, pp. 109–130, Feb. 2005.
[46] C. Lamnatou, G. Notton, D. Chemisana, and C. Cristofari, “Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies,” *Energy Build.*, vol. 84, pp. 378–387, Dec. 2014.
[47] S. Gerbinet, S. Belboom, and A. Léonard, “Life Cycle Analysis (LCA) of photovoltaic panels: A review,” *Renew. Sustain. Energy Rev.*, vol. 38, pp. 747–753, Oct. 2014.
[48] A. Sumper, M. Robledo-García, R. Villafáfila-Robles, J. Bergas-Jané, and J. Andrés-Peiró, “Life-cycle assessment of a photovoltaic system in Catalonia (Spain),” *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 3888–3896, Oct. 2011.
[49] WWF and Allianz SE, “Climate Scorecard Sweden,” 2009.
[50] “electricityMap | Aktuellt CO2-utsläpp från elproduktion,” 2018. [Online]. Available: https://www.electricitymap.org/?page=country&solar=false&remote=true&wind=false&countryCode=SE. [Accessed: 16-Sep-2018].
[51] A. Moro and L. Lonza, “Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles,” *Transp. Res. Part D Transp. Environ.*, Jul. 2017.
[52] J. Remund and S. Kunz, “Meteonorm 7.2.” 2018.
[53] M. Hofmann, S. Riechelmann, C. Crisosto, R. Mubarak, and G. Seckmeyer, “Improved synthesis of global irradiance with one-minute resolution for PV system simulations,” *Int. J. Photoenergy*, vol. 2014, 2014.
[54] R. Luthander, J. Widén, D. Nilsson, and J. Palm, “Photovoltaic self-consumption in buildings: A review,” *Appl. Energy*, vol. 142, pp. 80–94, 2015.
[55] SMHI, “Normal globalstrålning under ett år | SMHI,” 2009. [Online]. Available: https://www.smhi.se/klimatdata/meteorologi/stralning/normal-globalstralning-under-ett-ar-1.2927. [Accessed: 23-Jul-2018].
[56] Tabula, “TABULA WebTool,” 2012. [Online]. Available: http://webtool.building-typology.eu/#bm. [Accessed: 23-Jul-2018].
[57] Energimyndigheten, “Energistatistik för flerbostadshus 2016,” Eskilstuna, 2017.
[58] J. Widén and E. Wäckelgård, “A high-resolution stochastic model of domestic activity patterns and electricity demand,” *Appl. Energy*, vol. 87, no. 6, pp. 1880–1892, Jun. 2010.
[59] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, and E. Wäckelgård, “Constructing load profiles for household electricity and hot water from time-use data—Modelling approach and validation,” *Energy Build.*, vol. 41, no. 7, pp. 753–768, Jul. 2009.
[60] Thermia, “Thermia Mega XL Technical Specifications,” 2018. [Online]. Available:

www.thermia.se. [Accessed: 23-Jul-2018].
[61] M. Y. Haller, E. Bertram, R. Dott, T. Afjei, F. Ochs, and J. C. Hadorn, "Review of component models for the simulation of combined solar and heat pump heating systems," in *Energy Procedia*, 2012, vol. 30, pp. 611–622.
[62] Z. Chen, S. Furbo, B. Perers, J. Fan, and E. Andersen, "Efficiencies of Flat Plate Solar Collectors at Different Flow Rates," *Energy Procedia*, vol. 30, pp. 65–72, Jan. 2012.
[63] F. Mauthner and S. Herkel, "TECHNOLOGY AND DEMONSTRATORS Technical Report Subtask C-Part C1 C1: Classification and benchmarking of solar thermal systems in urban environments."
[64] G. Hellstrom, "Duct Ground Heat Storage Model. Manual for Computer Code," 1989.
[65] Energimyndigheten, "Elcertifikatsystemet är ett marknadsbaserat stödsystem. Läs mer om systemet här." [Online]. Available: http://www.energimyndigheten.se/fornybart/elcertifikatsystemet/om-elcertifikatsystemet/. [Accessed: 16-Sep-2018].