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Energimyndighetens titel på projektet – engelska Swedish contribution to Comfort&Climate Box Annex – a collaboration between IEA TCPs and Mission Innovation	
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1 Foreword

RISE Research Institutes of Sweden has together with the two universities, KTH Royal Institute of Technology and Dalarna University and the two heat pump manufacturers Nibe and Thermia cooperated in the research project "Swedish contribution to Comfort and Climate Box Annex – a collaboration between IEA TCPs and Mission Innovation" founded by the Swedish Energy Agency through the research programme TERMO. The project has been running for 2,5 years.

The project has been the Swedish contribution to an international collaboration project within IEA's Technology Collaboration Programme – the joint Heat Pumping Technologies TCP Annex 55 and Energy Storage TCP Annex 34 "Comfort and Climate Box – Speeding up market development for integrating heat pumps and storage packages".

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3 Sammanfattning

En Comfort and Climate Box (CCB) i sitt grundutförande är en värmepump i kombination med ett energilager och en integrerad styrning. I det här projekt har begreppet även inkluderat styrning i kombination med solceller och/eller ett varierande elpris samt, för några av CCB-koncepten, komfortkyla. Internationellt kan CCB-lösningar bidra till att minska koldioxidutsläppen från värmesektorn avsevärt genom ökad elektrifiering. Både i Sverige och i andra länder kan de bidra till stabilisering av ett elnät med ökad andel förnybar intermittent elproduktion. En CCB kan ha olika fokusområden, men det här projektet har i första hand fokuserat på flexibilitet och styrfunktioner i kombination med lagring.

Tre Comfort- och Climate Box-koncept har utvecklats inom projektet:

- Bergvärmepump i kombination med solceller, energilagring, passiv kyla och integrerad styrning av CCB.
- Luft/vatten-värmepump i kombination med solceller, energilagring, kyla och integrerad styrning av CCB.
- Frånluftsvärmepump i kombination med solceller, energilagring och integrerad styrning av CCB.

De tre koncepten ovan utvärderades genom simuleringar i TRNSYS. Simuleringarna användes i första hand för att utvärdera olika alternativ för lagring av energi i kombination med nya styralgoritmer. Fokus för de utvecklade styralgoritmerna var att antingen öka egenförbrukningen av internt producerad solel och/eller minska driftskostnaderna vid ett rörligt elpris. Dessutom gjordes simuleringar av komfortkyla i IDA ICE för att utvärdera skillnader mellan ett direkt- och ett indirekt system för distribution av kylan i huset.

Resultaten från simuleringarna visar att de ekonomiska besparingarna för de utvecklade styrfunktionerna är blygsamma baserat på elpriserna för 2019 i Sverige. En huvudorsak är de små variationen i elpris över dygnet för det utvärderade året. Men högre fluktuationer i elpris och en ökad tillämpning av effekttariffer är att vänta i framtiden. Eftersom besparingarna i driftskostnaden är relativt låga är det nödvändigt att hålla investeringskostnaderna nere för att få en acceptabel livscykelkostnad. Med elpriser från 2019 kan besparingarna i form av lägre driftskostnader inte kompensera för de investeringar som krävs för ytterligare energilager.

Baserat på lärdomar från simuleringarna utvecklades en prototyp för CCB-konceptet baserad på en bergvärmepump och dessutom utvecklades och implementerades nya styralgoritmer för en frånluftsvärmepump i en värmepump. För att utvärdera bergvärmepumpsprototypen utvecklades en ny laboratorietestmetod för testning av funktionalitet, styrning och prestanda. Testmetoden som utvecklats är en kompensationsmetod baserad på en avvägning mellan komplexitet och möjligheten att få tillförlitliga resultat vid test av prototypens funktion och prestanda med fokus på utvärdering av de smarta styrfunktionerna. Denna typ av metod skulle även kunna användas i framtida standarder för att utvärdera CCBs på marknaden. Utvärdering av prototypen visar att CCB:n kan planera värmeproduktionen, och därmed elförbrukningen, över dygnet utifrån ett varierande elpris eller förväntad produktion av solel.

Resultaten från detta projekt leder till att värmepumpstillverkare kan vara bättre förberedda för framtiden, då prisstrukturen för el och effekt, högst sannolikt, kommer att förändras på grund av ökad elektrifiering och en större andel förnyelsebar el i elmixen – till fördel för så väl slutanvändare som el- och nätbolag.

4 Summary

A Comfort and Climate Box (CCB) in its basic version is a heat pump in combination with energy storage and an integrated control. In this project, it also included control in combination with PV-panels, a fluctuating electricity price and, for some of the CCB concepts, comfort cooling. Such a solution can considerably contribute to decarbonization of the energy sector through electrification. In addition, it can contribute to stabilizing an electricity grid with more renewable but intermittent electricity production. A CCB can have different focus areas, but this project has in first-hand focused on flexibility and control functions in combination with storage.

Three Comfort and Climate Box concepts has been developed within the project:

- Ground source heat pump in combination with PV-panels, energy storage, passive cooling and integrated control of the CCB.
- Air source heat pump in combination with PV-panels, energy storage, cooling and integrated control of the CCB.
- Exhaust air heat pump in combination with PV-panels, energy storage and integrated control of the CCB.

The three concepts above were evaluated by simulations in TRNSYS. The simulations were in first-hand used to evaluate different alternatives for energy storage combined with new control algorithms. Focus for the developed control algorithms in the simulations was to either increase the self-consumption of internally produced solar PV-power and/or decrease the running costs. In addition, simulations of comfort cooling were made in IDA ICE in order to evaluate differences between a direct- and an indirect system for distributing the cooling in the building.

The result from the simulations shows that the economical savings with the developed control functions are modest with the electricity prices for 2019 in Sweden. One main reason is that the variation in electricity price over the day was small for the year evaluated. But higher fluctuations in electricity price and an increased use of power tariffs are to be expected in the future. Since the savings in running cost are relatively low there is a need to keep the investment costs low to get an acceptable life cycle cost. With electricity prices from 2019, the savings in lower running costs can not compensate for the investments for additional energy storage needed.

Based on learnings from the simulations, a prototype was developed for the CCB concept based on a ground source heat pump (GSHP) and in addition new control algorithms for an exhaust air heat pump were developed and implemented in a heat pump. In order to evaluate the GSHP prototype, a new laboratory test method was developed for testing of the functionality, control and performance. The test method developed, is based on a compensation method and developed to be a trade-off between complexity and the possibility to get reliable results when testing functions and performance of the prototype with focus on the evaluation of the smart control functions. This type of method could be implemented in future

test standards for evaluation of CCBs on the market. Evaluation of the prototype shows that the CCB can plan the heat production, and thereby the electricity consumption, over the day based on a varying electricity price or expected production of PV-electricity.

The outcomes from this project, results in that heat pump manufacturers are better prepared for the future when the price structure for electricity and power will, most likely, be changed due to increase electrification and a larger share of renewables in the mix – for the benefit for the end users as well as for the utilities.

5 Introduction

RISE Research Institutes of Sweden has together with the universities, KTH Royal Institute of Technology and Dalarna University and the heat pump manufacturers Nibe and Thermia cooperated in the research project “Swedish contribution to Comfort and Climate Box Annex – a collaboration between IEA TCPs and Mission Innovation”. The project has been the Swedish contribution to an international collaboration project within IEA’s Technology Collaboration Programme – the joint Heat Pumping Technologies TCP Annex 55 and Energy Storage TCP Annex 34 “Comfort and Climate Box – Speeding up market development for integrating heat pumps and storage packages”.

The central concept in the project is the Comfort and Climate Box (CCB). In this project, a CCB is defined as a combined package consisting of a heat pump, an energy storage and integrated controls. The package may form an actual physical unit but can also consist of separate modules that form an integrated “virtual package”. A CCB should not just be a set of components that have been put together. Rather, all components of the CCB should be designed to work together in a modular fashion and should be operated under a dedicated and optimal integrated control strategy.

Based on the archetypes developed within the international project, the Swedish project has focused on, in first-hand, the archetype “Flexibility” (see chapter 5.3 below) with focus on smart control in combination with storage in order to lower the running costs and/or increase self-consumption of PV-power.

5.1 Goal and scope

The project goal was to develop concept solutions for three new types of Comfort and Climate Boxes (CCB) with focus on control, integral design, simple installation and affordability. This should be done by combining heat pumps with different types of energy storage and controls to meet heating and cooling needs in detached houses. The solutions should be developed /optimized primarily for the conditions on the Swedish market but should also be well suited to other similar markets.

The three concept solutions to be evaluated are:

- A ground source heat pump in combination with PV-panels, energy storage, passive cooling and integrated control of the CCB.
- An air source heat pump in combination with PV-panels, energy storage, cooling and integrated control of the CCB.
- A exhaust air heat pump in combination with PV-panels, energy storage and integrated control of the CCB.

For energy storage, the potential for at least three options should be evaluated: water tanks, heat storage in PCM (phase change material) and electricity storage in batteries.

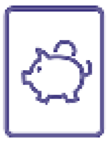
Based on the results from evaluations for the concept solutions, a prototype should be developed and tested.

5.2 Limitations

- The CCB concepts should primarily be developed and evaluated for single-family dwellings on the Swedish market.
- The time frame for energy storage is over the day, up to maximum a few days. Seasonal storage is not included in the project.

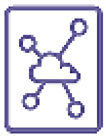
5.3 CCB Archetypes

Four "archetypes" for possible implementation strategies that form the focus and goal of CCB development was defined within the international collaboration project (Annex 55/34). The four archetypes are:



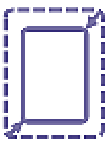
Affordability

- Low investment costs for the end user
- In general, this means lower energy efficiency and limited opportunities for flexibility



Flexibility

- High flexibility and good opportunities for smart grid services.
- In general, it results in larger storage volumes and smart control functions.
- Depending on goals and control strategies, energy efficiency can both increase or decrease.



Compactness

- Focus on compact products that occupy a small area both indoors and outdoors for the end user.
- In general, this results in smaller storage volumes and lower energy efficiency.

Energy efficiency

- Focus on the best possible performance under different conditions.
- In general, this leads to larger storage volumes and higher investment costs.

6 Background

Heating of the built environment constitutes a significant part of Sweden's energy use. Many of our single-family homes today are heated with the help of heat pumping technology that utilizes renewable energy and with the help of electricity converts this into usable heat. In the future energy system in Sweden, as well as the rest of Europe and the world, an increasing part of the electricity will be produced with the help of renewable and intermittent energy sources. In many parts of Europe, there is already a challenge in managing power variations on both the production and user side, and this challenge is likely to become bigger in the Swedish energy system as well. This is especially true if the Swedish government's goal of a fully renewable electricity system is to be achieved by 2040.

The electric heat pumps that are installed today are strongly connected to the electrical system and can both be a challenge, but above all an opportunity to meet the power challenge. Its possibilities for doing this increase markedly if the technology is combined with different types of energy storage and smart control for this.

From a global perspective, the demand for comfort cooling in the world is increasing sharply, not least in the housing sector. This is largely the case in developing countries that have strong economic growth, such as India. Even in Europe, the demand for comfort cooling is increasing, even in more northern latitudes. The hot summer of 2018 led to many suppliers selling out of comfort cooling equipment in Sweden as well. Heat pumping technology can be used for both heating and cooling and with smart innovative solutions, this technology can offer very resource- and energy-efficient comfort cooling solutions.

The present status in Sweden in relation to this project is described in IEA HPT Annex 55 / ECES Annex 34 "CCB" Task 1 report for Sweden, See appendix A. The Swedish Task 1 report includes an overview of the Swedish energy system and the price structure for electricity. A summary of relevant Swedish energy policies for the CCB concept is included as well as a market status for heat pumps and other already existing CCBs in Sweden. Finally, the report summarises several earlier Swedish research projects in the area. Below follows a summary of the status for existing CCBs on the Swedish market, for more information see Appendix A.

6.1 Existing CCBs on the Swedish market

The status of existing Comfort and Climate Box solution in Sweden depends on what is supposed to be included in the concept.

A Comfort and Climate Box (CCB) is defined to a be a combination of a heat pump, an energy storage and integrated control. If one includes a heat pump that can deliver space heating (SH) and domestic hot water (DHW) in the CCB concept, there are already plenty of CCBs on the Swedish market. In this case the DHW tank is the only heat storage (except for the water in the space heating distribution system and the thermal inertia of the building). These two functions are normally included in a Swedish heat pump with a water-based distribution system for a ground source-, air source- or exhaust air heat pump. In these systems the integrated control is normally altering between the different operation modes. For this relatively simple Comfort and Climate Box (CCB) concept, there are relatively few barriers identified on the Swedish market.

For a more complex CCB, including more functions, such as integrated control based on an external signal for electricity price or on-site produced electricity, fewer CCB solutions are identified on the market, but products exist. However, the performance of such products on the market have until now only been evaluated in relation to the following functions: performance at space heating (SH) mode, space cooling (SC) mode, domestic hot water (DHW) production, separate electric or heat storage, integrated control for solar PV (photovoltaic) and smart grid but not for the combination of all these functions.

Table 1. Market overview of existing functions for a CCB, for details see Appendix A

Active cooling	Some heat pump models (mainly ASHP) have an already built-in function for active cooling. Others have it as an additional module.
Passive cooling	Several of the Swedish heat pump manufactures has additional cooling modules for their GSHP in order to provide cooling. There are also heat pump models with a built-in passive cooling function.
Remote control and monitoring	The large heat pump manufacturers in Sweden all have a solution to remotely control and monitor the heat pump via a cloud-based service.
Control based on Nord Pools day-ahead prices.	Some of the large heat pump manufacturers today has the function to make their premium heat pump models communicate with Nord Pool in order to get information about hourly electricity prices the next day. Based on this, the heat production can be planned to minimize the heating cost by making the heat pump work the most when the prices are low.
Control based on solar	One heat pump manufacturer identified sells PV panels for end consumers. The PV panels are prepared for connection with the heat pump via a communication module and the heat pump has functions in order to adjust the heat production to the solar production in order to increase self-consumption of internally produced electricity. There are also existing smart home solutions that can control the flow of locally produced solar in order to increase self-consumption.

The market overview shows that many of the functions for the comfort and Climate Box concept already exist on the market in one way or another. The focus for the project was to put them together in a good way, improve control functions and make the concept work in combination with energy storage in an integrated way and to develop a test method for evaluation for the different functions.

7 Roadmap

Within the international Comfort and Climate Box project (Annex 55/34) a joint roadmap to support the roll-out of CCB was developed based on the intermediate results from the contributions from the participating countries, see Appendix B. Sweden was responsible for the development of the international roadmap. Below follows a shorter introduction and a summary of the main recommendations.

7.1 Introduction to roadmap

According to IEA's recently published report "Net Zero by 2050 – A roadmap for the global energy sector" (2021) [10] one of the defined key milestones, are "*no new sales of fossil fuel boilers by 2025*" and that "*50% of heating demand is met by heat pumps in 2045*". To fulfil this the stock of installed heat pumps needs to increase from 180 million units in 2020 to 600 million units in 2030 (more than triple) and thereafter a tenfold increase to 1800 million units in 2050.

For all regions of the world, it has been concluded that increased electrification of the building, transport and industry sectors is one of the main pathways to reach net zero carbon emissions, which requires a strengthened electricity system with zero net emissions of greenhouse gases. To achieve these policy goals, several different implementation strategies for the CCB concept can be used.

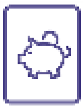
Heat pumps and storage units are typically designed to give the best energy efficiency. That means high COP and low thermal losses. When looking at those components from a system perspective, the performance goals for a CCB may be extended beyond energy efficiency.

7.2 Main recommendations

In many locations, the roll-out of heat pumps could be realized and accelerated if the heat pumps are integrated in Comfort and Climate Boxes (CCB), i.e. an integrated combination of heat pump, energy storage and control, designed to work together. However, depending on the actual main barriers and drivers in a particular location (country or region), different strategies are recommended to be implemented - Affordability, Flexibility, Compactness or Energy efficiency.

Recommendations for each of the four CCB archetypes describe in chapter 5.3 are listed below. In Appendix B the recommendations are further elaborated and described from the perspective of different stakeholder groups.

7.2.1 Affordability



To realize a massive roll-out of heat pumps (integrated in CCBs or not), a market demand must be created. For this to happen there must, first of all, be a decent business case for the end consumer, in comparison to less sustainable competing alternatives, at least for the life-cycle cost.

In case the **running cost is too high**, in comparison to competing, less sustainable alternatives, the recommendations to *policy makers* are:

- To make a tax shift, to increase the tax on fuel that causes CO_2-emissions and decrease it on electricity or to introduce some type of fees or price for CO_2-emissions.
- To create incentives, e.g. subsidies, to refurbish buildings to decrease the overall heating demand and thereby the running cost.
- To incentivize flexibility, to make the use of energy storage more cost effective and attractive for the building owners.

In case the running cost is low or acceptable, but the main barrier is **high upfront cost:**

- The recommendation to *policy makers* is to create and offer end consumers subsidies for investment in clean heating equipment.
- The recommendation to *utilities* and *manufacturers* is to offer alternative business models for using a heat pump or CCB as main heating equipment, e.g. rental schemes or leasing of equipment.

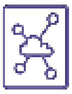
In case the **overall life cycle cost is too high** (no matter if it depends on high running or upfront cost) the recommendation to *manufacturers* is:

- To make the products “sufficient efficient”, not add additional features to the product and focus on mass production of a limited number of models.
- Make the products ”plug-and-play” to minimise installation and maintenance cost.

In addition, the recommendation to both *policy makers* and *manufacturers* is to

- Ensure capacity building, to educate installers as well as others in the value chain of Comfort and Climate Boxes.

7.2.2 Flexibility



A massive roll-out of heat pumps will in some locations create an additional pressure on the electric grid. To overcome this barrier, a solution would be to roll-out (a large share of the) heat pumps integrated in Comfort and Climate Boxes (CCB) focused on optimising flexibility performance.

If **available electric power capacity is an issue** at certain occasions, either due to lack of available production capacity and/or transmission capacity or due to a high share of renewable but intermittent production of electricity in the mix etc.

The recommendations to *policy makers* are to:

- Promote energy storage in buildings.
- Develop and revise labelling schemes which promotes clean heating solutions which could balance the electricity grid.
- Invest in electric infrastructure – both grid and production facilities of renewable electricity.

The recommendations to *utilities* are to:

- Implement tariffs that stimulates off-peak-hour operation of the heating system and incentivizes reduction of electricity demand during peak hours.
- Inform the end users or consumer organisations on how they can influence their energy bill by being a part of the electricity capacity market and incentivise to contribute demand-control/flexibility.
- Use harmonized price structures (over regions and countries) and to not change the price structures two often, i.e. every year. The manufactures need to know which type of price structures they should develop control systems for.
- Investigate in new ways of funding of Comfort and Climate Box solutions like rental schemes, leasing etc.
- Create a better link to installers of heat pumps and Comfort and Climate Box solutions.

The recommendations to *aggregators* are:

- Investigate in new ways of funding of Comfort and Climate Box solutions like rental schemes, leasing etc.
- Inform the end users or consumer organisations on how they can influence their energy bill by being a part of the electricity capacity market and incentivise to contribute demand-control/flexibility.

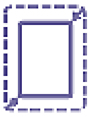
The recommendations to *manufacturers* are to:

- Investigate in new ways of funding of Comfort and Climate Box solutions like rental schemes, leasing, etc.
- Make control strategies for Comfort and Climate Boxes for combinations with solar PV and smart grid.

- Make your products ”plug-and-play”.
- Make your communication protocol standardized (open).
- Acquire more knowledge about energy storage and solar energy.

The recommendations to *standardisation organisations* are:
- Develop standards for combinations of heat pumps, energy storages and integrated control.
- Develop standards for communication protocols.

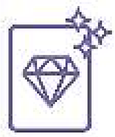
7.2.3 Compactness



In some countries or regions, space constraint is one of the main barriers to increase user acceptance of heat pumps as heating equipment. To overcome this barrier, a solution would be to roll-out (a large share of the) heat pumps integrated in Comfort and Climate Boxes (CCB) focused on optimising compactness.

The main recommendations to *manufacturers* are to:
- Design the CCB as compact as possible.
- “Boxify” the products. Do not underestimate how much it could increase user acceptance and facilitate for installers if the products are delivered as a “box”.
- Keep the volume of the energy storage limited and the possibility of using the building construction as heat storage should be utilized.

7.2.4 Efficiency



The “Efficiency” archetype, corresponds most closely to a traditional top-of-the-line heat pump / storage system found on the market today. The policy measures implemented so far have spurred the development of high-efficiency heat pumps, that are able to work in a wide operating range. This focus and implementation strategy has taken the technology to its present status, where it is well recognized by policy makers and recommended by IEA to be the most frequently used heating technology for buildings in a net zero emission scenario.

The other three archetypes, or implementation strategies, have so far less often been specifically targeted by research, product development, standardization or policy measures. Therefore, these implementation strategies need to get more attention in the future by all stakeholders.

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7.2.5 Further recommendations

Besides of pure rational economic and technical arguments, there are other drivers and barriers for end consumers to select a heat pump – integrated in a Comfort and Climate Box or not, which need some attention. On many places the awareness of climate change is increasing, but the knowledge of heat pumping technologies as one of the solutions might be low.

In case the awareness of the technology is low:

- The recommendation to policy makers is to invest in information campaigns to inform both end users, new business developers and investors.
- The recommendation to manufacturers is to inform end users that Comfort and Climate Boxes could be a multiservice provider – it could offer comfort - heating, hot water and cooling. In addition, it can improve the end users' possibilities to affect their heating/electricity cost. Moreover, it will decrease the end users CO_2 footprint.

8 Methodology simulations

Chapter 8 includes methodology and description of the simulations performed within the project in order to evaluate the performance for the different CCB concepts developed. Performance during space heating and production of DHW has been evaluated in TRNSYS [11], based on simulations for a Swedish single-family building with PV-panels on the roof. The TRNSYS simulations are used to evaluate the potential of different control algorithms in combination with alternatives for storage. In addition, simulations in IDA Indoor Climate and Energy (ICE) [12] have been made to evaluate different strategies for comfort cooling. Here the main research question has been to compare the potential for an indirect with a direct system for distributing the cold in the building.

Draft versions of the three concepts solutions described in chapter 8.1 below was developed and simulated in TRNSYS to evaluate the performance of each concept in combination with new control algorithms. Focus for the developed control algorithms in the simulations has been to either increase the self-consumption of PV-power and/or decrease the running costs. In chapter 8.3-8.6 below the methodology for the simulations of each CCB concept are described mor in detail, as well as the cooling simulations. In chapter 9 the results from the simulations are presented.

8.1 CCB Concepts

The three Comfort and Climate Box concepts developed include a heat pump in combination with energy storage and integrated smart control adapted primarily for single-family houses on the Swedish market.

The three concept solutions are:

- Ground source heat pump in combination with PV-panels, energy storage, passive cooling and integrated control of the CCB.
- Air source heat pump in combination with PV-panels, energy storage, cooling and integrated control of the CCB.
- Exhaust air heat pump in combination with PV-panels, energy storage and integrated control of the CCB.

In Figure 1 an energy flow chart is shown including all three concepts.

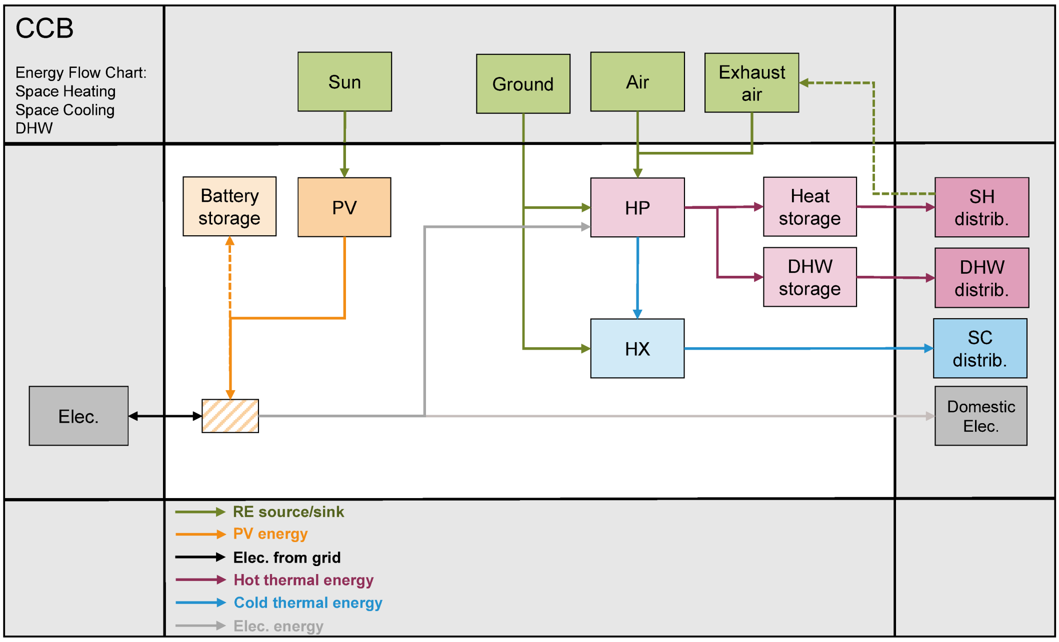

Figure 1. Energy flow chart for the three different CCB concepts

8.1.1 Alternatives for energy storage

Storage of energy is central in the CCB concept and the following energy storage alternatives has been investigated within the project:

- Storage in water tanks
  - Space heating buffer tank
  - Domestic hot water tank (DHW-tank)
  - Pre-heating tank (PH-tank) for DHW (pre-heats the tap water before it enters the ordinary DHW tank)
- Storage of heat in the buildings thermal mass (By changing the set temperature for indoor temperature and allow larger variations in indoor temperature)
- Storage of heat in tanks with PCM materials.
- Storage of electricity in a stationary battery

Based on discussions in the project group, including both researchers and representatives from the heat pump manufacturers it was decided to evaluate the following storage options in the TRNSYS simulations: DHW-tank, PH-tank, the buildings thermal mass and battery.

It was not possible to evaluate all alternatives in the simulations and after literature research and discussions in the project group it was decided not to include storage in PCM-materials in the simulations. For storage related to space heating, storage in the buildings thermal mass was prioritized over a buffer tank.

8.1.2 Key figures for evaluation of performance.

A number of key figures has been identified in order to evaluate the performance of the simulated alternatives. In Table 2 below the main key figures used are summarized.

Table 2. Main key figure for evaluation of performance

Key-figure	Unit	Definition	Equation
Electricity use			
Total electricity use	kWh/yr		
Purchased electricity from grid	kWh/yr		
Solar			
Self-consumption	%	$R_{self-cons} = \frac{E_{consupmtion} - E_{grid-purchase}}{E_{PV-yield}}$	Eq. 1 [13]
Self-sufficiency	%	$R_{Suff} = \frac{E_{consumption} - E_{grid-purchase}}{E_{consumption}}$	Eq. 2 [13]
Economy			
Net annual cost	SEK/yr		
Life cycle cost	SEK		
Environment			
GWP	kg CO_2-eq		
Cooling			
Cooling power	W		
Number of high temperature hours	h/yr	Hours per year with an indoor temperature above 25°C.	

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8.2 General setup simulations heating and DHW

The TRNSYS simulations focus on evaluating the CCB concepts when used for space heating and production of domestic hot water (DHW) for a single-family building located in Norrköping, Sweden (located 160 km south of Stockholm on the Swedish east coast). A full year has been simulated based on climate data and power prices for 2019, with a simulation step of 1 to 3-minutes. The DHW profile and the domestic electricity demands was derived using load generator with one minute resolution based on a stochastic Markov-chain model according to Widen et al (2009) [1] and for the DHW demand, the model has been calibrated to comply with Bales et al (2015) [2]. For all three cases the building simulated is a single-family dwelling, but the size and energy performance differ depending on the heat pump type simulated since different types of heat pumps are normally installed in different types of buildings, especially the building used for the EAHP concept differs from the building used for the GSHP and the ASHP. Table 3 shows an overview of the energy performance of the buildings used for the simulations in TRNSYS.

Table 3. Overview energy performance of buildings (base case)

	Unit	GSHP	ASHP	EAHP
Building area	m2	125	125	143
Space heating	kWh/yr	11760	12 020	12150
DHW	kWh/yr	3430	3780	3490
Elec. for appliances	kWh/yr	5210	5210	3640
Spec. SH	kWh/m^2,yr	94	96	85
Spec. heat (SH+DHW)	kWh/m^2,yr	122	126	109
PV panels	kWp	5	5	5

The simulations are in first-hand used to evaluate different alternatives for storage combined with new control algorithms, in addition different sizes and temperature levels of the storages have been evaluated. The alternatives simulated varies from one concept solution to another. The control algorithms can be divided in two main groups; algorithms to increase self-consumption of PV-power and algorithms that decrease the running costs by producing more heat when the electricity price is low or for periods with no peak load costs and store for hours with higher energy prices.

*Table 4. Summary of alternatives for CCB concepts evaluated in TRNSYS simulations**

Heat Pump
GSHP
ASHP
EAHP
Storage alternatives
DHW tank (additional tank volume or higher temperature)
Pre-heating tank for DHW
Battery
Building thermal mass (changes in indoor temperature)
Control algorithms
Increased self-consumption of PV-electricity
Decreased running cost

**Note that not all combinations have been evaluated*

8.2.1 Price scenarios

The results from the TRNSYS simulations give information about the buildings total electricity use as well as the amount of bought electricity. Based on this the buildings yearly running costs for electricity have been evaluated based on different electricity price scenarios. For some of the cases the LCC cost has also been calculated including investment costs etc. The scenarios are a combination of three components – energy price contract terms (hourly vs. monthly), network pricing schemes (volumetric energy vs. capacity), and the current micro producer tax reduction available for PV electricity generation fed into the electric grid.

Table 5. Overview of price scenarios for electricity

	S1	S2	S3	S4	S5	S6	S7	S8
Contract[1]	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly
Network[2]	Energy	Energy	Capacity	Capacity	Energy	Energy	Capacity	Capacity
Tax reduction[3]	No	No	No	No	Yes	Yes	Yes	Yes

[1] Refers to the type of contract a homeowner will have with the electricity supplier, hourly prices with a fixed fee or monthly prices with a larger fixed fee.
[2] Refers to the network owner's business model of charging based on volumetric energy usage (Energy) or peak loads (Capacity). Both have the same fixed fee.
[3] Refers to the presence of the 0.60 SEK/kWh (0.06 Euro/kWh) micro producer tax credit applied on PV generation sold to the grid.

8.3 CCB based on GSHP, TRNSYS simulations

The first concept solution consists of a ground source heat pump in combination with PV-panels and a thermal energy storage in the form of a domestic hot water tank. In Figure 2 an energy flow chart of the concept simulated is shown.

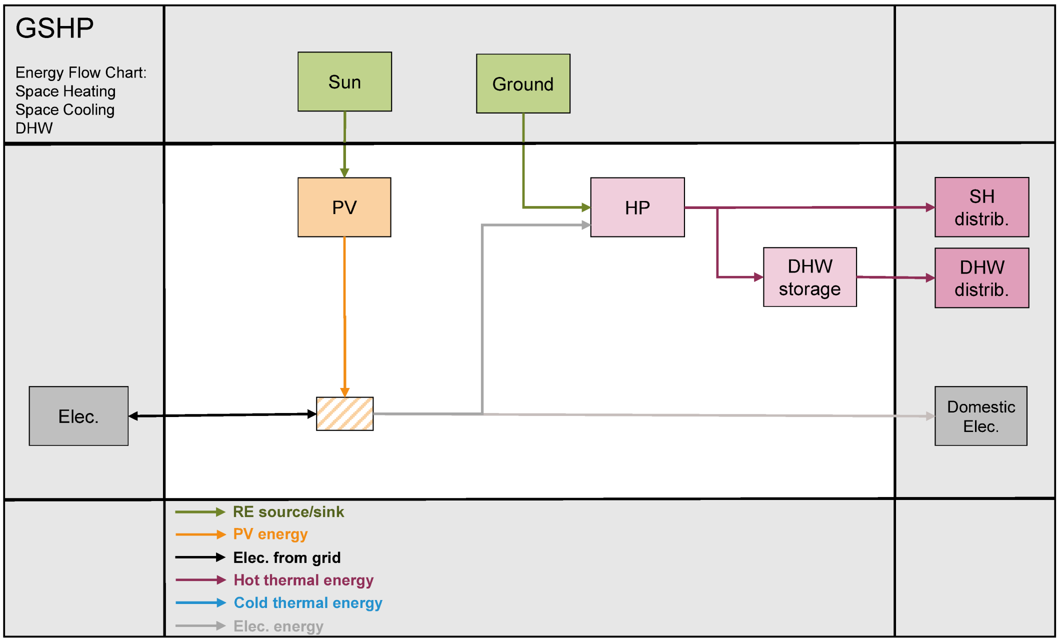

Figure 2. Energy flow chart of the CCB concept based on a GSHP simulated in TRNSYS

8.3.1 System Design

The CCB configuration is based on a single-family house occupied by four people. The building has been modelled using Type56 in TRNSYS and has the characteristics of a Swedish building from 1960s. The main inputs used for the building model are presented in Table 6.

Table 6. Main inputs for the building model

Floor area	U-value (walls)	U-value (roof and floor)	U-value (windows)	Ventilation	Infiltration
125 m^2	0.6 $W/m^2/K$	0.3 $W/m^2/K$	1.2 $W/m^2/K$	0.4 ACH[1]	Variable, simulates opening of windows

[1]*Air Changes per Hour*

Space heating (SH) and domestic hot water (DHW) are both provided by a variable speed ground source heat pump. The heat pump has a peak compressor power of 5 kW, reached at a frequency of 88 Hz. At these conditions the GSHP can provide 13 kW of heating power with a COP of 2.6. The system has been modelled based on a performance map, with a compressor speed that ranges from 20 to 88 Hz.

The heat pump in its basic configuration is equipped with a 180l storage tank for DHW, while no tank is used for the SH. The temperature of the water used for SH is calculated based on the heating curve of the building, while the top node temperature of DHW has been set at 55°C with a dead band of ±3°C.

The electricity is supplied both by the power grid and a 5kW roof mounted PV system. The panels are modelled using Type562 in TRNSYS, where an efficiency of 17% and a tilt of 25° have been set as inputs.

For the simulations, 1-minute weather data for Norrköping from the year 2019 from SMHI is used and averaged to match the 3-minute simulation time-step. Table 7 summarizes the main boundary parameters of the simulated system.

Table 7. Main boundary conditions of the system

Heat Pump	PV-panels	Storage tank	Ground source	Building	Location
Brine to water	South orientation 25° tilt	1 for DHW with 180 l capacity	Single borehole U-type	Single family house with 4 occupants	Norrköping
Variable speed (20-88 Hz)	5 kW	Optimization study on the size of the tank	Non-grouted	Building from the 60s with modern windows	Weather data from SMHI (2019)
Monovalent	Type 562 in TRNSYS		200 m depth		

The system has been simulated with two different control strategies:

- A “normal” strategy, where the heat pump is working independently from the PV system and is supplying thermal power only based on the occupants’ demand.
- A “solar” strategy that activates every time there is overproduction from the PV system. In this condition the heat pump increases its compressor speed to match the available power. The DHW tank is used as a thermal storage since the extra thermal power is used to heat the top node temperature of the DHW tank up to 67.5°C, with the aim of increasing the self-consumption of the CCB.

Figure 3 demonstrates how the strategies work showing PV production, electricity load and top node temperature in the DHW tank.

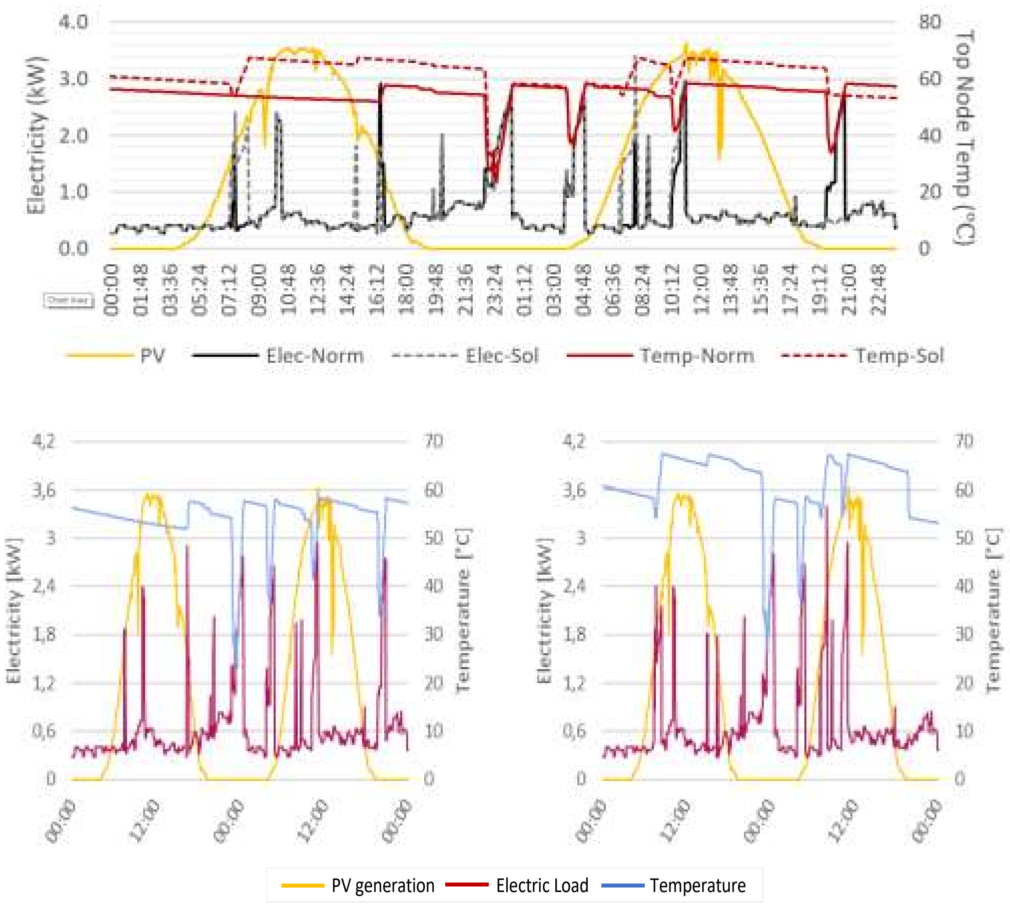

Figure 3. Comparison of the normal (Norm) and solar (Sol) control strategies

The resulting annual heating demand is 11,766kWh$_{th}$, which corresponds to 94 kWh$_{th}$/m^2 per year. The domestic hot water profile gives an annual demand of around 170l/day, which amounts to 3427kWh$_{th}$/yr, while the electricity demand for lights and appliances amounts to 5214kWh$_{el}$/yr. Figure 4 shows the monthly demand of each energy need for the baseline heating system (normal control, 180 l tank) converted to electricity. On a 3-minute time step the peak heating demand corresponds to 9.92kW$_{th}$, which is reached in February, and in that condition the heat pump compressor is operating at 3.04kW$_{el}$ with a COP of 3.26. Figure 4 shows the monthly electricity demands of the simulated building.

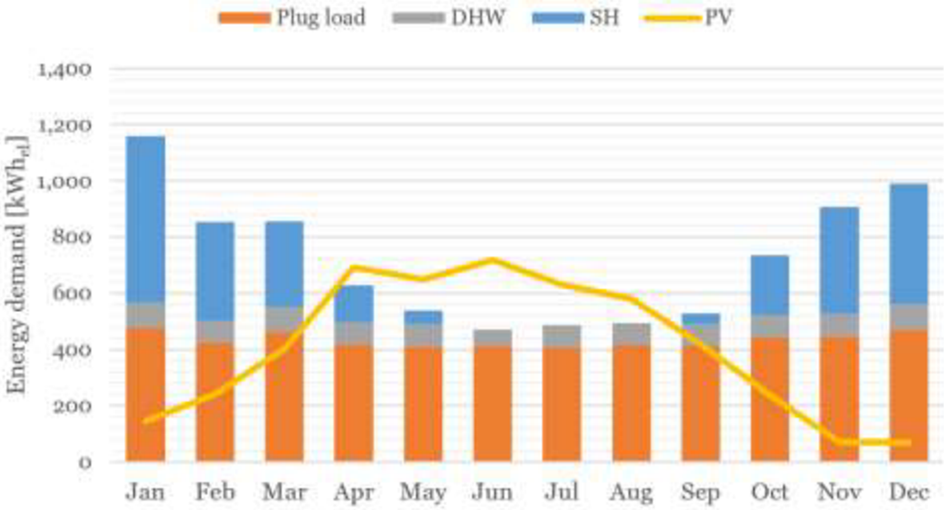

Figure 4. Monthly electricity demand of all types for the simulated building.

8.4 CCB based on ASHP, TRNSYS simulations

The concept simulated consists of an air-to-water heat pump combined with PV-panels and an energy storage, either a thermal storage or a battery. As thermal storage a domestic hot water tank (DHW), an additional pre-heating tank for domestic hot water or the buildings thermal inertia have been evaluated. An overview of the system configuration is illustrated in Figure 5. The simulations are made in TRNSYS 18 [11].

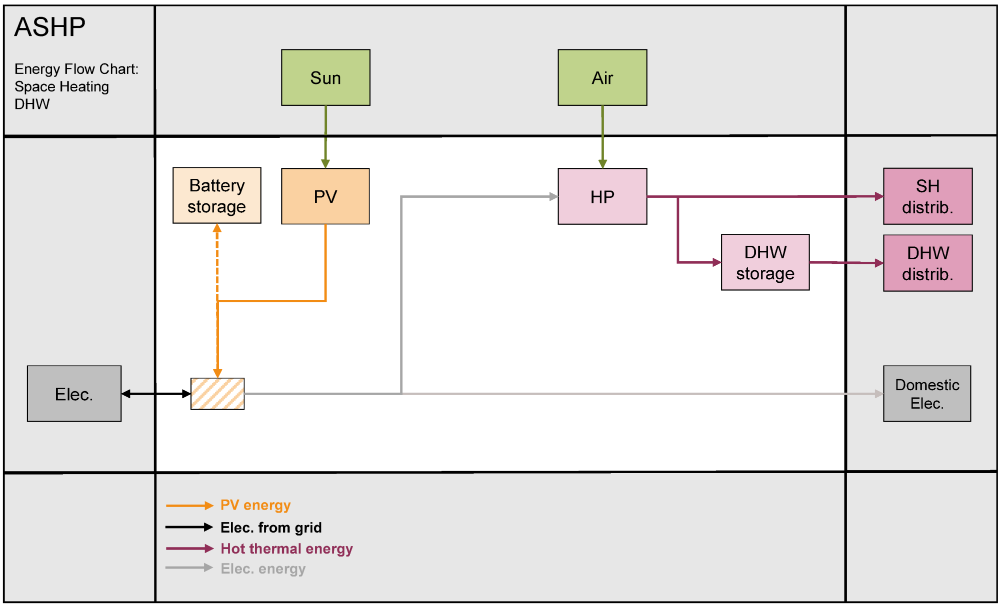

Figure 5. Energy flow chart of the CCB concept based on ASHP simulated in TRNSYS.

8.4.1 System Design

The CCB configuration is based on the same single-family building as was used for the GSHP concept, a 125 m^2 building with radiators. The energy performance of the two buildings is close to each other but not identically due to smaller different in set values for indoor temperature, ventilation etc. The building is assumed to be occupied by 4 people and has been modelled using Type56 in TRNSYS. A summary of the main characteristics for building model are presented in Table 6 above. The indoor set temperature is 21°C in the base case, which gives an annual space heating demand of 12 000kWh$_{th}$/y, corresponding to 96 kWh/m^2 per year. The domestic hot water profile used gives an annual DHW demand of approximately 3 800 kWh$_{th}$/yr, while the electricity demand for lights and appliances amounts to 5 200 kWh$_{el}$/yr.

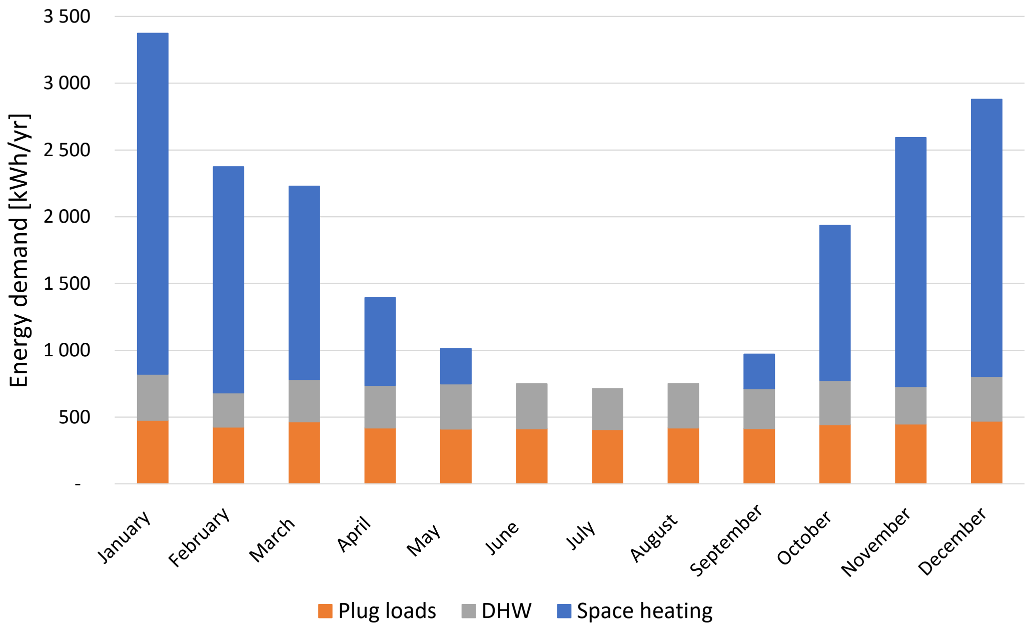

Figure 6. Monthly energy demand for the simulated building

Space heating (SH) and domestic hot water (DHW) are provided by a variable speed air-to-water heat pump with a capacity range of approximately 3-9 kW$_{heat}$ at +2°C outdoor temperature. The heat pump has been modelled based on a performance map in TRNSYS, where the heat pumps performance and heating capacity are dependent on compressor speed, supply- and outdoor temperature. The heat pump system has a built in electric auxiliary heater that is activated to provide additional heat if needed. For the simulated building and using climate data for 2019 in Norrköping, the backup heater never starts. The heat pump in its basic configuration is equipped with a 180l storage tank for DHW and no space heating buffer tank. The supply temperature for space heating is based on the heating curve of the building and start- and stop criteria's for the space heating is based on the indoor temperature, assuming the same temperature in the whole building. The DHW production has been set to start at a top node tank temperature of 48 and stop at 52°C. The control algorithm of the model prioritizes production of DHW over the space heating demand.

The electricity is supplied both by the power grid and a 5kW roof mounted PV system, with a tilt of 25°. For the simulations, weather data for the year 2019 obtained from SMHI has been used and the Swedish city of Norrköping has been chosen as location. The simulation time-step was set at 1-min.

The PV panels are connected to a regulator and an inverter, which is modelled with Type48 (mode 1) in TRNSYS. The regulator/inverter model is prepared for connection to a battery. The regulator/inverter (Type48) compares the buildings total electrical load with the electricity generated by the PV-panels. Possible excess electricity is either delivered to a 12Ah battery (if such is attached and not fully charged) or distributed to the electrical grid. Type48 also models the conversion from AC to DC.

Table 8 summarizes the main boundary parameters of the simulated system.

Table 8. Main characteristics for the CCB concept based on an ASHP system i.e., the boundary conditions of the base case

Heat Pump	PV-panels	Storage	Building	Location
Monovalent Air-to-water heat pump	South orientation, 25° tilt	DHW tank (180l)	Single family house with 4 occupants	Norrköping
Variable speed (3-9 kW_{heat})	5 kW			Weather data from SMHI (2019)

8.4.2 Control algorithms and storage

The model of the base case, described above, was used to develop, and test different control strategies in combination with different alternatives for storage. Control algorithms were developed with the aim of either increasing self-consumption of PV-electricity or decreasing the operation cost for a pricing scenario.

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Table 9. Overview of performed (X) simulations for different control algorithm and storage alternatives

Control algorithm	Base case DHW tank 180l	Battery 12Ah	DHW set-value T_{DHW}	DHW pre-heating tank	Building set-value T_{indoor}
1. Base case	X				
2. PV		X		X	
3. Price			X	X	X
4. Time			X	X	X

Three control algorithms were evaluated in the simulations for the ASHP.

PV-algorithm

The PV-algorithm focus on increasing the self-consumption of internally produced PV-power. The algorithm activates when in time there is overproduction from the PV system (the PV-power produced is higher than the electricity demand of the house). It then triggers a signal that depending on system design either allows the battery to be charged or allows for the heat pump return flows (from both space heating and production of DHW) to heat the water in a pre-heating tank, which is used to refile the DHW tank instead of the 10°C fresh water normally used. Additionally, if the HP return flow is zero and there is a surplus greater than 1 kW of electricity and the temperature in the pre-heating tank is below 54 °C a different signal is activated which activates the heat pump until the temperature in the preheating tank is above 54°C or the entire excess has been utilised. This last part was mostly added to ensure that the surplus available during summer (when no space heating is required) could be utilised.

For the system with a battery the algorithms of the electrical storage battery model (TYPE 47b) shipped with TRNSYS was used. Discharge of the battery is possible whenever the FSOC (fractional state of charge) of the battery is higher than 0.3 and there is a deficiency between the power generated by the PV panels and the electricity demand of the building. Charging and discharging properties of the battery is available in the table below.

Table 10. properties of the battery. Limits for charging and discharging of the battery.

Battery properties	Value
High limit on fractional state of charge (FSOC)	0.9
Low limit on FSOC	0.3
Charge to discharge limit on FSOC	0.15

To utilize the energy available in the pre-heating tank the temperature of the tank must be above 20 °C additionally the energy can only be discharged whenever the DHW tank is refiled. This implies that the energy stored in the pre-heating tank cannot be used to cover energy losses in the DHW tank. The model could potentially be refined by including the possibility of heating the DHW tank when the temperature is below a curtain temperature, also to making it possible to use excess PV electricity to heat the DHW tank to its maximum temperature setting prior to heating the pre-heating tank.

As a result of storing energy as electricity or heat, the amount of sold electricity decreases which effects the revenues for sold electricity.

Price-algorithm

The price algorithm is based on Nord Pools day-ahead prices. The three hours with lowest spot market price during the day are defined as low-price hours and the three hours with the highest spot market price is defined as high-price hours. Based on if the hour is defined as a low- or a high-price hour the set values for the different evaluated energy storage alternative are changed according to below:

- Elec. price T_{indoor}: For the case when the buildings thermal mass is used as energy storage, the set value controlling the indoor temperature (heating curve) is changed with +0.5°C for a low-price hour and -0.5°C for a high-price hour. The set values for when the heat pump starts, and stops are changed with the same values, see Figure 7 below.
- Elec. price $T_{DHW\text{-}tank}$: When the DHW-tank is used as energy storage the set value for the tank is increased with 10°C for low-price hours and decreased with 5°C for high-price hours.
- Elec. price PH-tank: For the case with a pre-heating tank, a low-price hour activates the use of the pre-heating tank, and the return flow (space heating water) is used to pre-heat the tap water in a pre-heating tank of 75 l before the tap-waters enters the ordinary DHW-tank. For high-price hours no changes to the settings are made and the return flow is by-passed the preheating tank.

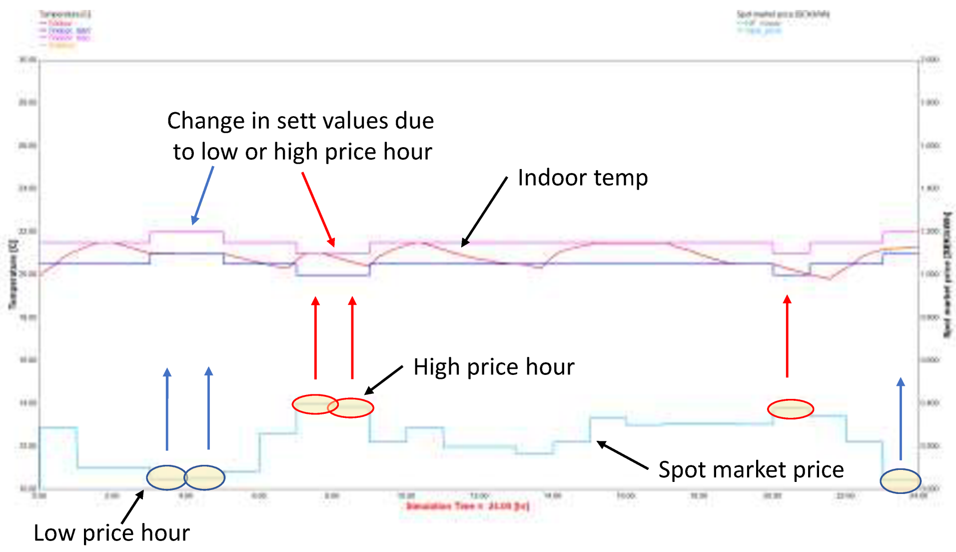

Figure 7. Schematic overview of the price algorithm. A "low-price hour" increases the set value and a "high price hour" decreases the set value. In this example the set value for indoor temperature is changed.

Time-algorithm

The time algorithm is a simplified version of the price-algorithm. The algorithm is based on the assumption that the electricity price is generally lower during the night but increases in the morning. This makes it possible to use the control algorithm without any external input about electricity prices.

- Time T_{indoor}: For the case when the buildings thermal mass is used for energy storage the set value controlling the indoor temperature (heating curve) is changed with +0.5°C from 03:00-06:00 and -0.5°C from 06:00-09:00. The set values for when the heat pump starts and stops are changed with the same values.
- Time $T_{DHW\text{-}tank}$: When the DHW-tank is used for energy storage the set value for the tank is increased with 10°C from 03:00-06:00 and decreased with 5° from 06:00-09:00.
- Time PH-tank: For the case with a pre-heating tank, the pre-heating tank is activated from 03:00-06:00, and the return flow is used to pre-heat the tap water in a pre-heating tank of 75l before the tap-waters enters the ordinary DHW-tank.

8.5 CCB based on EAHP, TRNSYS simulations

The third concept solution consists of an exhaust air heat pump in combination with PV-panels and thermal energy storage based on a pre-heating tank for DHW and/or changed set values for the DHW tank. In addition, storage in the building by changing the set values for floor heating is used as well as an electric battery. In Figure 8 an energy flow chart of the concept simulated is shown.

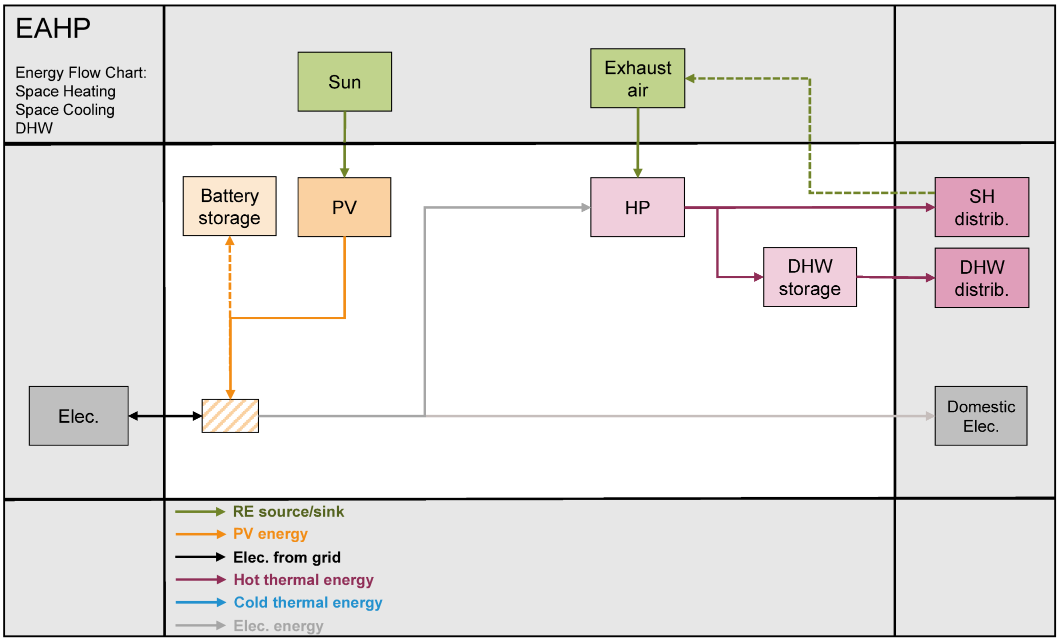

Figure 8. Energy flow chart of the CCB concept based on EAHP simulated in TRNSYS.

8.5.1 System design

The reference building is a typical Swedish single-family house (SFH) of one floor with a gabled roof. The house has an overall U-value of 0.2 W m^{-2} K^{-1}, 143 m^2 heated floor area using a radiant concrete floor heating system or radiators on demand. A detailed model of the house with six zones shown in Figure 9, is developed in the simulation software TRNSYS 17. TRNSYS's type 56 is used for the house model. The two main zones (1 and 2, living room and kitchen respectively) have a set temperature of 21°C which can be adjusted individually upon demand. The utility room and bedrooms (zones 3, 5 and 6) have 20 °C while the bathroom has 22 °C. The ventilation rate is 0.5 air changes per hour, and infiltration is 0.033 m3/s. Internal window shading is applied with 80% shading factor if the room temperature goes above 23 °C, and the infiltration is increased above 24 °C to account for opening of windows.

A compact, variable speed, exhaust air heat pump is used and delivers heat either for SH or for DHW. The heat pump is modelled with the type 581 in TRNSYS based on detailed measured data of the heat pump operation in steady state for the full range of operation. The 180l DHW tank is modelled with the non-standard type 340, as well as the additional 253l tank. The difference is that the 253l tank has an internal heat exchanger which preheats the tap water and thus has the advantage to avoid legionella formation. The SH is supplied by the heat pump through a 25l buffer store modelled by type 60. In space heating mode, the heat pump is controlled according to a heating curve and compensatory control algorithm dependent on the SH supply temperature. Moreover, an electric auxiliary heater is activated in steps when the thermal power provided by the heat pump is insufficient to meet thermal power need.

The lithium-ion battery system has a capacity of 7.2 kWh of the type LiFePO4 and the PV inverter is bi-directional. The modelling of the PV-battery system is done with a combination of the types 194 and 47a and equations to include detailed losses of the system. The battery management system is actually modelled as connected to the electrical junction box of the building and can control the import or export electricity to the grid, while controlling the charging and the discharging of the battery storage. The battery is allowed to discharge down to 20% of the SOC or 0.2 of the FSOC (fractional state of charge) and the maximum charge limit is set to 100% SOC or 1 of the FSOC.

Figure 9. Layout of the building that is modelled with 6 thermal zones (left side) and the actual front view of the house (right side).

Table 11. Energy demand of the household and PV annual yield in the base case.

Household DHW, appliances data and heating demand, base case	**Energy** [kWh/yr]
DHW discharge energy	3487
SH demand	12146
PV electricity yield	5119
Electricity for appliances	3644

In addition to the developed control algorithms (see [3] for details), an battery (variant 1) or an extra pre-heating tank for DHW (variant 2) were implemented in the system to increase the self-consumption of PV-electricity by utilizing the electrochemical storage (batteries) and by storing thermal energy in the compact domestic hot water tank (activate the heat pump to increase the set point in order to overheat beyond the reference setpoint).

The extra hot water tank (variant 3) has an internal heat exchanger which preheats the tap water when there is PV excess energy. The objective of the Price algorithm which is used in variants (3-6) is to control the heat pump system in order to adjust the space heating demand or overheat the compact tank or even to preheat the extra tank according to the spot market price signal and the near future price forecast. More details can be found in Psimopoulos, E., et al. [3]. In Table 12 an overview of simulations is shown.

Table 12. Simulation variants for the EAHP system.

	Algorithms		**Storage options**			
Variants	**Price**	**PVxs**	**Battery**[1]	**DHW store temp**	**Extra DHW tank**	**Building**[2]
Base case						
1		X	X	X		
2		X		X	X	
3	X			X		X
4	X			X	X	X
5	X	X		X	X	X
6	X	X		X		X

[1] Battery is only used with PVxs (excess electricity)
[2] The building uses floor heating in zones 1 and 3 by varying the set temperature (see Figure 9)

The base case includes no control between the PV system and the heat pump operation and no extra storage type. For the case of the thermal mode during overheating of the compact DHW-tank and the additional tank the heat pump compressor speed up and the load demand is adjusted to the available excess PV electricity. The auxiliary heater is restricted during the predefined summer period or whether a threshold of ambient temperature is exceeded. This is done as there is a risk that any benefits of the algorithms are negated by unnecessary use of the normal control of the auxiliary heater. In the electrical mode (variant 1) the excess available PV electricity is consumed initially to overheat the compact DHW-tank and then by the battery system.

8.6 Cooling, IDA ICE simulations

Simulations of comfort cooling were done in IDA ICE [12] in order to evaluate possibilities to improve the comfort related to cooling. The simulations have focused on passive cooling from the bore hole for a single-family building with an installed GSHP. The cooling is distributed to the indoor air using a fan coil. Both a Swedish villa with “normal” heating demand and a low energy building were included in the simulations. The prototype of the IDA ICE model is a low energy house which is used as research house located at RISE premises in Borås, Sweden. Figure 10 shows the prototype house and the corresponding IDA model.

Figure 10. Prototype of the single-family house (left) and the IDA model (right).

The single-family house has a total heated floor area of 155 m^2 and consist of 2 floor levels. The house is equipped with balanced ventilation with heat recovery, and the total air supply flow rate is 60 l/s.

8.6.1 System Design

In the simulations, passive cooling with a direct and an indirect system were modelled. The schematic view of the direct and indirect system is shown in Figure 11. As shown in in Figure 11, in the direct system, brine from the borehole heat exchanger is directly connected to the fan coil and thus cools down indoor air directly. For the indirect system, there is an indirect water loop distributes cooling between the brine and indoor air. The major difference between the two systems is that water vapour condensation (on pipes etc.) is allowed in the direct system while this is not allowed in the indirect system. Thereby, for the direct system one need to handle the condensed moisture in order not to case problems. On the other hand, with a direct system one will have a larger cooling power due to larger temperature differences, compared to an indirect system. The minimum se temperature for air leaving from the fan coil and sent back to the room is 15 °C for the direct system, and it is 18 °C for the indirect system. The actual air temperature leaving the fan coil (i.e., simulated) is 15-25°C depending on the cooling demand. In the IDA model, room cooling set point is 25 °C in base case (this means that fan coil starts to cool down the house when the temperature exceeds 25 °C).

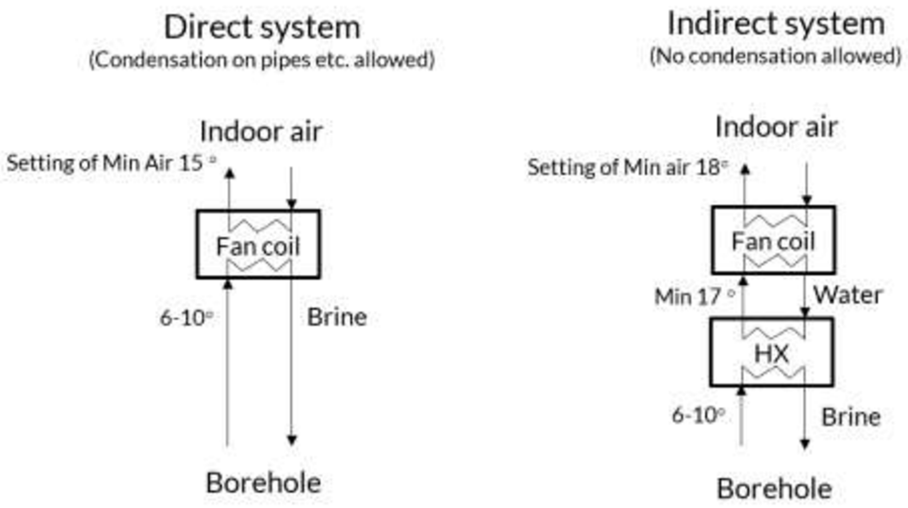

Figure 11. Schematic view of the direct and indirect cooling system.

In the IDA model, one fan coil is used and it is assumed to be located at the living room in the 2nd floor level. The living room (at the 2nd floor level) is connected to the three sleeping rooms and to one bathroom, see Figure 12.

Figure 12. Layout of the 2nd floor. The fan coil is located in the living room and provides cooling to the surrounding living spaces.

Several cases were simulated, see Table 13 below, including the type of cooling (i.e., direct or indirect).

Table 13. Summary of IDA ICE case studies for both the low energy and normal Swedish single-family house.

Case number	Type of cooling	Cooling set point for T_{indoor} (°C)	Ventilation flow rate (l/s)
1	Direct	25	60
2	Indirect	25	60
3	Indirect	25	Jul 16 – Aug 31: 100 l/s, Rest of the year: 60 l/s
4	Indirect	Jul 16 – Aug 31: 21°C Rest of the year: 25°C	60
5	Indirect	Jul 16 – Aug 31: 21°C Rest of the year: 25°C	Jul 16 – Aug 31: 100 l/s, Rest of the year: 60 l/s

One sensitivity analysis made was to decrease the comfort cooling set point, from the ordinary 25°C to start cooling at an indoor temperature of 21° during the summer period. Another variation simulated was to increase the ventilation flow rate during the summer period. Finally, the combination of increased ventilation flow rate and a cooling set point of 21°C was simulated. The windows are assumed to be closed during the entre simulation period for both the normal house and the low energy house. The results are evaluated in terms of cooling capacity, energy use and number of hours the house being overheated.

9 Results simulations

Below follows the simulation results for each type of Comfort & Climate Box. Chapter 9.1includes results from the concept based on a GSHP. In chapter 9.2 results related to the ASHP are presented, and in 9.3 results related to the EAHP. Finally, chapter 9.4 includes results from the comfort cooling simulations. Background and methodology are described in chapter 8.

9.1 CCB based on GSHP

In this section the result from the simulation of CCB based on GSHP are presented. The conditions for the simulations are presented in chapter 8.3.

In normal operation conditions, without a control system taking electricity produced by the PV panels into consideration, the total annual electricity consumption amounts to 8646 kWh_{el} of which 77% is supplied by the power grid, giving a value of self-sufficiency of 22.9%. The annual PV production corresponds to 4851 kWh_{el}, resulting in a self-consumption of 40.9%.

Once the “solar” control strategy is applied, the annual electricity demand increases to 8796 kWh_{el}, but the share of self-consumed PV electricity is also increasing, lowering the grid purchases to 74% of the total electricity supply. The self-consumption and self-sufficiency of the new system increase respectively to 47.3% and 26.1%. Figure 13 shows the difference in the monthly electricity supplied by each technology.

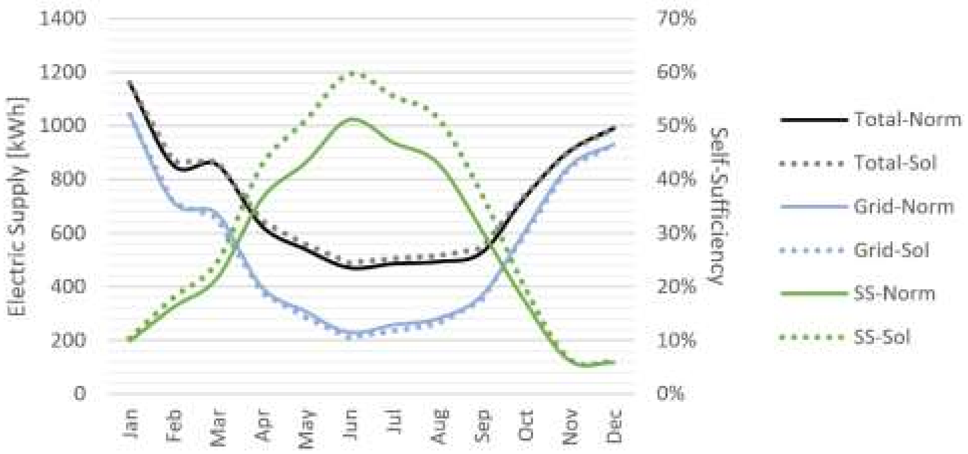

Figure 13. Electricity supplied by grid and PV in the normal (left) and optimized (right) operation strategies.

To evaluate the possibility to further improve the performances of the system under the new control strategy, a sensitivity analysis on the tank size has been performed. More specifically, the tank volume was increased from 180l up to 1000l.

From Figure 14, showing the duration curve of the top node temperature, it can be noticed that the operating time of the new control strategy can be extended to more than 4000 h per year already with the 300l tank, but it increases only of few hundred hours more with the 1000l tank.

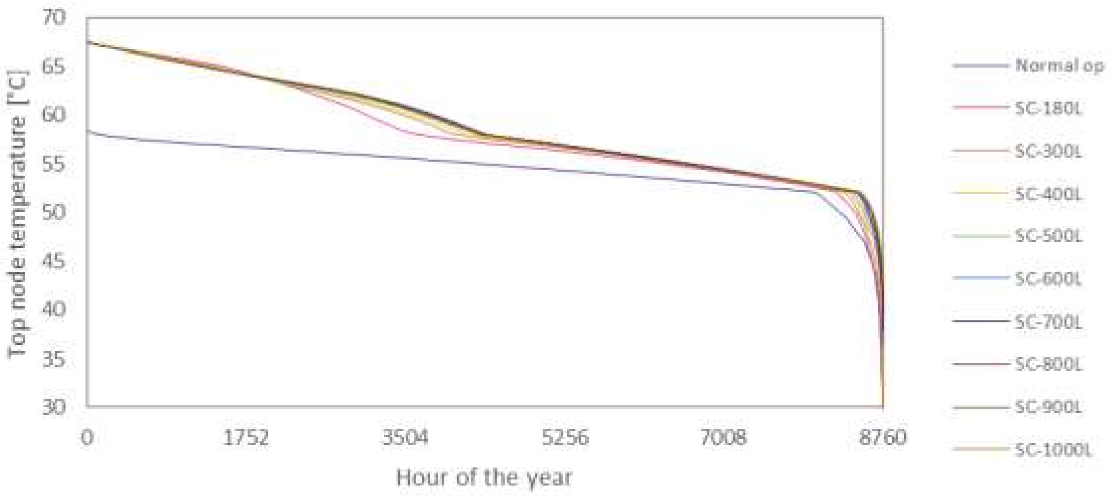

Figure 14. Duration curve of top node temperature for normal operation and self-consumption (SC) strategy for different tank sizes.

The increase of the tank size also creates a negative effect on the average COP, especially in the summer months, when the new control strategy is active the most. The heat pump has lower performances when operates at higher temperatures at the condenser, and as soon as the new control strategy is active the average COP drops. Then, by increasing the size of the tank the new control strategy stays active for more hours, resulting in a lower efficiency of the heat pump on a monthly basis. Figure 15 shows how the average COP changes for the different operation strategies.

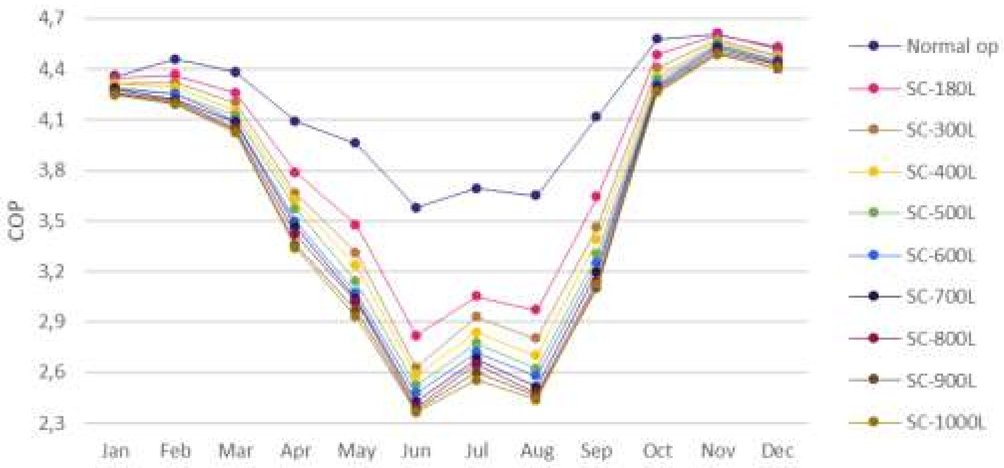

Figure 15. Monthly average COP for normal operation and self-consumption (SC) strategy for varying tank sizes.

Regarding the electricity consumption, the more the volume of the DHW tank increases, the more the overall electricity demand increase. However, the self-consumed electricity generated by PV increases as well, lowering the grid purchases up to 700l in volume. This can be observed in Figure 16, which shows the absolute variation of electricity consumption and self-consumption of the systems.

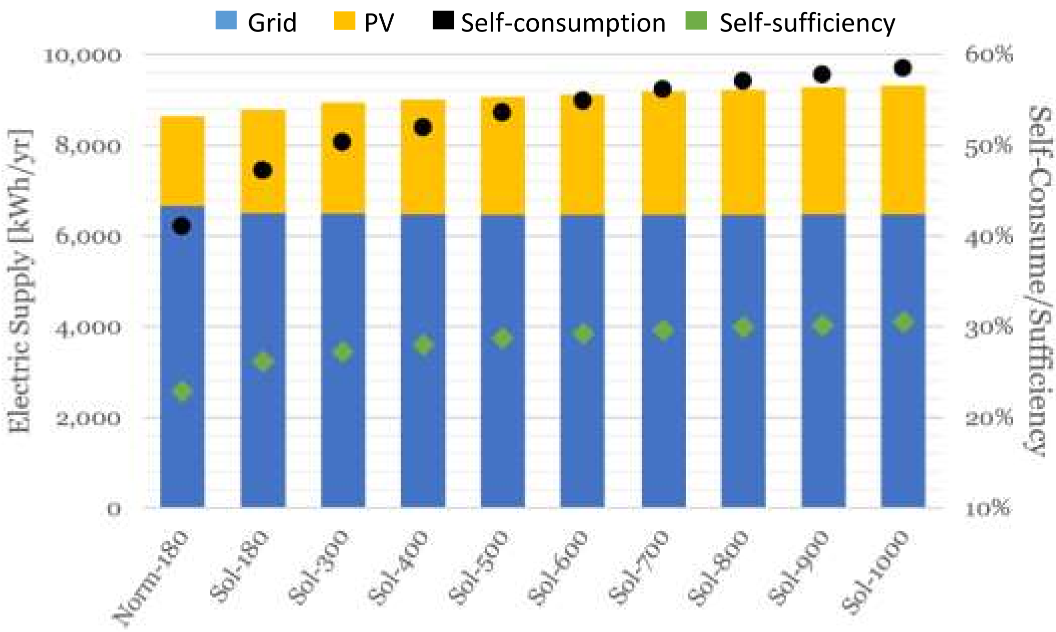

Figure 16. Absolute variation of electricity supply and self-consumption for normal and solar strategies for different tank sizes.

The largest impact on technical performance comes from simply changing the control strategy but keeping the baseline 180l tank, where self-consumption increases from 41% to 47% and grid purchases fall by 2.4%, see Figure 17 . The maximum savings comes from the 700l tank with a 3% reduction in grid purchases, equivalent to 203 kWh/yr. While self-consumption and self-sufficiency increase, most of the PV generation is turned into waste heat given that total annual demand increases by 533 kWh/yr over the baseline system. Above 700l, all of the stored solar energy is lost to waste heat.

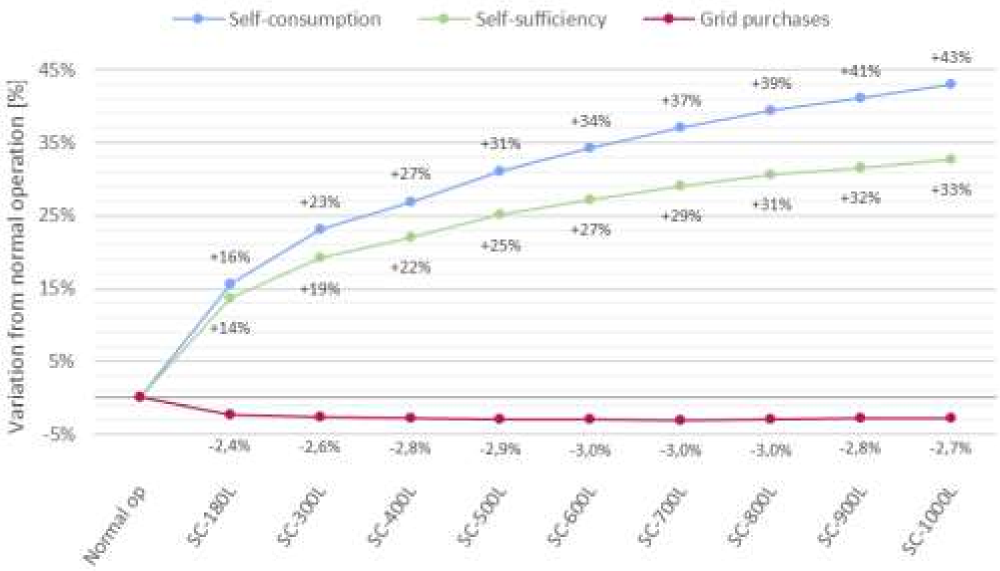

Figure 17. Relative variation of KPIs for normal operation and self-consumption (SC) strategy for different tank sizes.

The extra amount of electricity needed for larger tanks is the result of increasing thermal losses due to larger surfaces of the tank. The thermal loss increase is relatively small when the operation mode switches from the normal one to the one that improves the self-consumption, but a rapid increase is noticed as soon as the volume of the tank is increased.

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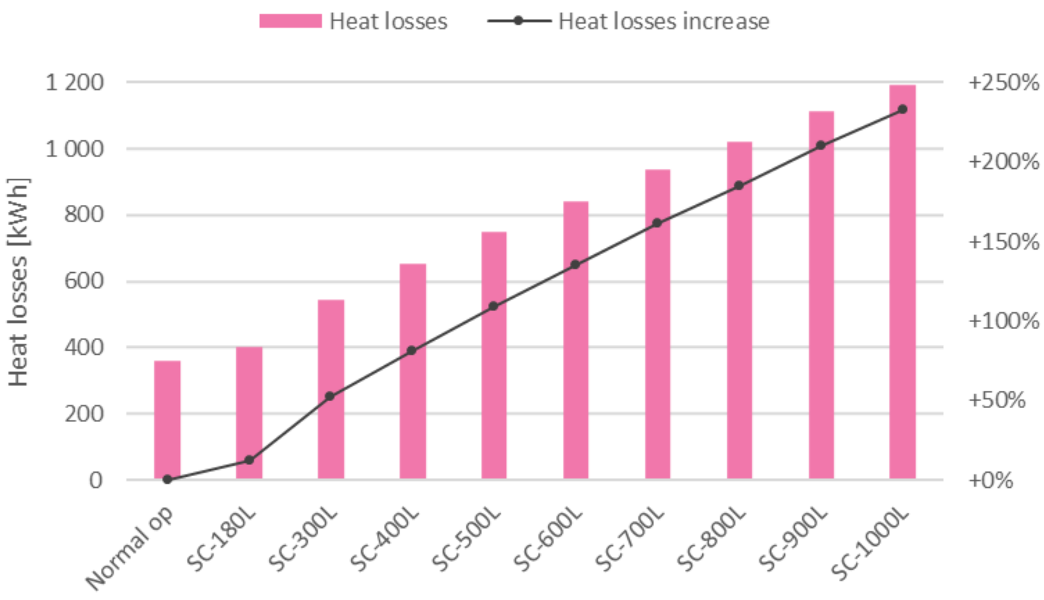

Figure 18. Heat losses in DHW tank at normal operation and self-consumption (SC) strategy for different tank sizes

As noted above, 67.5°C is the maximum top node temperature of the solar control, however higher temperatures would enable more energy storage for a given volume and reduce the tank's surface area for losses. Figure 19 shows higher maximum temperatures for the 180l tank up to a maximum of 72.5°C, 5K higher than the original solar control strategy. The setting with the lowest grid purchases is 71.5°C at 6462kWh/yr, a 42kWh/yr savings from the original 67.5°C setting. This is comparable to the results of the 700l tank in Figure 16, however the smaller 180l tank's losses over the year adds only 201kWh/yr to the total energy usage – less than half of the 700l tank.

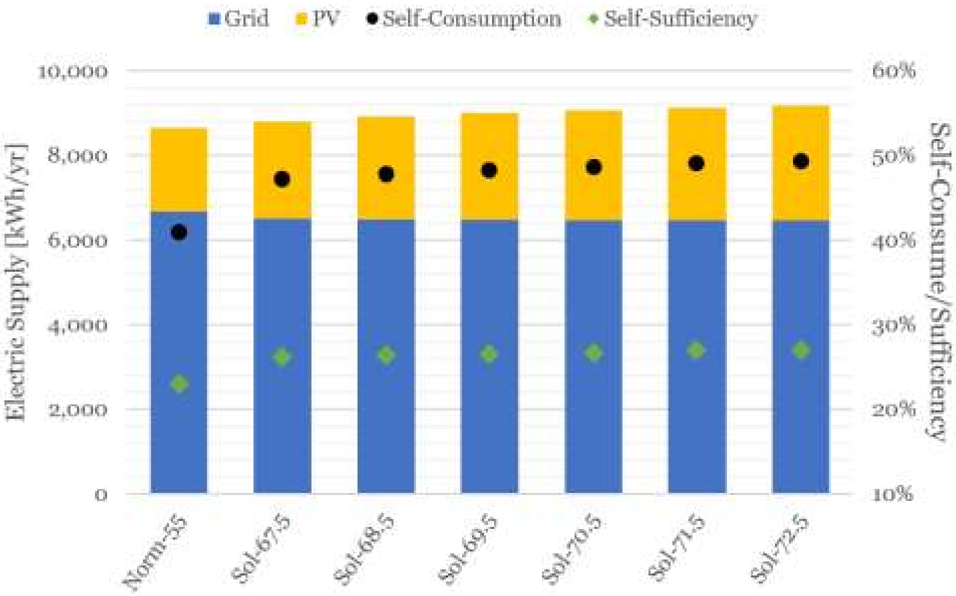

Figure 19. Absolute variation of electricity supply and self-consumption for normal and solar strategies with increasing maximum tank temperatures

9.1.1 Economic evaluation

Figure 20 shows how the electricity costs change due to self-consumption strategies and the price scenarios from Table 5. It is clear that the largest influence on annual cost are the micro producer tax reduction (PS05-08) that discourage self-consumption and reduce costs by 16% with the normal control. With the solar control (180l) the savings are only 15% and when the 700l tank is used the savings are only 12% from the baseline.

Table 14. Overview of price scenarios for electricity (copy of Table 5)

	S1	S2	S3	S4	S5	S6	S7	S8
Contract	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly
Network	Energy	Energy	Capacity	Capacity	Energy	Energy	Capacity	Capacity
Tax reduction	No	No	No	No	Yes	Yes	Yes	Yes

Considering price scenarios, the lowest costs are found using an hourly contract and energy-based network metering. Since capacity pricing is applied only during daytime hours (07-19), PV is able to reduce network costs as compared to a home without PV, just not as much as with energy based network pricing.

With a 180l tank, the solar controller is only able to reduce costs when using volumetric network pricing without tax reduction (PS01, PS02), but only by 0.8% or about 75 SEK. In the worst case with tax reduction, hourly energy and network capacity pricing (PS07), the solar controller increases annual costs by 2.8%. With the 700l tank, the costs are always higher, up to 8.7% higher in the worst case (PS07).

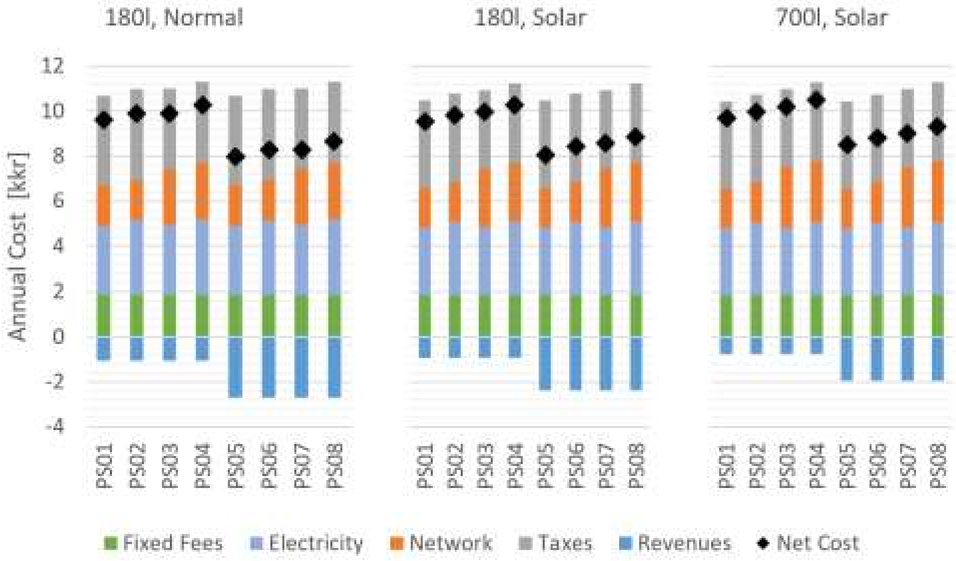

Figure 20. *Annual operational costs by system and price scenario, shown with each cost component for electricity*

When considering the 15-year life cycle costs, the effect of the solar control becomes even less noticeable. Figure 21 shows total life cycle costs (TLCC) where the difference between controllers for the 180l tank is less than 1% in all price scenarios. The 700l tank has both higher operational costs (OPEX) and a capital cost (CAPEX) for the larger tank, leading to a 25% higher TLCC for a given price scenario.

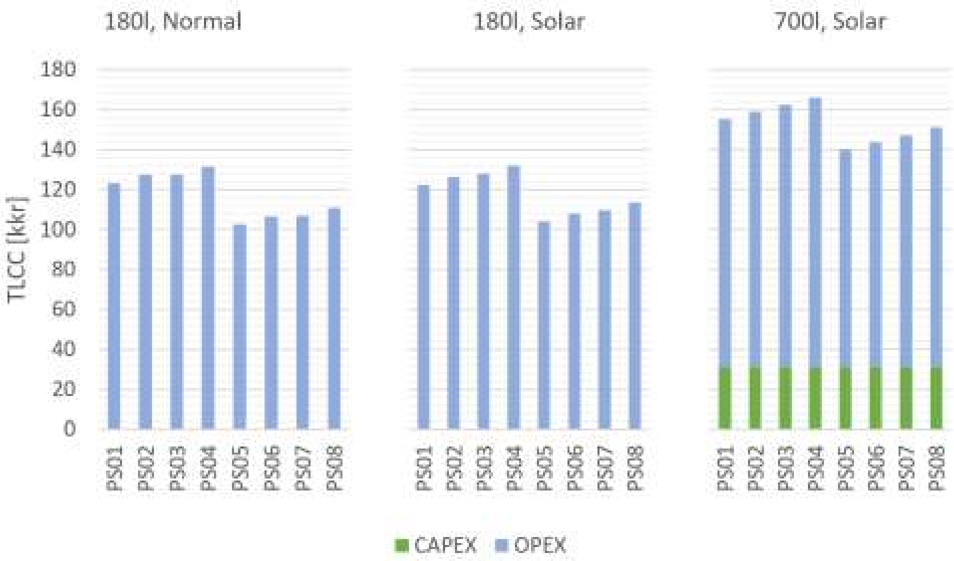

Figure 21. Total life cycle cost for a GSHP with 180l DHW-tank in normal operation (left) compared to a CCB with solar algorithm activated with either a 180l (middle) or a 700l DHW-tank (right).

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9.1.2 Conclusions CCB based on GSHP

- There is a trade-off between additional PV energy storage in water tanks and increased losses due to increased size and temperature of the storage tank and reduced efficiency of the heat pump.
- Self-consumption is increased with larger hot water stores, however at large tank volumes (700l and higher) all marginal PV self-consumption is converted to waste heat.
- The high efficiency of a monovalent GSHP reduces economic savings potential of the self-consumption algorithm, with annual operating costs reduced by less than 1% in the best pricing case.
- Standard tank sizes currently used by manufacturers are suitable for self-consumption control strategies.
- High temperatures are recommended as the main self-consumption control technique since there are no new equipment investments and losses during seasons of low-irradiance are minimized.

9.2 CCB based on ASHP

9.2.1 Results PV control algorithm

The simulation results presented below shows the variation in electricity demand from the grid for different storage solutions. The aim of the algorithms used is to increase PV self-consumption. The logic of the algorithm is such that if a surplus of electricity is generated from the PV panels the excess can be stored either as heat (in a tank which can be used to pre heat domestic hot water) or electricity (in a battery).

Figure 22 below shows the building’s total electricity use over the simulated year compared to the bought electricity from the grid for the different alternatives. The difference between total electricity demand and bought electricity is covered by internally produced solar.

As can be seen in the graph below, the total electricity demand is relatively similar for all alternatives (black bars in Figure 22). Regarding the annual amount of bought electricity, the base case has the highest demand (blue bars in Figure 22). For the cases with a preheating tank the annual amount of bought electricity decreases slightly with increased size. The least amount of electricity from the grid is required for the case with a battery.

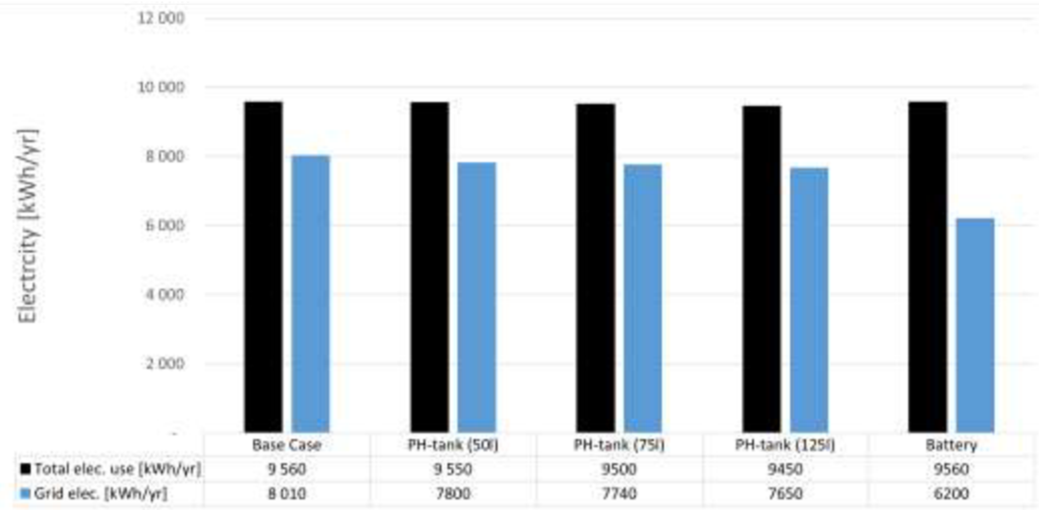


Figure 22. Total annual electricity demand for the building (in black) and annual amount of electricity bought from the grid (blue). Base case is compared to three different sizes of pre-heating tanks and a battery.

Similar to the result in Figure 22, Figure 23 illustrates the advantages of implementing storage solutions to the system. Rather than describing amount of bought electricity Figure 23 illustrates the result in terms of self-consumption. As the algorithm used is intended to increase the self-consumption using different types of storage solution it is not surprising that all cases performs better that the base case. It is not suitable to compare the results for the battery and the storage tanks with each other as they are not designed to be able to store the same amount of energy, they are also implemented in different parts of the system. The battery has the potential of reducing the total amount of bought electricity and the pre-heating tank can only decrease the amount of bought electricity for heating the domestic hot water.

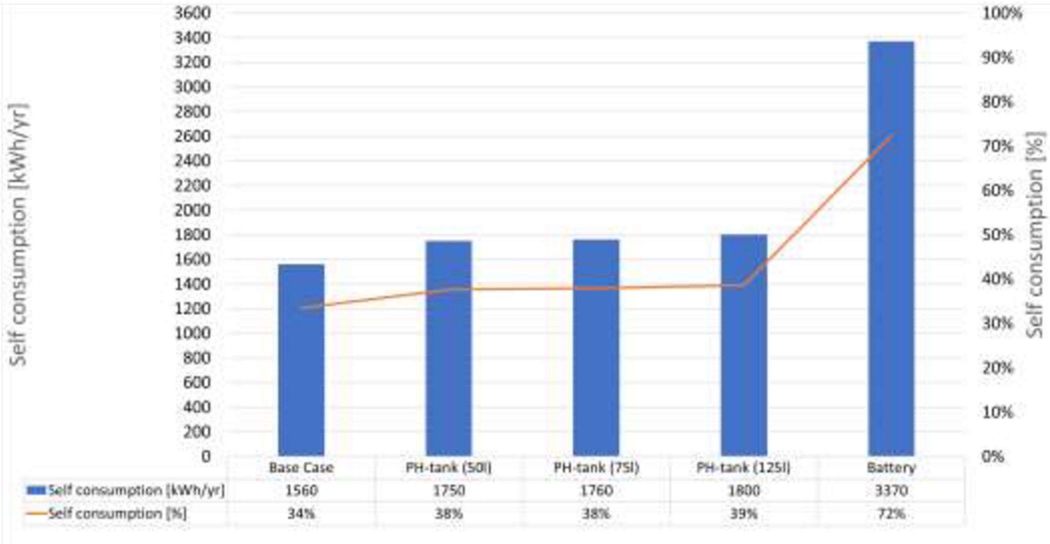


Figure 23. Self-consumption of electricity for base case, three cases with different sizes of pre-heating tanks and a case with battery.

9.2.2 Economic evaluation PV algorithm

The annual electricity cost is calculated for the building in total, including electricity use for space heating, DHW and plug loads. The cost includes purchased electricity, fixed fees and for some of the price scenarios a peak capacity cost. Revenues from sold excess PV electricity is also included in the net total cost. In Figure 24 the electricity cost for the base case is compared to two sizes of a pre-heating tank and an electric battery for each price scenario, see Table 5.

Table 15. Overview of price scenarios for electricity (copy of Table 5)

	S1	S2	S3	S4	S5	S6	S7	S8
Contract	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly
Network	Energy	Energy	Capacity	Capacity	Energy	Energy	Capacity	Capacity
Tax reduction	No	No	No	No	Yes	Yes	Yes	Yes

The black bar in Figure 24 shows the net cost for the different alternatives and price scenarios. As can be seen in Figure 24, and even more clear in Figure 25, the alternative with a battery in combination with the PV-algorithm is the best chose in order to reduce the running costs. For this case the annual running cost decreases with above 12% for price scenario 1 and 2 (with no tax reduction for sold solar and a network fee based on electricity consumption. On the other hand, the battery also comes with the highest investment cost. The LCC cost has not been calculated for this case but Figure 39 shows the results for a similar system but based on an EAHP. Here the LCC costs for the alternative with the battery are the highest of the compared systems.

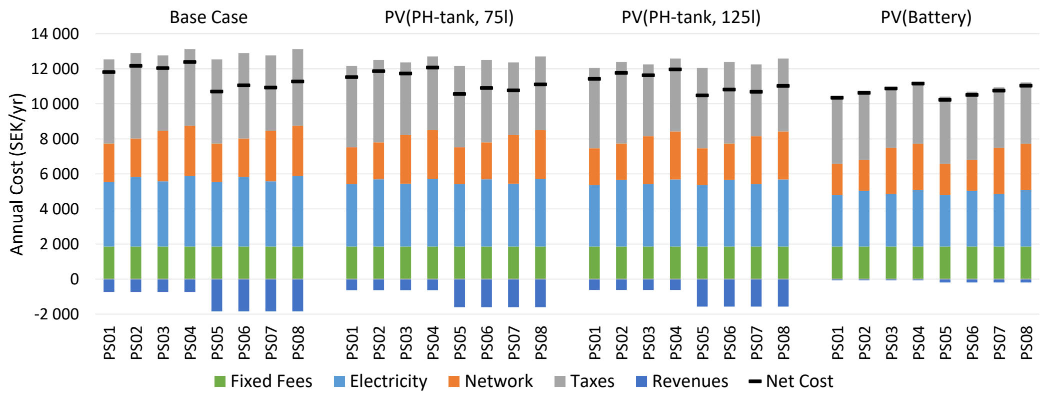


Figure 24. Breakdown of annual electricity cost and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 5. Base case is compared with the three different storage alternatives combined with an activated PV algorithm. The total annual electricity cost (net cost) for each case is shown with black lines.

Figure 25 shows that the saving potential is largest for the case with a battery for storage, but also a pre-heating tank reduces the electricity costs with a few percent.

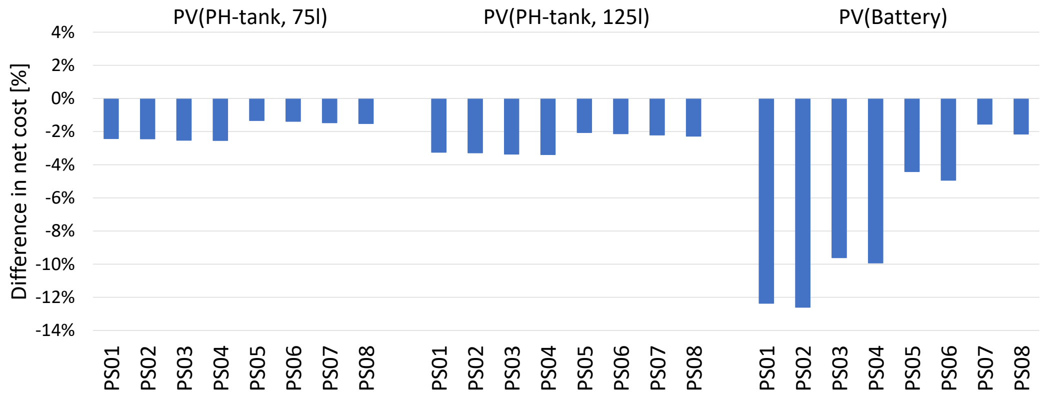


Figure 25. Difference in net yearly electricity cost compared to base case for the three different storage alternatives combined with an activated PV algorithm.

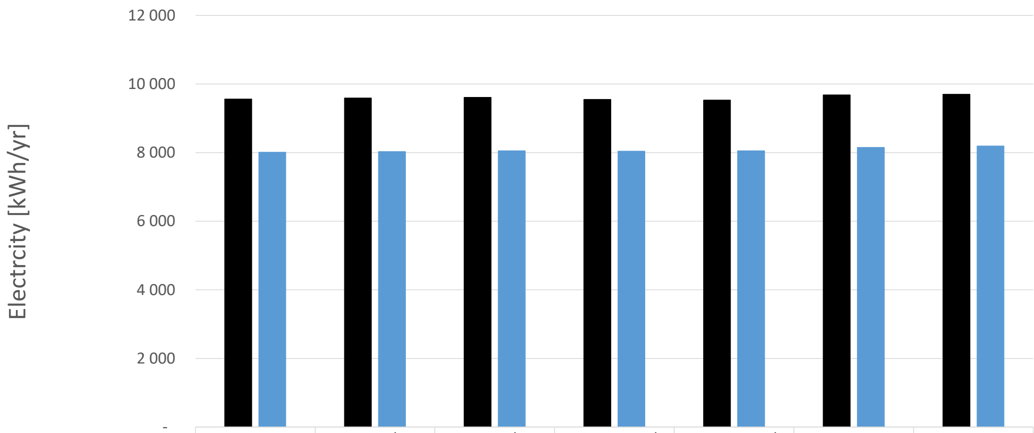
9.2.3 Results price- and time control algorithm

The simulation results presented below shows the results with an activated price or time algorithm combined with three different alternatives for storage, The DHW-tank, an additional pre-heating tank for tap-water or the buildings thermal mass, thereby changing the set values for the indoor temperature. The results are compared with a base case with no smart control algorithms activated or any additional storage except for the ordinary DHW-tank. The total annual electricity use includes electricity use for space heating, DHW and plug loads (for lights, white goods, electronic equipment etc), where the plug loads represent around 54% of the building's total electricity use.

Figure 26 below shows the buildings total electricity use over the simulated year compared to the bought electricity from the grid for the different alternatives. The difference between total electricity demand and bought electricity is covered by internally produced solar.

As can be seen the total electricity demand is relatively similar for all alternatives., with a small increase in electricity demand for in first-hand the control algorithms using the DHW-tank as storage. Higher set temperature gives lower COP and thereby increases the electricity consumption, while a lower set temperature increases COP. Especially for the alternative with DHW-tank the lower set values during high-price hours cannot compensate for the lower COP during low-price hours. A higher tank temperature also increases the tank losses. Those losses are only partly assumed to reduce the heating demand of the building in the simulations.

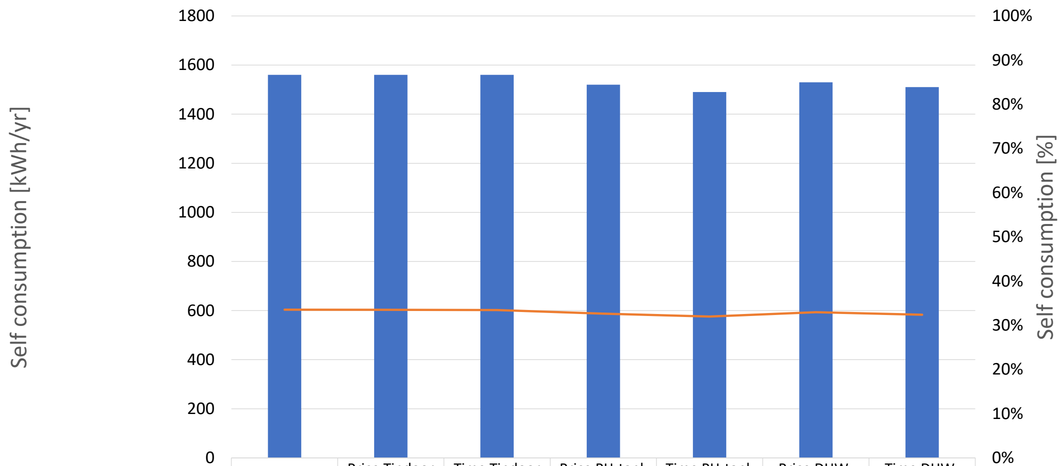
A somewhat higher electricity demand is expected for this control algorithm. The question to be answered if could lead to overall lower cost for the electricity.



	Base Case	Price Tindoor 0.5°C	Time Tindoor 0.5°C	Price PH-tank (75l)	Time PH-tank (75l)	Price DHW-tank	Time DHW-tank
Total elec. use [kWh/yr]	9 560	9 590	9 610	9 550	9 530	9 680	9 700
Grid elec. [kWh/yr]	8 010	8 030	8 050	8 040	8 050	8 150	8 190

Figure 26. Total yearly electricity demand for the building compared to electricity bought from the grid. Base case is compared with the three different storage alternatives combined with an activated price- or time algorithm.

In Figure 27 the self-consumption is shown for the different cases compared to the base case. The difference in self-consumption between the alternatives is small. Since neither the price nor the time algorithms focus on increased use of PV electricity this is what can be expected. Any differences in results are more due to coincidences in how the electricity use is distributed over the day than the result of active control to increase the proportion of internally used solar.



	Base Case	Price Tindoor 0.5°C	Time Tindoor 0.5°C	Price PH-tank (75l)	Time PH-tank (75l)	Price DHW-tank	Time DHW-tank
Self consumption [kWh/yr]	1560	1 560	1 560	1 520	1 490	1 530	1510
Self consumption [%]	34%	34%	33%	33%	32%	33%	32%

Figure 27. Self-consumption for base case compared with the three different storage alternatives combined with an activated price- or time algorithm.

9.2.4 Economic evaluation price- and time algorithm

The annual electricity cost is calculated for the building in total, including electricity use for space heating, DHW and plug loads. The cost includes purchased electricity, fixed fees and for some of the price scenarios a peak capacity cost. Revenues from sold excess PV electricity is also included in the net total cost. In Figure 28 the electricity cost for the base case is compared to the three storage alternatives with an activated price algorithm.

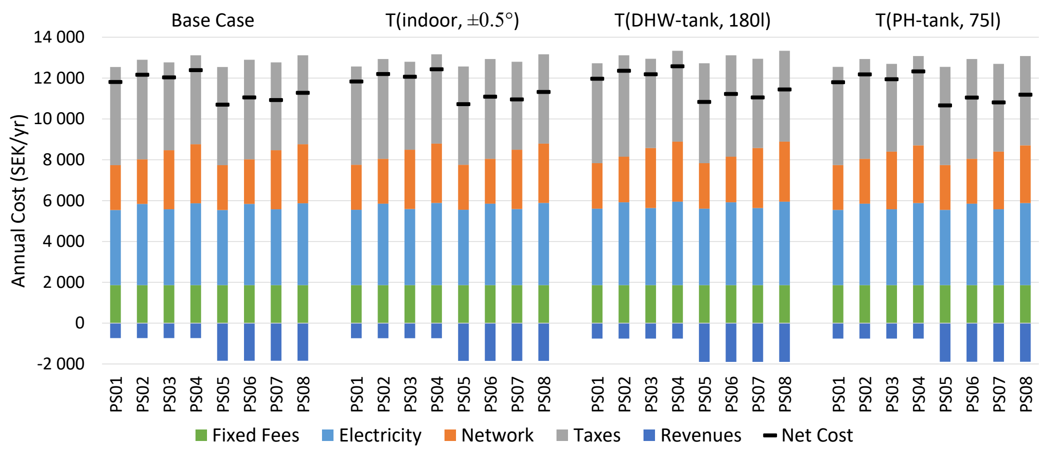


Figure 28. Breakdown of annual electricity cost and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 5. Base case is compared with the three different storage alternatives combined with an activated price algorithm. The total annual electricity cost (net cost) for each case is shown with black lines.

The percentage difference in net cost for the three storage alternatives with an activated price algorithm compared to base case is shown in Figure 29. As can be seen the potential savings are small, close to negligible, but the alternative with a pre-heating (PH) tank is the most promising alternative for savings related to the running cost. A disadvantage with a PH-tank compared to the other alternatives are the need for an extra tank leading to both higher investments costs and a larger area needed for the unit. Storage in the DHW-tank with the algorithm evaluated in these simulations are the least promising alternative and risk to lead to higher electricity costs. The results from the simulations show that the saving potential are larger for dwellings with a capacity-based network fee (PS03-04 and PS07-08) than for a traditional business model for the network fee, based on energy use.

Note that since the plug loads represent over 50% of the building's total electricity demand, a saving of 1% of the total electricity cost represent roughly 2% savings of the heating cost.

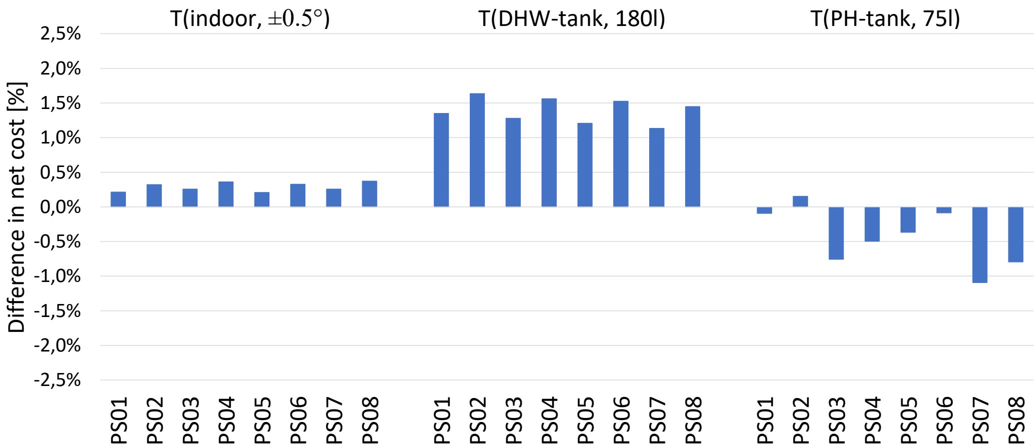


Figure 29. Difference in net yearly electricity cost compared to base case for the three different storage alternatives combined with an activated price algorithm.

Figure 30 shows electricity cost for the base case compared to the three storage alternatives but this time with an activated time algorithm, followed by Figure 31, which shows the difference in net yearly cost for the same alternatives. The general trend is similar to the trend for the price algorithm.

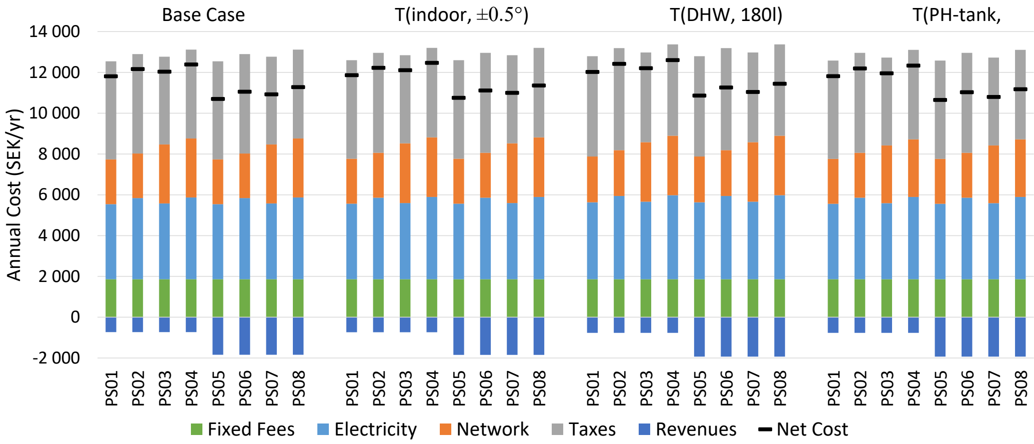


Figure 30. Breakdown of annual electricity cost and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 5. Base case is compared with the three different storage alternatives combined with an activated time algorithm. The total annual electricity cost (net cost) for each case is shown with black lines.

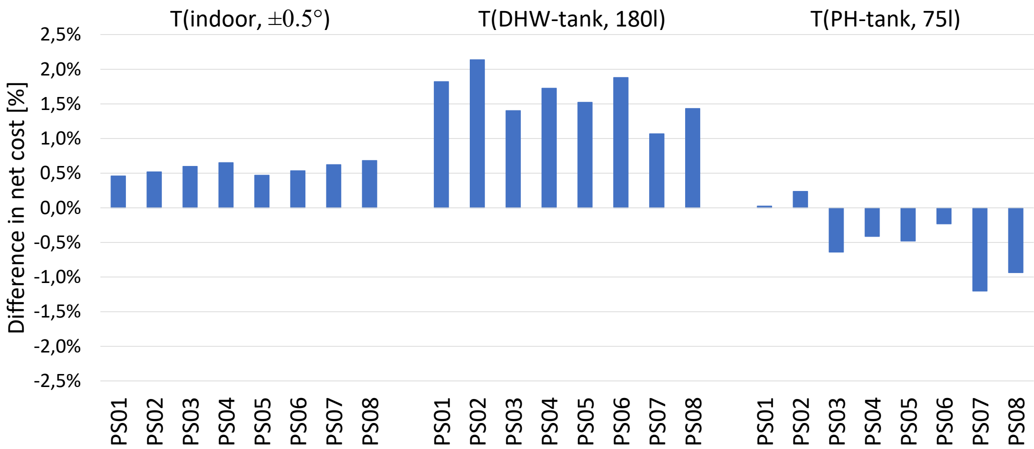


Figure 31. Difference in net yearly cost compared to base case for the three different storage alternatives combined with an activated time algorithm.

The simulations shows that the economical savings related to the price algorithm and an energy storage using a PH-tank is relatively small (0-1.5%) with the price variations from 2019 in electricity area 3 in Sweden, see Figure 31. For the case with energy storage in the buildings thermal mass or the DHW-tank the net annual electricity cost even increases. One reason for this is the fact that the price- and time algorithm forces the heat pump to run more during cold night hours when the electricity prices are low which leads to lower efficiency. Compared to the ground source and exhaust air heat pumps the air source heat pump are more affected by low night temperatures. Higher set points for DHW also reduces the heat pumps COP and leads to higher heat losses, which is not fully compensated for during the hours with lower set values.

9.2.5 Increased price volatility

The economical evaluation is based on electricity prices from 2019, but 2019 was a year with rather small variations in electricity price, especially compared to 2021, see chapter 11.1 for details. Since the electricity prices are connected to the weather conditions, it is not possible to run the simulations with electricity data from another year without also update the weather data. Instead, in order to evaluate the impact of higher price variations but still use weather data from 2019, the price volatility has been increased. To evaluate the impact on a higher price volatility the daily price volatility has been increased in steps of 50% up to 200%.

In Figure 32 the savings in net cost for the building's total electricity demand over the year is compared to the base case for different control algorithms activated and with increased price volatility. The calculations are based on price scenario 1, with hourly energy prices, a network fee based on electricity consumption and no tax reduction for sold PV electricity, see chapter 8.2.1 for more information. The figure also includes a sensitivity analysis for the settings for an increased variation in indoor temperature, where a variation of 0.5°C is compared with the results with an allowed variation in indoor temperature of 1°C and 1.5°C respectively. The results show that an increasing price volatility increases the savings when the algorithms are activated, but the potential savings are still modest. This is the case for all algorithms evaluated. The economical savings for the control algorithm combined with a pre-heating tank reduces the net electricity cost for the building's total electricity use (including space heating, DHW and plug loads) with 0-1.5% depending on price volatility and electricity price scenario, see Figure 32 and Figure 33. For the case where the set values for the indoor temperature is used for storage, an increased price volatility results in that the net cost goes from higher than base case to lower, even though the savings are small. For the algorithm "Time Thouse 0.5°C" the electricity cost is foreseen to increase, also with a larger price volatility.

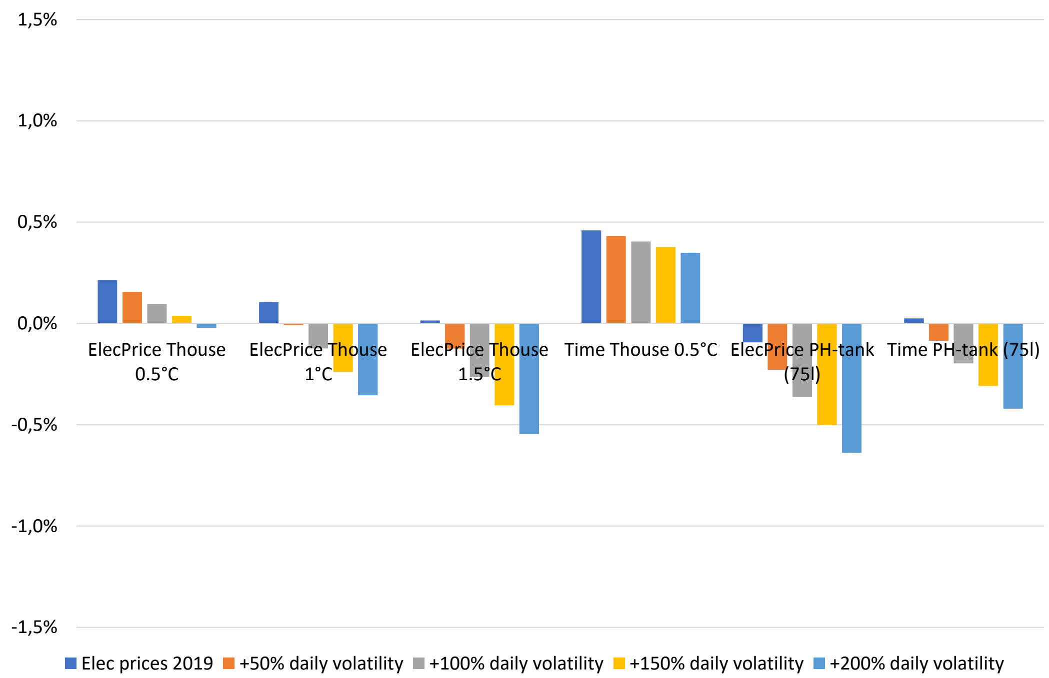


Figure 32. Percentage change in yearly running cost for the buildings total electricity consumption compared to base case based on different control algorithms and price volatility for price scenario 1 (hourly energy prices, a network fee based on electricity consumption and no tax reduction for sold PV electricity).

Figure 33 shows the variations in net electricity costs for the same control algorithms and with increasing price volatility as presented in Figure 32 but for price scenario 3, including hourly energy prices and tax reduction for sold PV electricity but with a network fee based on the peak loads (Capacity) instead of based on volumetric energy usage as in price scenario 1.

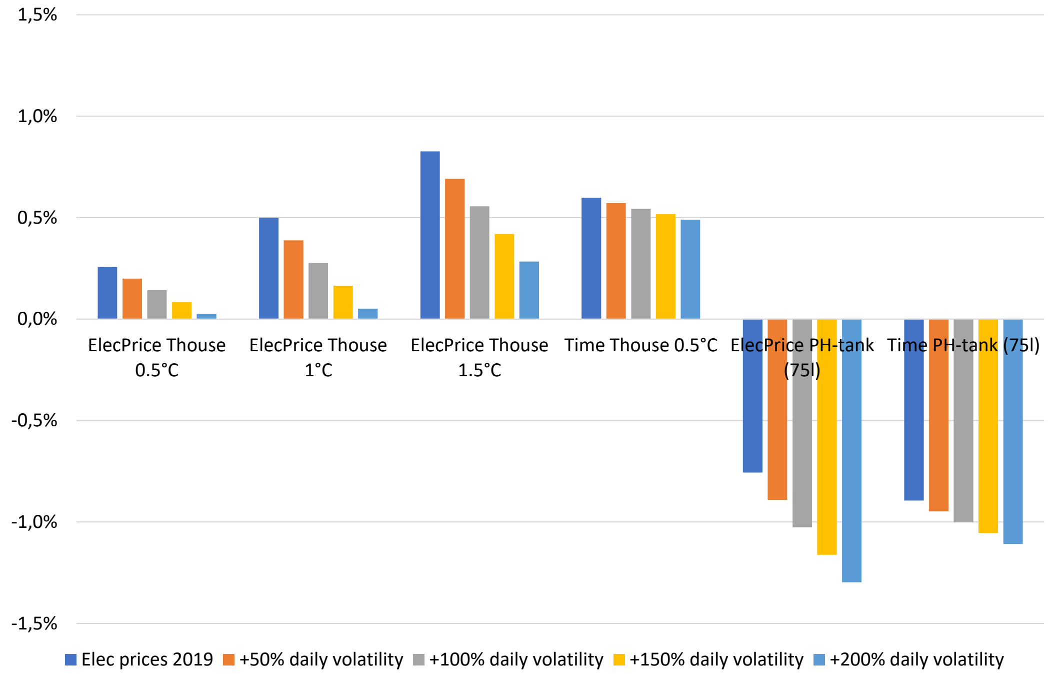


Figure 33. Percentage change in yearly running cost for the buildings total electricity consumption compared to base case based on different control algorithms and price volatility for price scenario 3 (hourly energy prices, a network fee based on the maximum capacity use and no tax reduction for sold PV electricity).

As can be seen in the figures above the economical savings increase with increasing price volatility for all control algorithms evaluated. Since the purpose with the algorithms are to shift electric loads from high price hours to low price hours it is logical the savings increases with increasing variations in electricity price. An interesting trend can be seen for the algorithm that changes the set values for indoor temperature during high and low-price hours. For price scenario 1 the savings increases with higher variations in set values (going from 0.5°C to 1.5°C), but for prices scenario 3 the trend is the opposite. This is related to the network fee, that in scenario 1 is based on the electricity consumption and in scenario 3 is based on the peak load. The algorithm is not constructed to minimize the peak loads and a higher variation in the set values for indoor temperature risk to lead to larger in peak loads.

9.2.6 Impact on comfort

Activating the price- or time algorithms the set values for indoor temperature or DHW production is changes for hours defined as low- or high price hours, see chapter 8.4.2 for details. But changing the set values for indoor temperature or the DHW-tank increase the risk for low temperatures and thereby lower comfort. To evaluate the impact on comfort the number of hours with a simulated indoor temperature below 20°C as well as a tap water temperature below 38°C has been counted for the price- and time algorithms. This is done in the end of each simulated hour during the year (thereby it is possible with shorter periods of low temperatures in between, that has not been included in Figure 34 below). Activating the PV-algorithm focus on increasing self-consumption of PV-electricity and are foreseen to have no impact on comfort.

As can be seen in Figure 34 the number of hours with low indoor temperatures increases for the "T_{indoor}" alternatives compared to the base case and the other cases. It can be added that none of the alternatives have any hours with a simulated indoor temperature below 19°C. In the same way the number of hours with a low tap water temperature increases with the "DHW Tank" alternative. But for none of the cases there is a large increase in hours with low temperatures and thereby the impact on comfort using the price algorithm can be considered relatively small.

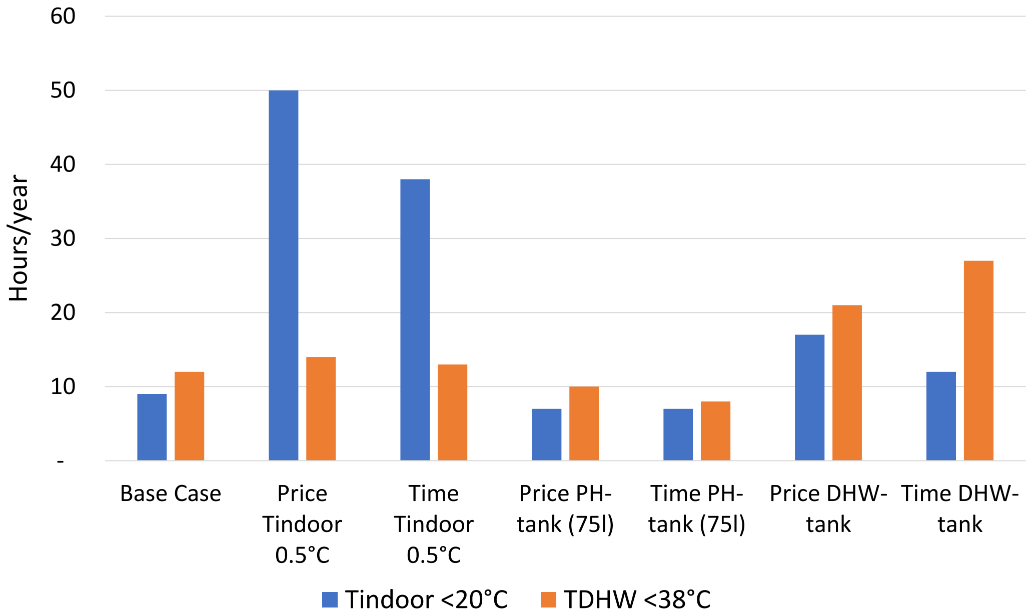


Figure 34. Number of hours during the year with an indoor temperature below 20°C or a DHW temperature below 38°C. Base case is compared with the three different alternatives for storage and an activated price or time algorithm.

In chapter 9.2.5 a sensitivity analysis was made including increased changes in set values for the indoor temperature, thereby increasing the risk for low comfort. In Figure 35 the number of hours with an indoor temperature below 20°C and 19°C is counted. A can be seen the numbers of hours below 20°C increases to over 200h when the set value is changes with 1°C. How fast the number of low temperature hours increases depends highly on the thermal inertia of the building.

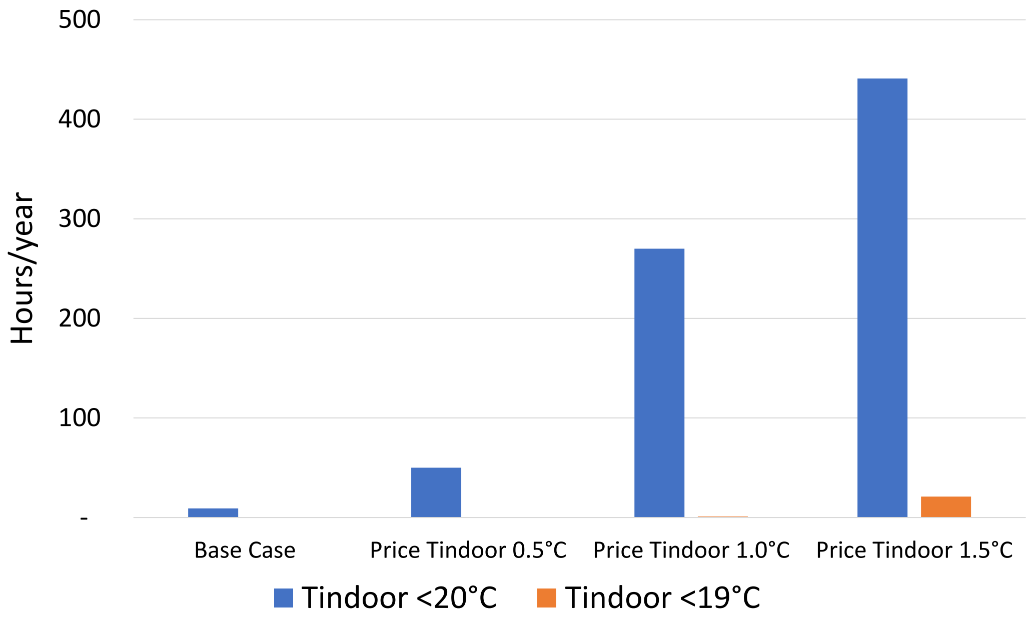


Figure 35. Number of hours during the year with an indoor temperature below 20°C or below 19°C. Base case is compared with storage in the buildings thermal mass for three different changes in set temperature during high/low price hours.

9.2.7 Conclusions for CCB based on ASHP

- The PV-algorithm combined with a battery has the largest potential to decrease the running cost, but the investment cost for a battery is high compared to other storage alternatives.
- For the price- and time algorithms the economical savings are modest or negligible based on electricity prices from 2019.
- The variations of the electricity prices in Sweden 2019 were too small to give an impact of the overall yearly running cost.
- Trade-offs:
    - More heat produced during nights, when the electricity price is low, gives lower COP for an ASHP due to lower outdoor temperatures.
    - Higher set values for DHW tank, in order to move electricity consumption to low price periods, give higher tank losses and lower COP.

9.3 CCB based on EAHP

In this section the result from the simulation of CCB based on EAHP are presented. The conditions for the simulations are presented in chapter 8.5. In Table 16 a summary of the different simulations performed are summarized.

Table 16. Simulation variants for the EAHP system (copy of Table 12).

	Algorithms		Storage options			
Variants	Price	PVxs	Battery[1]	DHW store temp	Extra DHW tank	Building[2]
Base case						
1		X	X	X		
2		X		X	X	
3	X			X		X
4	X			X	X	X
5	X	X		X	X	X
6	X	X		X		X

[1] *Battery is only used with PVxs (excess electricity)*
[2] *The building uses floor heating in zones 1 and 3 by varying the set temperature (see* Figure 9)

In Figure 36 below the results for all six simulated variants described in Table 16 is shown. As can be seen the most promising alternatives are Variant 1, with a battery for storage and variant 2, using an additional pre-heating tank for storage. These two alternatives are further analysed below.

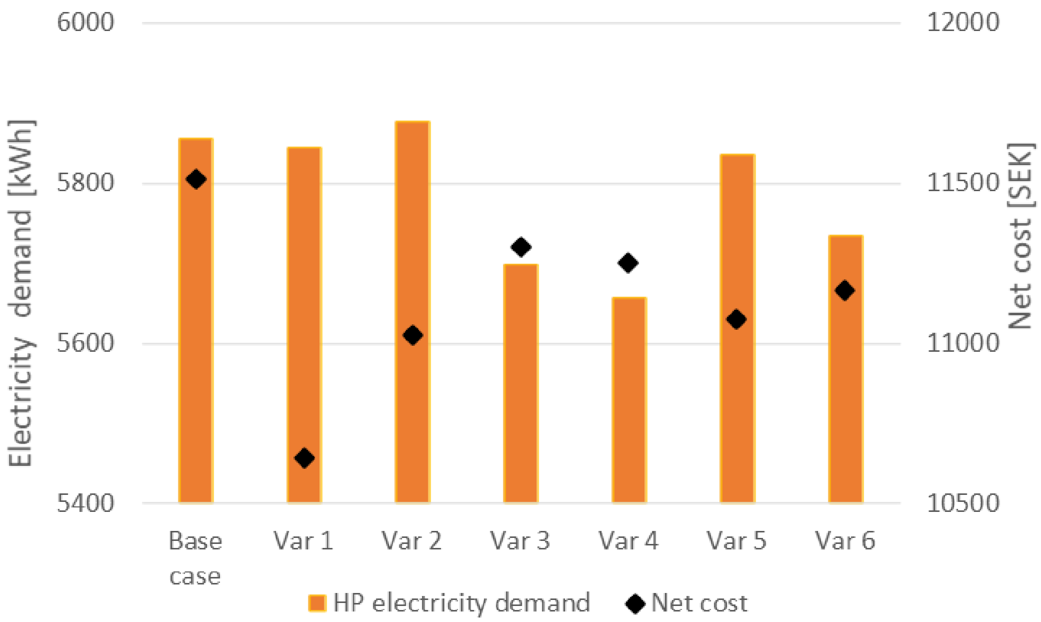


Figure 36. Annual net cost of electricity (based on price scenario 1) and total electricity use of the HP for all six variants compared to the base case

The simulation results which include variants 1-the addition of a battery and 2-the addition of an extra tank (see Table 16) in combination with an activated "PVxs" algorithm compared to the base case are shown in *Figure 37*. The figure shows the key figures self-consumption and self-sufficiency and the final purchased electricity from the grid.

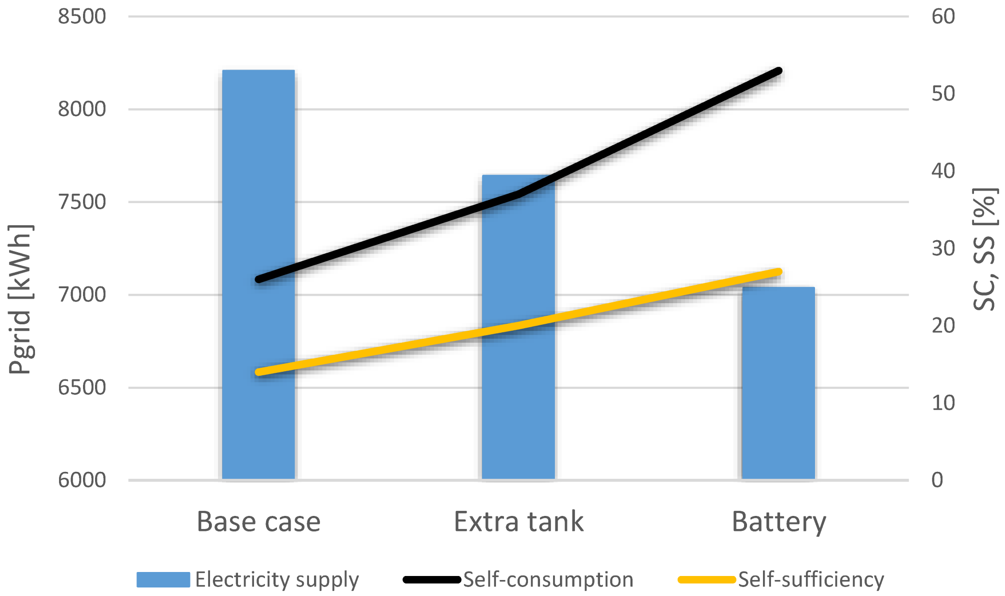


Figure 37. Key indicators (electricity supply from the grid, self-consumption and self-sufficiency) of the two additional storage types (variants 1 with a battery and variant 2 with additional PH-tank, both also including an increased DHW storage temperature) compared to the base case.

Table 17 lists the cost calculations in SEK/yr for each of the two variants compared to the base case.

Table 17. Breakdown of the final electricity cost (in SEK) based on price scenario 1, including annual fees.

	Income	Cost	Net cost
Base case	1499	13012	11512
Variant 1	854	11496	10642
Variant 2	1252	12276	11025

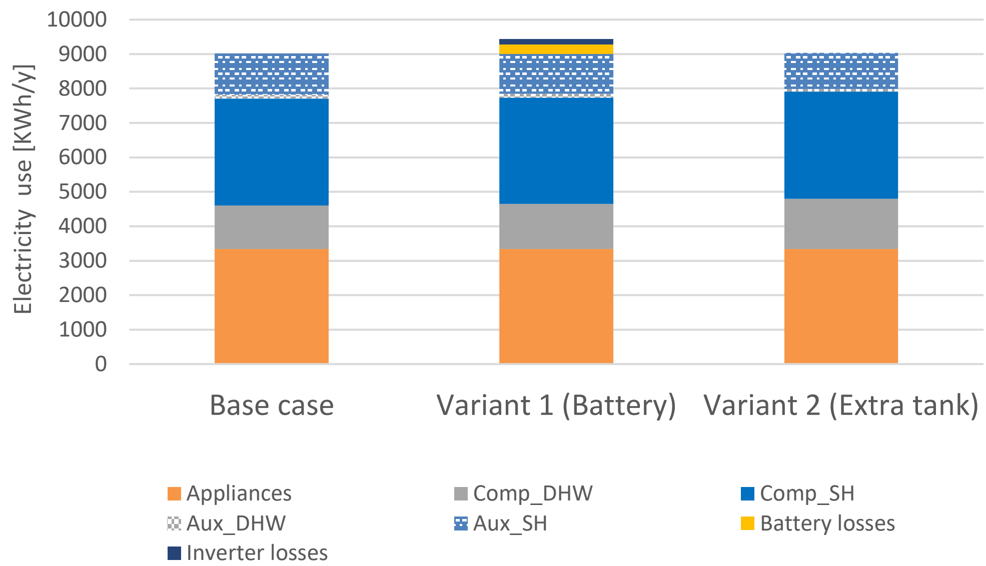


Figure 38. Breakdown of the electricity use of the heat pump components (compressor and aux heater for SH and DWH) for variant 1 and 2 as well as the related losses of the battery system (variant 1).

For the case of the battery storage, a small increase in the total electricity use is noted, which is caused by the combined inverter and battery charge and discharge cycle losses.

9.3.1 Economic evaluation

Figure 23 shows the economic results and specifically the breakdown of the annual net cost of the addition of the two examined storage types compared to the base case for the eight respective contract scenarios for energy and power prices, which are listed in Table 5.

Table 18. Overview of price scenarios for electricity (copy of Table 5*)*

	S1	S2	S3	S4	S5	S6	S7	S8
Contract	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly
Network	Energy	Energy	Capacity	Capacity	Energy	Energy	Capacity	Capacity
Tax reduction	No	No	No	No	Yes	Yes	Yes	Yes

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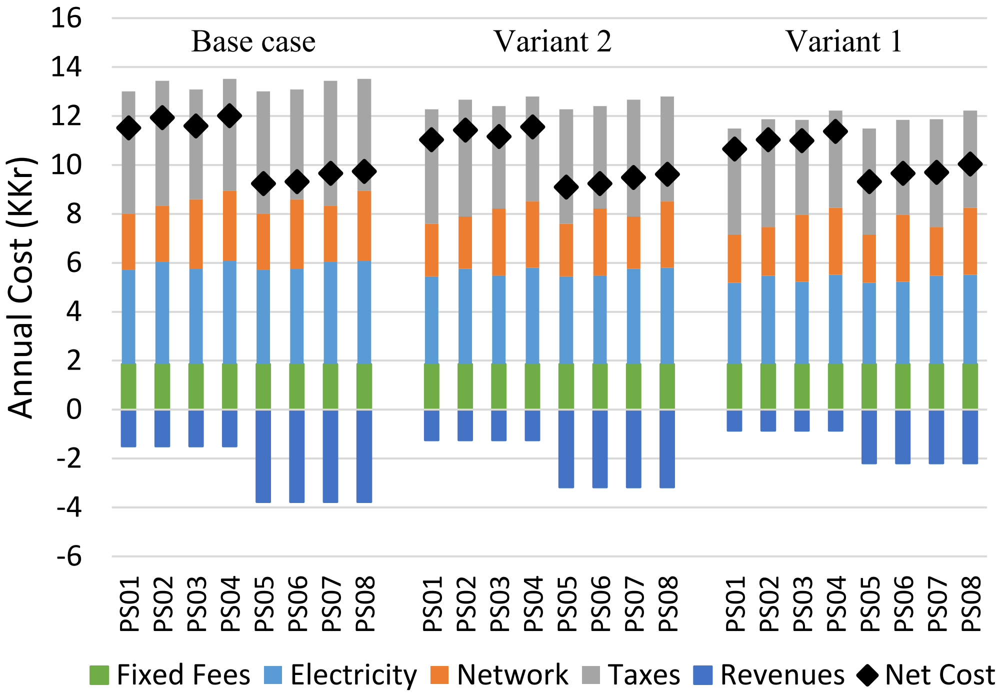

Figure 23. Breakdown of annual operational electricity cost components and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 5. Base case is compared with the two different storage alternatives and an activated PVxs algorithm. The total annual electricity cost (net cost) for each case is shown with diamonds.

It can be noticed from Figure 23 that scenario 4 (monthly prices and capacity cost) results in the highest net annual cost and this trend is similar for the two examined energy storage types. The battery storage (variant 1) has the highest impact on net cost savings for price scenario S1, including the combination of hourly energy prices, a network fee based on volumetric energy usage and no tax reduction. The result is a marginal decrease among the 4 optional scenarios with or without tax reduction.

In Figure 39 the results of the life-cycle cost calculations are shown. The results for life cycle cost calculations for the two examined energy storage alternatives show that during the lifetime of 15 years the additional investment cost cannot be compensated for, despite the associated electricity cost savings and revenue for any of the cases. Neither of the additional storage options are cost effective for these boundary conditions (investment, tariffs, electricity price, climate, loads). Especially the battery option results in great net cost savings, but the option has also the highest capital cost. However, the thermal storage is not far off the base case life cycle cost. It should be noted that no capital subsidy is considered for the battery storage purchase.

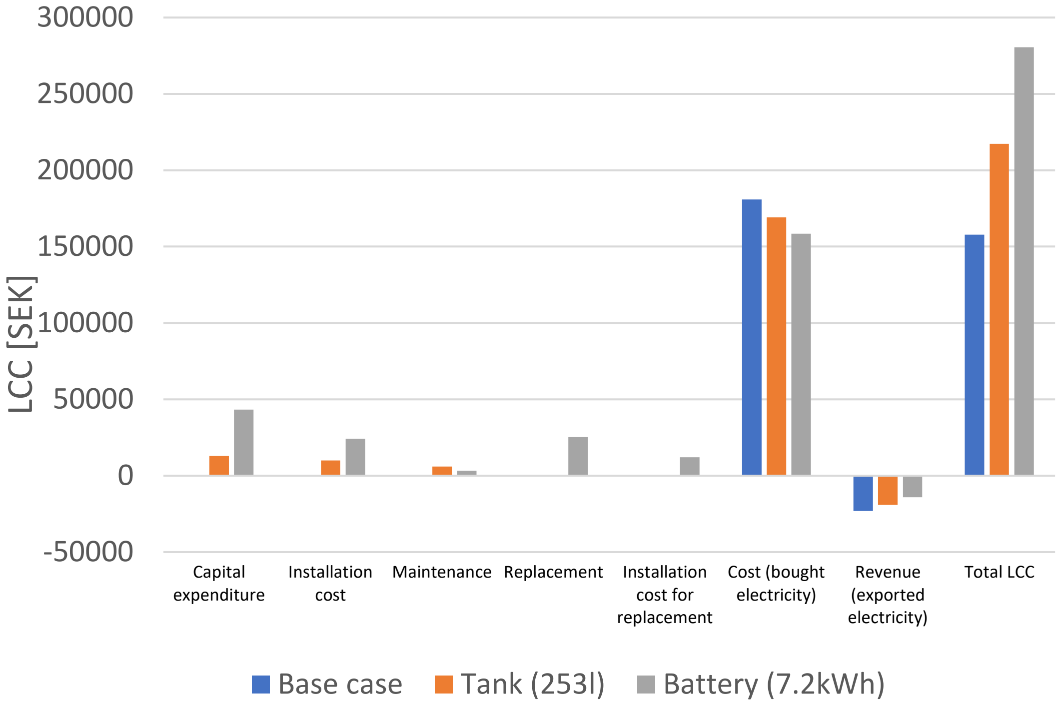

Figure 39. Life cycle cost of the addition of the two energy storages (tank and battery) compared to the base case excluding the capital cost of the photovoltaic system and the heat pump.

9.3.2 *Environmental evaluation*

For the case of the EAHP system a life cycle assessment is realized to examine the impact of the addition of each energy storage scenarios such as the 253 L thermal tank and the 7.2 kWh electrical storage as described in chapter 8.5. The examined period is limited to 15 years, approximately the expected service life time of the HP. The life cycle inventory data are based of the environmental product declaration data of a lithium iron phosphate (LiFePO4) battery bank and on the material content of the hot water tank and the results of the operational phase energy use obtained with the help of SimaPro 9.1.1. Average European electricity mix is used for the production phase of both energy storage types and for the operational energy use phase is used the average emission factor of the electricity mix of Sweden (0.055 kg CO_2-eq / kWh) of the year 2018. Moreover, it is assumed that both energy storage types will be recycled and not disposed in the end of the life and a net benefit of 12 kg CO_2-eq / kWh of the battery pack is estimated.

The assessed impact indicator is the global warming potential (kg CO_2-eq). Figure 40 shows the global warming potential impact of the associated life stages of the energy storage types for the examined service life.

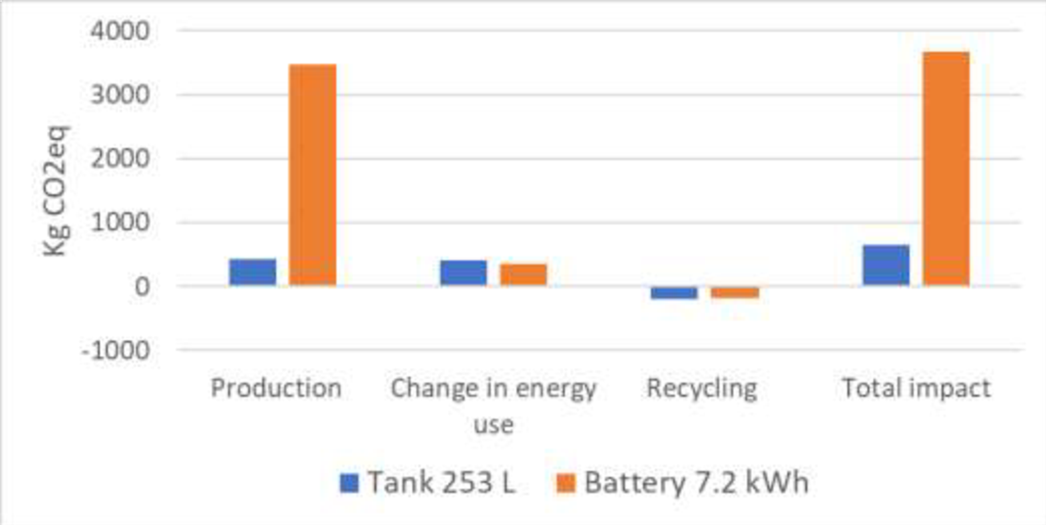

Figure 40. Global warming potential impact (kg CO_2-eq) of the associated life stages of the two energy storage types for the examined period of 15 years.

The carbon footprint impact of the electrical storage is found to be approximately 5 times the impact of the hot water tank. This is due to the higher impact of the production phase which is approximately 240 kg CO_2-eq / kWh of the lithium-ion storage and the fact that 2 battery banks are required in total.

9.3.3 Conclusions CCB based on EAHP

- The most promising alternatives simulated are an activated “PVxs” control algorithm, that maximizes the self-consumption of internally produced solar, in combination with additional storage. Either a battery or a pre-heating DHW-tank, and an increased DHW storage temperature compared to the base case
- The need for bought grid electricity can be reduced using the control algorithm (PVxs) and storages simulated.
    - Bought grid electricity is reduced with approximately 14% with a battery and 7% with a preheating DHW tank.
- The annual running cost can be reduced with 4-8%, if the tax credits for sold PV is removed (Price scenario 1 Sweden 2019)
- The life cycle cost and the impact on global warming for the two alternatives (PVxs-algorithm combined with a battery or PH-tank) will increase compared to base case.

9.4 Results for cooling

In this section the results from the cooling simulations, using a CCB based on a GSHP connected to a fan-coil, are presented. The conditions for the simulations are presented in chapter 8.6 and in Table 19 below there is a summary of the simulated cases.

Table 19. Summary of IDA ICE simulations for both the low energy and normal Swedish single-family house (copy of Table 13)

Case number	Type of cooling	Cooling set point for T_{indoor} (°C)	Ventilation flow rate (l/s)
1	Direct	25	60
2	Indirect	25	60
3	Indirect	25	Jul 16 – Aug 31: 100 l/s, Rest of the year: 60 l/s
4	Indirect	Jul 16 – Aug 31: 21°C Rest of the year: 25°C	60
5	Indirect	Jul 16 – Aug 31: 21°C Rest of the year: 25°C	Jul 16 – Aug 31: 100 l/s, Rest of the year: 60 l/s

The simulation results for the normal and low energy house from different case studies are presented in Figure 41-Figure 46 below.

Figure 41 shows the cooling energy for each case simulated. The yearly cooling energy used by the indirect system is approximately 2/3 of the cooling energy with direct cooling. The graph also shows that an increased ventilation decreases the use of cooling from the CCB.

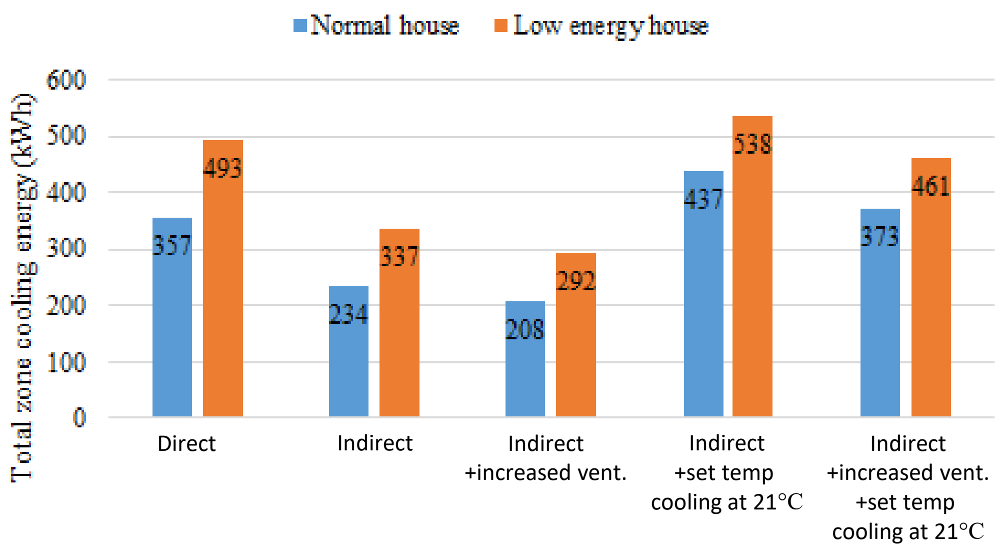

Figure 41. Zone cooling energy (sensible and latent) provided by the fan coil for a year.

In Figure 42 the electricity use by the ventilation in the house is shown. In the base case the ventilation fans are simulated to be running the whole year with an air flow of 60l/s to provide fresh air for the house. For the simulation cases with increased ventilation the flow rate is increased to 100l/s during the time period 16 July to 31 August. As can be seen in the figure the ventilation fan energy use is identical for the two cases with increased ventilation. Since the function are the same for the normal and the low energy house regarding ventilation, the energy used by the ventilation fans for the two houses are identical.

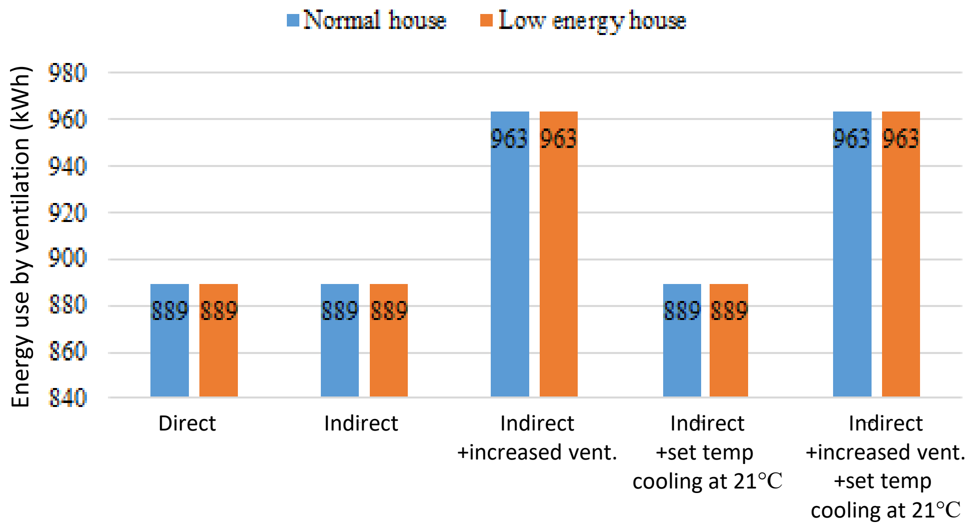

Figure 42. Yearly energy use by the ventilation fans (i.e., supply and exhaust fans). Note: ventilation fans are on all the time and increased ventilation flow rate is only applied during a specified time period in the summer.

Figure 43 shows the electricity used by the fan coil (to distribute the cooling to the indoor air). The electricity use is proportional to the fan coils time in operation. The fan coil is only activated when the cooling is needed (based on the indoor temperature) and is not running all the time. Thereby the energy use by the fan coil increases for the simulations when a lower set temperature is used. The figure also shows that the fan coil needs to run for shorter periods for a direct system compared to an indirect system indicating a higher cooling power for the direct system. Finally, the figure shows that the low energy house has longer periods of high indoor temperatures and thereby an increased need for cooling.

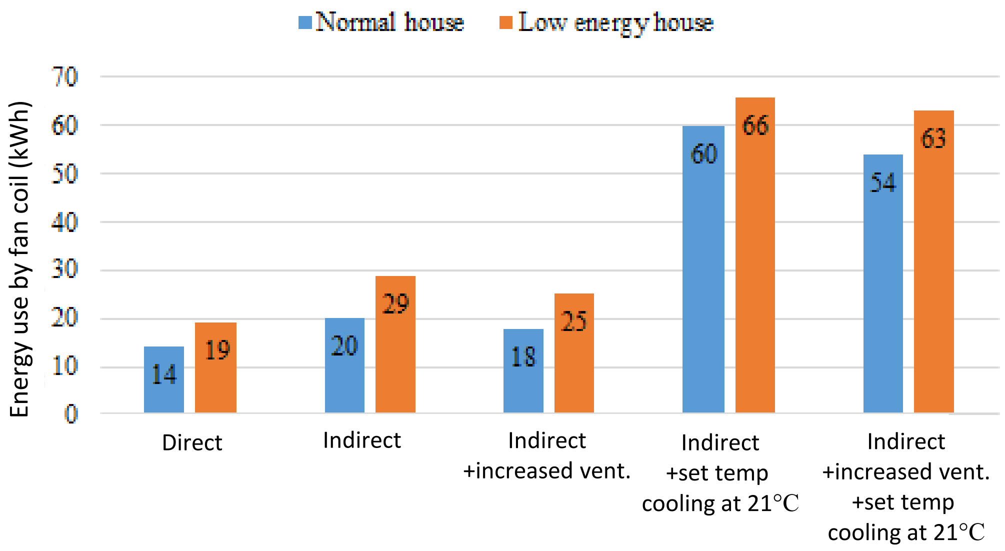

Figure 43. Yearly energy use by the fan coil. Note that the fan coil is only activated when cooling is needed and is not running all the time.

Figure 44 shows the required cooling power for direct cooling compared to the indirect cooling, for both the normal house and the low energy house. As can be seen, based on the simulations, the maximal cooling power provided by the direct system is about 1850W, which is about 1000W higher than that for the indirect system, which has a maximum cooling power around 820W. The reason for the lower cooling power for the indirect system is due to the smaller temperature difference for the indirect system compared to the direct system. With an indirect system there is an additional water loop distributing the cold from the brine to the fan coil, for the direct system the brine is heat exchanged directly with the indoor air in the fan coil, see Figure 11. In the indirect system the set temperature for the water loop is high enough to avoid moisture on pipes etc. This gives a smaller temperature difference and thereby a smaller cooling power.

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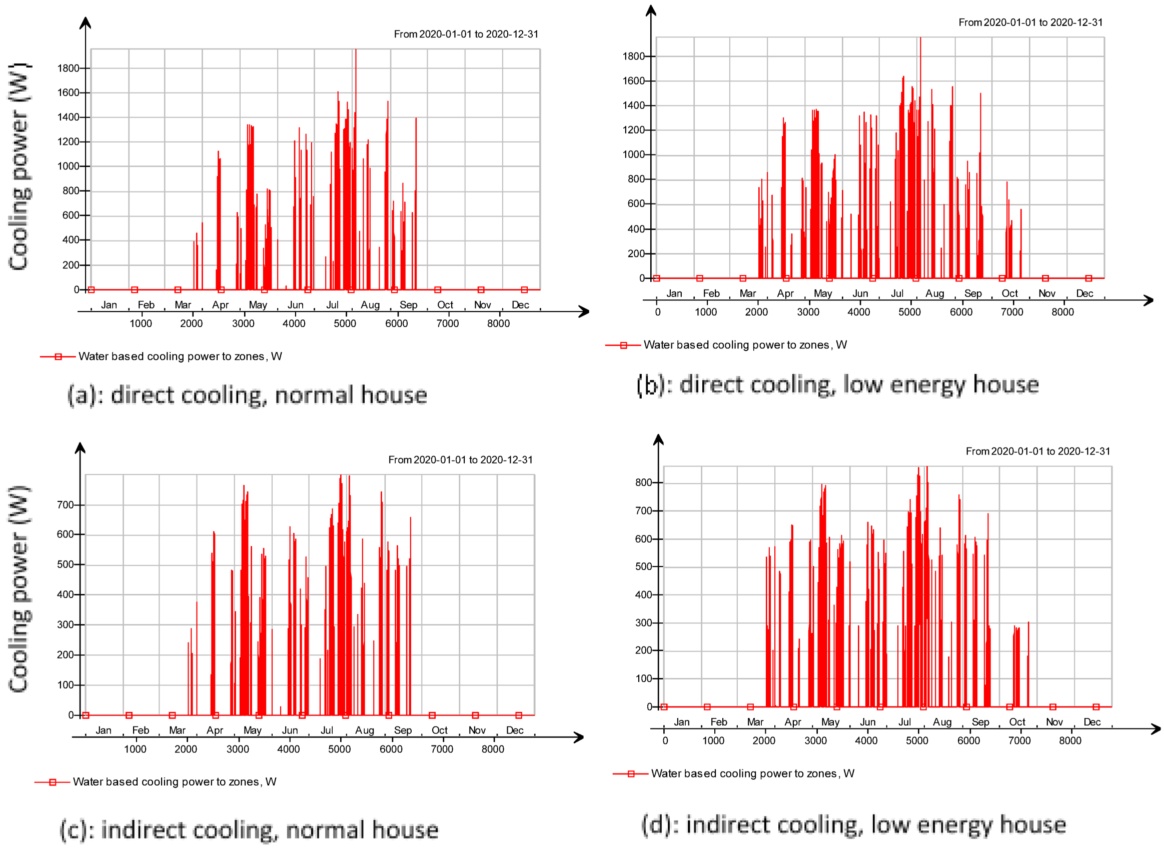

Figure 44. Cooling power (both sensible and latent) provided by the fan coil with direct and indirect system for the normal and low energy house.

It can be seen from Figure 45 and Figure 46 that the number of overheated hours is reduced greatly by both the direct- and the indirect systems (Locations of the three sleeping rooms can be seen in Figure 12). The direct system has a greater potential to reduce the number of overheated hours than the indirect system, but the difference is not very big. For the indirect system, increased ventilation flow rate and to start cooling earlier reduces the number of overheated hours among the studied indirect systems with different set-ups.

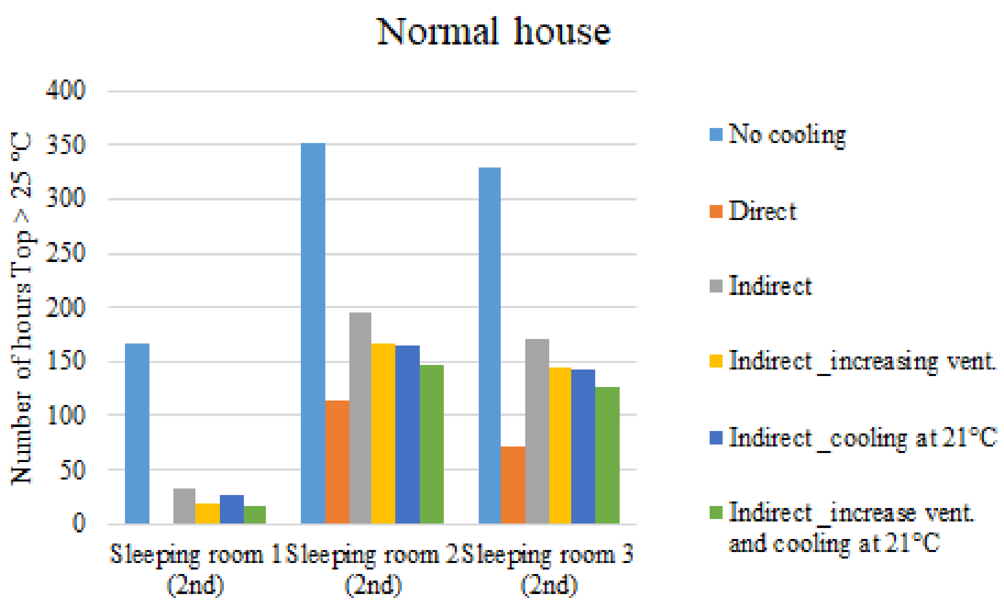

Figure 45. Comparisons of number of hours that the indoor temperature (Top) is above 25 °C from different case studies for the normal house

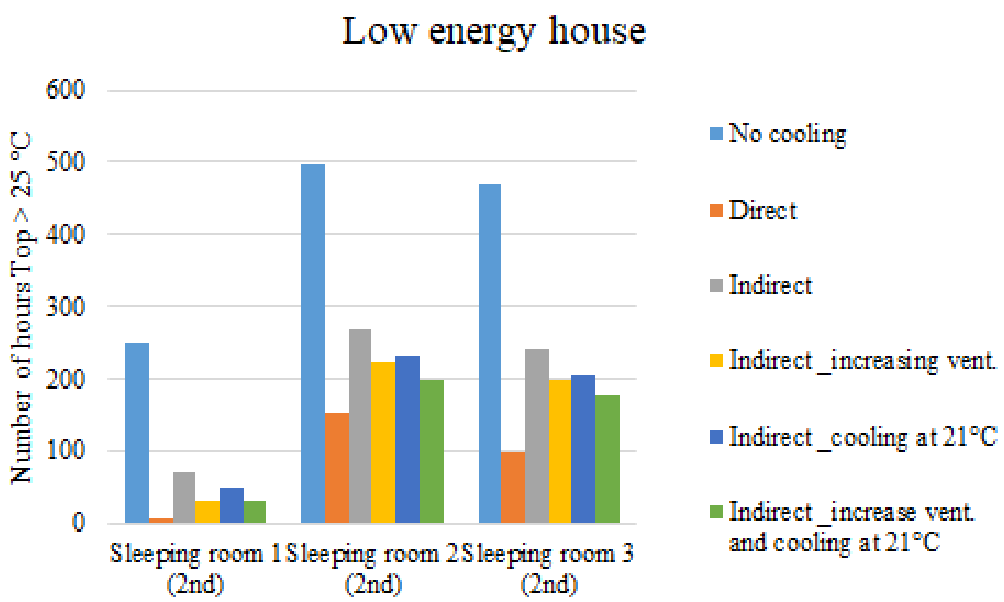

Figure 46. Comparisons of number of hours that the indoor temperature (Top) is above 25°C from different case studies for the low energy house

9.4.1 Conclusions comfort cooling

- The potential available cooling power of an indirect system is approximately half of the cooling power of a direct system.
- The number of overheated hours (indoor temperature >25°C) is reduced greatly by both the direct and indirect cooling systems.
- The direct system has a larger potential to reduce the number of overheated hours than the indirect system, but the difference is relatively small. The direct system could be associated with condensation of water vapour at pipes etc, which will not take place for the indirect system.
- For the indirect system, increased ventilation flow rate and to start cooling earlier reduces the number of overheated hours.

10 Prototype

Within this project, a prototype was developed on the CCB concept based on a ground source heat pump.

In addition, in this project also new control algorithms for an exhaust air heat pump were developed and implemented (in slightly modified form) in a heat pump, of which some are to be included directly in the products sold on the market.

10.1 Prototype CCB based on GSHP

A prototype of a CCB based on a ground source heat pump was developed within the project and evaluated in the lab. In addition to the ordinary functions of space heating (SH) and production of domestic hot water (DHW) it can provide passive cooling and energy storage.

The different selections for the design of the prototype were based on the outcomes from the different simulations performed within the project, discussions within the project group and the present product line of the manufacturer.

Testing of functions of the prototype was performed within the project as well as a system testing based on a newly developed 6-day method for testing in lab.

10.1.1 Prototype

The prototype developed within the project is based on the concept for a GSHP including space heating (SH), passive cooling via the borehole and production of DHW. For energy storage the prototype is equipped with both a 300 l buffer tank on the space heating side as well as a standard size DHW tank of 180 l. A shunt between the SH buffer tank and the radiators makes it possible to have a higher temperature in the tank than the supply temperature to the radiators/floor heating.

Two “smart” control functions were developed for the prototype and evaluated.

The control functions are:

- Price: The heat production is planned over the day to minimize the electricity cost, based on hourly electricity prices.
- Sun: The heat production is planned over the day to maximize self-consumption of internally produced electricity from PV panels.

10.2 Test method laboratory testing of a CCB prototype based on a GSHP

10.2.1 General about the test

Test methods for evaluation of heat pumps performance in existing standards today, are based on steady state performance. Normally the control system of the heat pumps is by passed to be able to achieve steady state conditions, good repeatability and avoid interaction with the control system of the test rig.

Existing alternatives to laboratory tests at steady state are field measurements or a “hardware in the loop” test method. A field measurement gives the most realistic results, but do not offer high repeatability. It is also time consuming to include all seasons in the evaluation, and it is still a risk that one does not get the variations in weather needed to be able to test the prototype in all conditions. An alternative is to use a “hardware in the loop” test method where data from the emulator is based on a simulation (of the heating demand of the house etc) that is running simultaneously with the laboratory test and exchanging data with the heat pump (hardware) during the test. This means a complex test method suitable for research. On example is the 6-day method developed by SPF and used by Högskolan i Dalarna [14]. In order to reduce the complexity and make the test more straight forward it was decided to go for a simplified system testing described below in this project. System testing in laboratory was chosen to be able to evaluate the prototype during all season but within a shorter time. This type of test method could be used in future standards to evaluation CCBs on the market.

Therefore, in this project a new test method was developed for testing of the functionality (control) and performance of the prototype. The method developed is a trade-off between complexity and the possibility to get reliable results when testing function and performance of the prototype with focus on the smart control functions. The prototype was tested in RISE laboratory in Borås during the summer and autumn 2021.

The test method simulates the conditions for a CCB installed in a single-family dwelling in Stockholm, Sweden for one up to six days. The method includes an emulator which updates data for the outdoor temperature, the forecast for produced PV power and electricity prices once per hour. Input to the test method for outdoor temperature and solar production is based on simulations in PV*SOL premium 2020 [8] for a representative house with PV panels and climate data for Stockholm from Meteonorm [7]. Different types of test methods have different advantages and disadvantages. One drawback with the test method used, compared to testing during steady state operation, is that it is more difficult to get identical test conditions from one test sequence to another, depending on tank temperature etc.

In the laboratory test the performance of the prototype was evaluated based on a compensation method developed within the project. This means that the control system of the heat pump adjusts its heating capacity to match a cooling load of the test rig (predefined for different test points). During the test, the SH and DHW heating performance are tested and evaluated simultaneously, and the prototype is free to alternate between SH and production of DHW as it is in a real installation.

Not testing the performance at steady state operation makes the test more realistic and the results and learnings are closer to the outcome from measurements in a real installation in the field, but with the advantage of being in a laboratory and thereby to being able to control the outdoor temperature profile independently of the weather conditions outside. In this way one can test the performance for all season in a shorter time.

The test sequence for the system test method used is as far as possible based on different already existing standards for heat pump testing. Tapping of DHW follows tap cycle Medium in EN16147:2017 table A.2 [4]. The brine temperature is set to 0/-3 according to standard rating conditions in EN14511-2:2018 [5]. The space heating demand simulated follows the outdoor temperature conditions and is based on the calculation methodology described in EN14825:2018 [6] with a chosen P_{design} of 5.85kW in cold climate (-22°C). The heat demand is assumed to decrease linearly from T_{design} down to 0 kW at an outdoor temperature of +16°C. Data is logged every 30 s during the whole test period.

Figure 47 shows an overview of the prototype and the test method used to evaluate the prototype in lab.

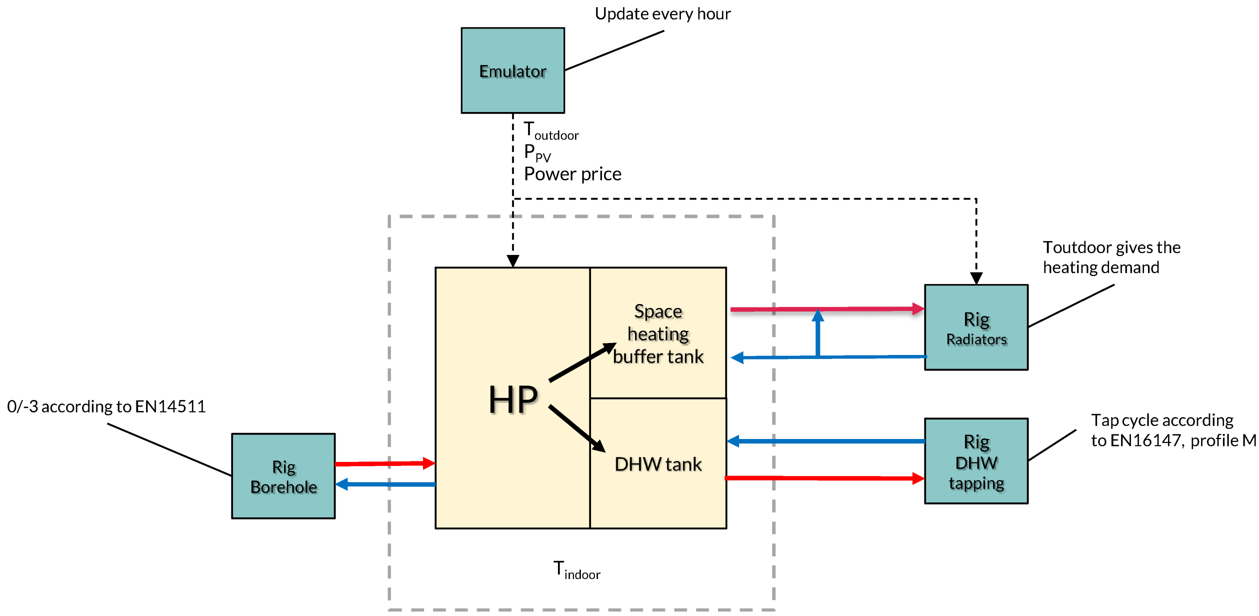

Figure 47. Overview of prototype and the test method.

10.3 Results laboratory testing CCB prototype GSHP

Two different tests were performed in order to evaluate the prototype; test of functions and a 6-days system testing.

10.3.1 Test method, test of functions

The functionality of the prototype and the smart control algorithms were evaluated using a 24-hour test simulating a fictive Swedish day in April, giving a day with both space heating demand and production of solar PV electricity. The fictive day has relatively large variations in outdoor temperature between night and day as well as production of PV electricity during the day, see Figure 48 below.

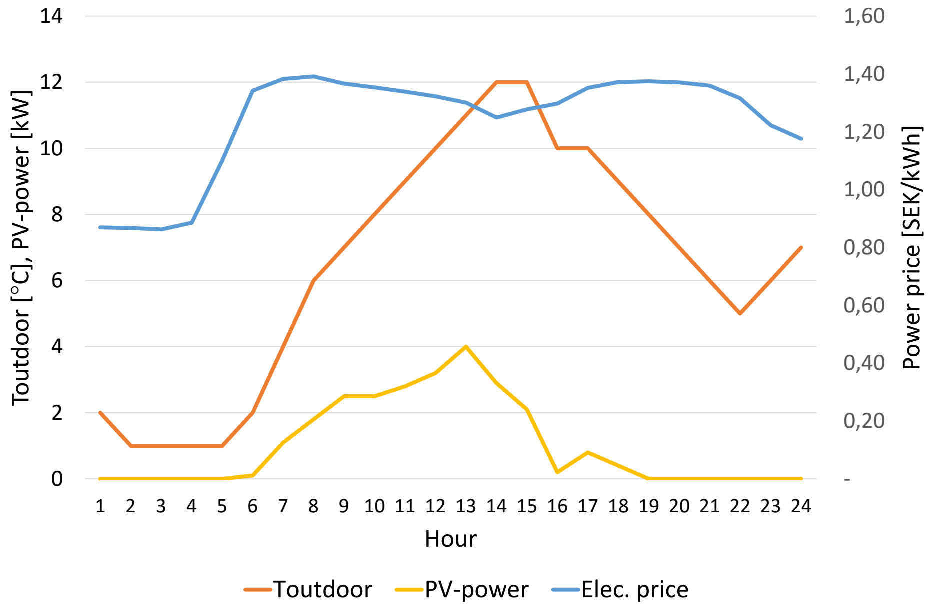

Figure 48. Hourly variations in outdoor temperature, production of PV power and electricity price used for test of functions of the GSHP CCB prototype.

The following tests were carried out in order to test the functions of the prototype and the integrated smart control.

1 Base case: 24 h test of space heating (SH) and DHW production without any smart control functions activated.
2 Price: 24 h test of SH and DHW production with price function activated.
3 Sun: 24 h test of SH and DHW production with sun function activated.
4 Price+Sun: 24 h test of SH and DHW production with both price and sun function activated.

10.3.2 Test method, 6-day test

In order to test the performance of the prototype and its smart control functions for a longer period and evaluate the prototype in conditions representing all seasons, a 6-day system testing was developed following the general method described in chapter 10.2.1 above. The test conditions were chosen to represent the conditions in Stockholm, Sweden during a full year. The test includes 2 winter days, 2 summer days and 2 spring/autumn days, see Figure 49 below.

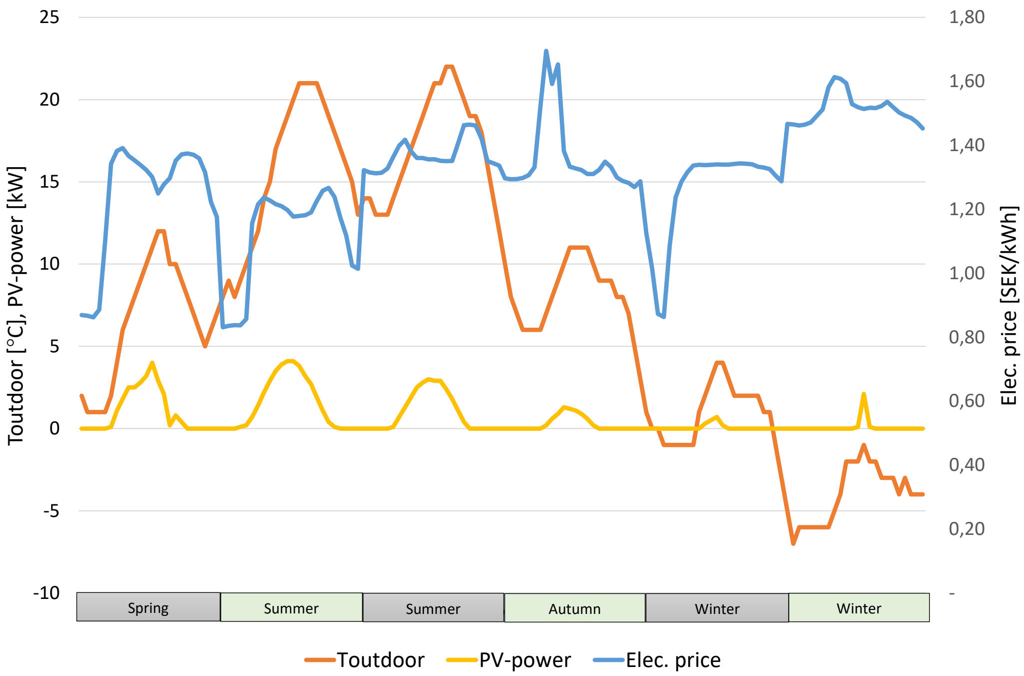

Figure 49. Hourly variations in outdoor temperature, production of PV-power and electricity price during the 6-day test including 2 summer days, 2 winter days and 2 autumn/spring days for test of the CCB prototype.

The results from the tested 6-days can be scaled up in order to representing a full year. Each hour in the 6-day test represents approximately 60.8 h in a full year according to eq. 1. In the same way the prototype's heat production and electricity consumption can be scaled up from the 6-day test to represent a full year.

$$1\ hour_{6-day\ test} = \frac{365}{6} \approx 60.8\ hours_{full\ yeat} \quad \text{Eq. 3}$$

Figure 50 and Figure 51shows a comparison for the distribution of hours depending on outdoor temperature and production of solar PV power for the 6-day test compared to a full year simulation of a single-family building with PV-panels in Stockholm, Sweden. The figure shows that one can represent the general trend of a full year relatively good in six days. What is missing in the 6-day test is in first-hand the extreme values.

One drawback with testing a full year in 6 days is the short time periods of each season and compared to a real installation it gives quick and sometimes unrealistic changes from one season to another. Depending on how the CCB is working and planning the heat production there is a risk that the test method does not capture the functionality and performance of the test object in a correct way.

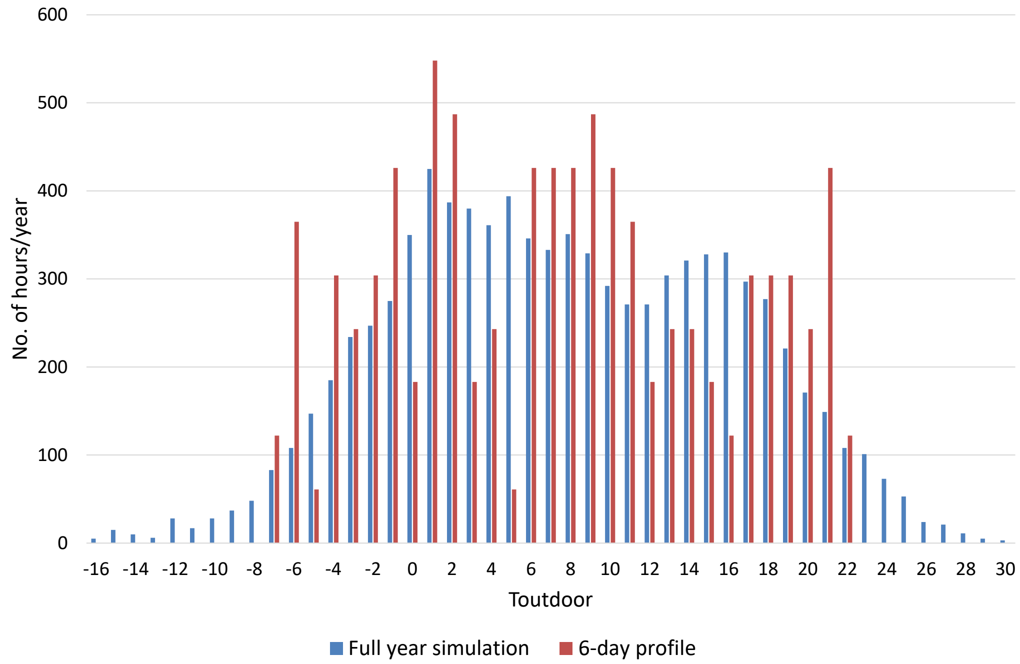

Figure 50. Comparison of an upscaled 6-day profile and a full year simulation. Showing the number of hours per year depending on outdoor temperature

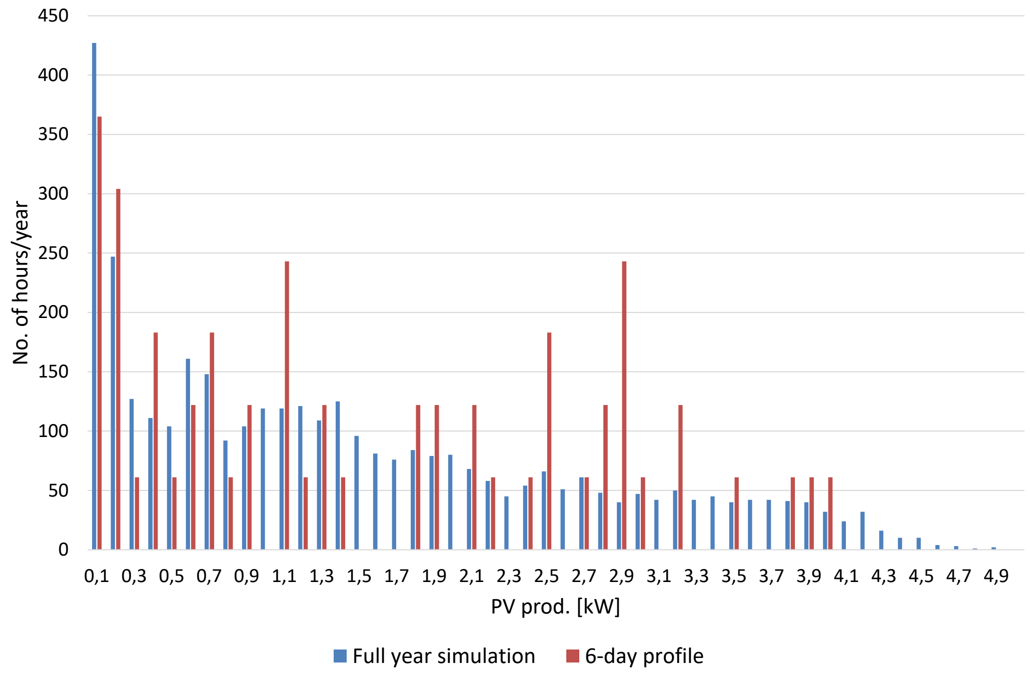

Figure 51. Comparison of an upscaled 6-day profile and a full year simulation. Showing the number of hours per year depending on solar production. Hours with no solar production excluded

10.4 Results for test of functions

In order to test the functionality of the smart control functions a 24 h test was carried out simulating a fictive day in April, see chapter 10.3.1 for details.

The following 24 h tests have been carried out in order to test the function of the prototype and the smart control integrated.

5. Base case: 24 h test of space heating (SH) and DHW production without any smart control functions activated.
6. Price: 24 h test of SH and DHW production with price function activated.
7. Sun: 2 4h test of SH and DHW production with sun function activated.
8. Price+Sun: 24 h test of SH and DHW production with both price and sun function activated.

In Figure 52 the measured variations in supply temperature depending on the outdoor temperature signal during the day for the base case is shown. In the same figure also the heating power supplied by the CCB to the radiator rig is shown.

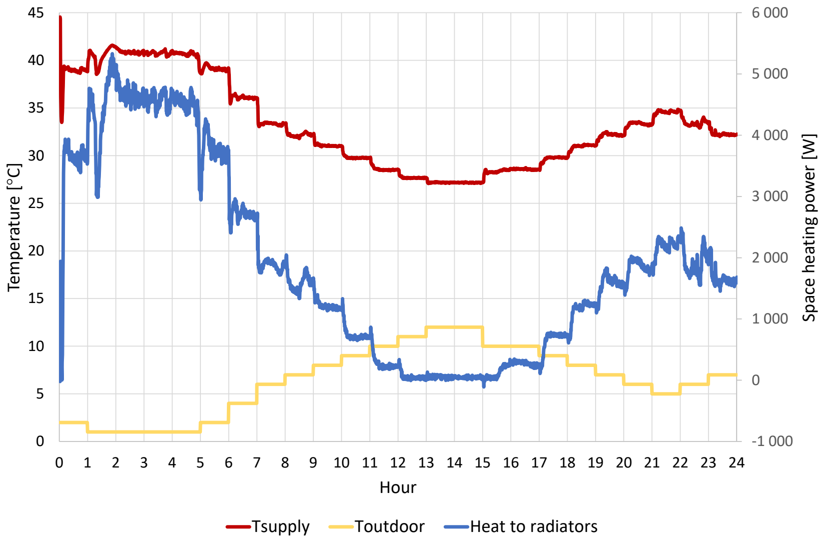

Figure 52. Heat to radiators, outdoor temperature, and supply temperature during the 24h function test for base case

The tapping pattern follows tap cycle M according to EN16147 [4]. Figure 53 shows the distribution of tapping over the day, starting with the first tapping at 07:00 in the morning and ending at 21:30.

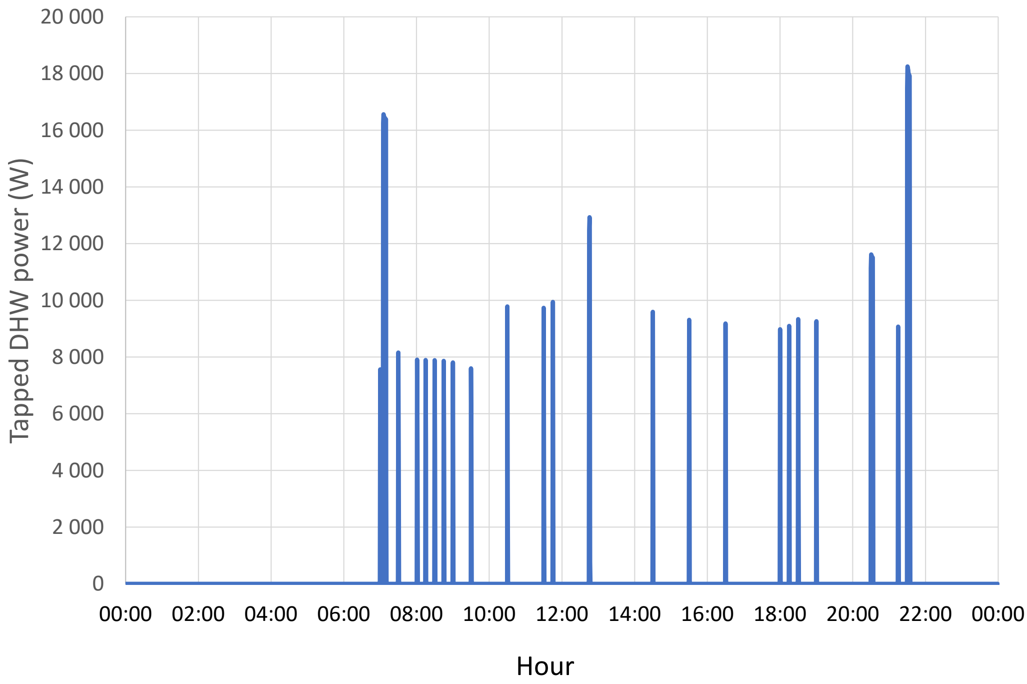

Figure 53. Distribution over the day for tapped DHW, following EN16147 tap cycle M. The graph shows the average heat power per 30 s.

The distribution of the electricity used per hour by the CCB prototype with the different control functions activated is shown Figure 54 below. In the graphs one can see how the distribution of the electricity use is changed over the day based on the activation of the different control functions.

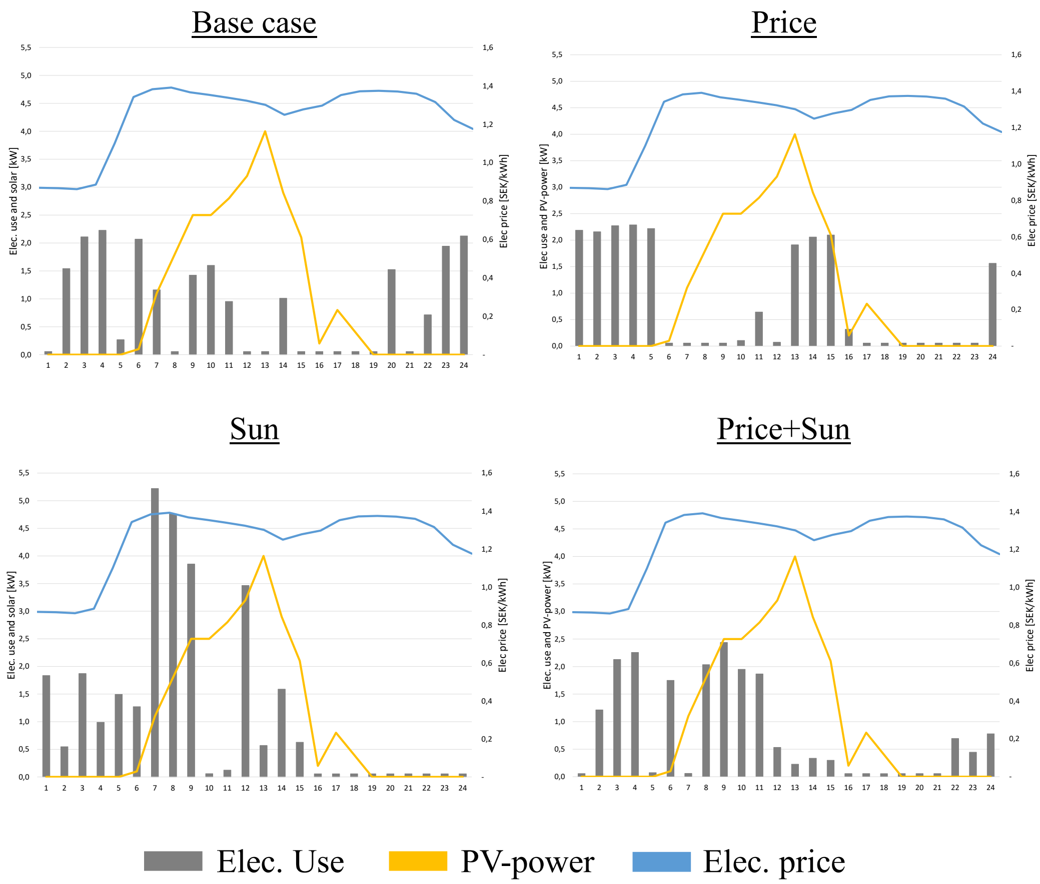

Figure 54. Comparison, distribution of total electricity used by the prototype during the 24h test of function with different functions for smart control activated.

Figure 54 shows the total electricity used by the prototype, including for both space heating, DHW production and other electricity consumers, such as internal pumps. One can see a clear change in the pattern of the electricity use over the day when the different control functions is activated, compared to the base case. With the "Price" algorithm activated the prototype follows the electricity price curve well and produces heat when the electricity price is low. The combined algorithms "Price+Sun" follows the price curve as well but also produces heat during the morning hours when there is production of solar PV power. In the results from the test of the "Sun" algorithm one can see that at around 07:00 the backup heater starts. This is due to low temperatures in the DHW tank, which triggers the backup heater to start. This indicates the need for further fine-tune of the settings of the prototype to avoid unnecessary usage of the backup heater.

Figure 55 shows the distribution of total electricity power (usage) and heating power to the space heating buffer tank for the same test as presented in Figure 54. During the test, there were no possibilities to measure the heating power of the DHW-tank. Thereby, in the graph time periods of electricity consumption (usage) without any corresponding heating production indicates production of DHW.

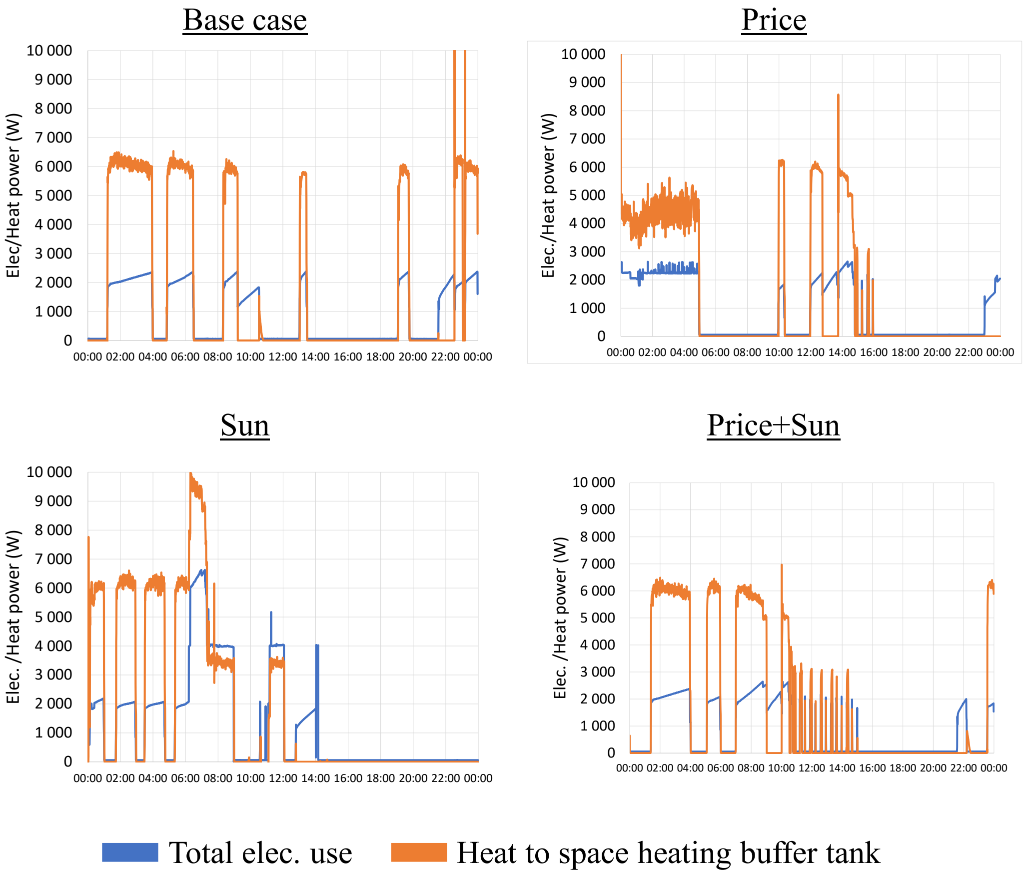

Figure 55. Comparison, distribution of total electricity used and heat to space heating buffer tank by the prototype during the 24h test of function with different functions for smart control activated.

10.5 Result 6-day test

The prototype was evaluated using the 6-day system test described in chapter 10.3.2. The results from the system tests have given valuable input to further adjustments needed for the prototype's control. The challenge when developing a smart control system based on response on external signals, is to make it operate correctly with the built-in control for safety functions (to avoid that a component breaks or are unnecessarily worn). Therefore, it is important that the smart control is integrated with the other control system of the heat pump. An external control system, which only allows the heat pump to start or stop or which only controls the heat pump through "deceiving" the input signal from the outdoor temperature sensor, could result in harmful or very inefficient operation for the heat pump (e.g. the compressor is not allowed to start and the back-up heater covers the heating demand). The results also show the complexity of testing a prototype using a new test method lasting for six days in laboratory with a data collection every 30s. In total three 6-day tests have been carried out, all with the "Price+Sun" algorithm activated.

Input from the tests to the further development of the prototype's control has mainly been related to how to alternate between space heating (SH) and production of DHW in a good way. During the first two test runs, the prototype had a tendence to allow low DHW temperatures without prioritizing production of DHW. Instead, this finally resulted in a start of the backup heater. The problem with too low DHW temperatures was also accelerated by an earlier version of the test method, where each tapping stops first when the correct amount of energy is tapped. With low DHW temperatures this can lead to a continuous tapping and thereby that the DHW tank is completely emptied of hot water.

After adjustments of the CCB control, to make sure the prototype starts to produce DHW in time, and adjustments of the test method, to reduce the risk that the test method triggers a continuous tapping in case of low DHW temperatures, a third 6-day test was started. This time the testing failed the second day due to a "Operating pressure alarm" caused by high pressure in the compressor. This alarm prevents all production of DHW and stops the compressor until it is manually offset. The reason for the alarm is likely a combination of condition. The prototype was running close to the its outer limits of the operating range, but the alarm is not directly related to the test of the smart control functions. Unfortunately, the alarm was not noted until after the test was completed and in addition the data logging failed during the last day of the test.

Figure 56 shows the distribution of the total electricity use and production of heat to the space heating tank. As can be seen in the figure the compressor is not running after the first day and no DHW is produced.

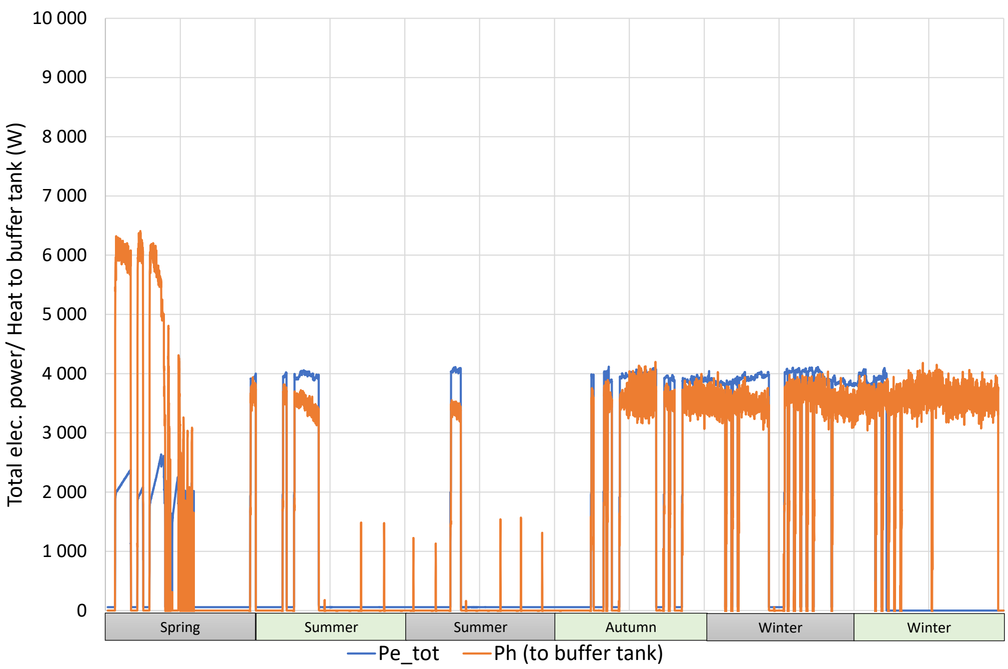

Figure 56. Distribution of total electricity used and heat to space heating buffer tank by the prototype during the 6-day test with the "Price+Sun" control activated.

Figure 57 shows the distribution of electricity use over the 6-day period compared to the electricity price and the PV-power production. The distribution of electricity use during the first spring day is similar to the results from the 24h function test. From day 2 the compressor stopped but for the two summer days (day 2 and 3 in the test) the power consumption is allocated to the hours with high solar production, even though the compressor is not running. From day 4 and onwards the heat demand increases, and it is hard to draw any conclusions without the compressor running.

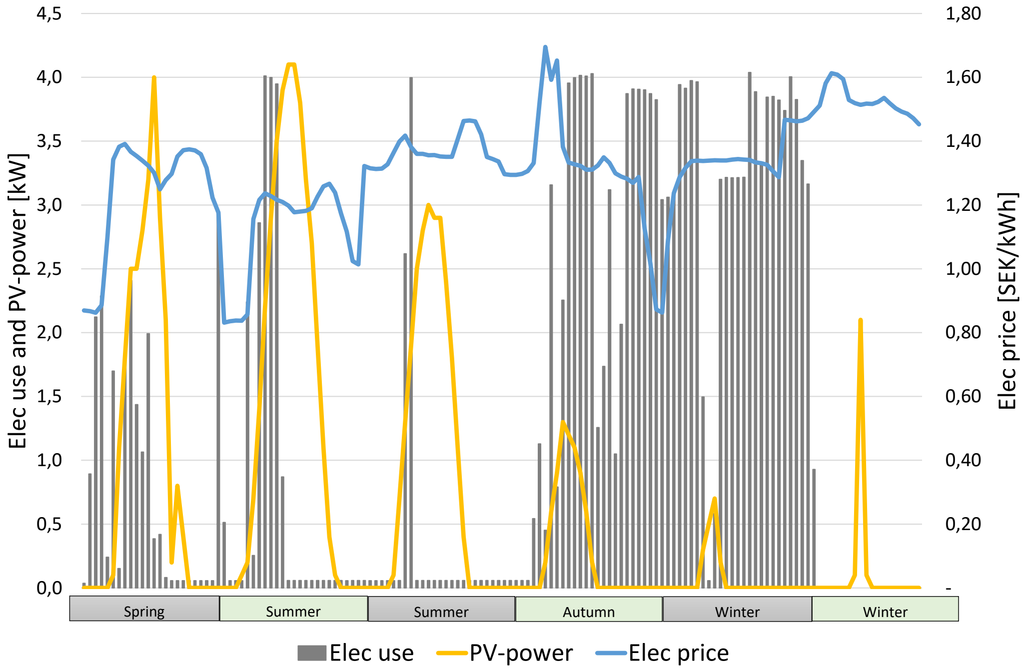

Figure 57. Distribution of total electricity used by the prototype during the 6-day test compared to the electricity price and solar.

In Figure 58 the temperature of the domestic hot water after the tank is shown. As can be seen the DHW temperature drops after the alarm day 2. The increase in temperature to approximately 20°C, seen during each night, is related to the water in the pipe being heated by the ambient temperature.

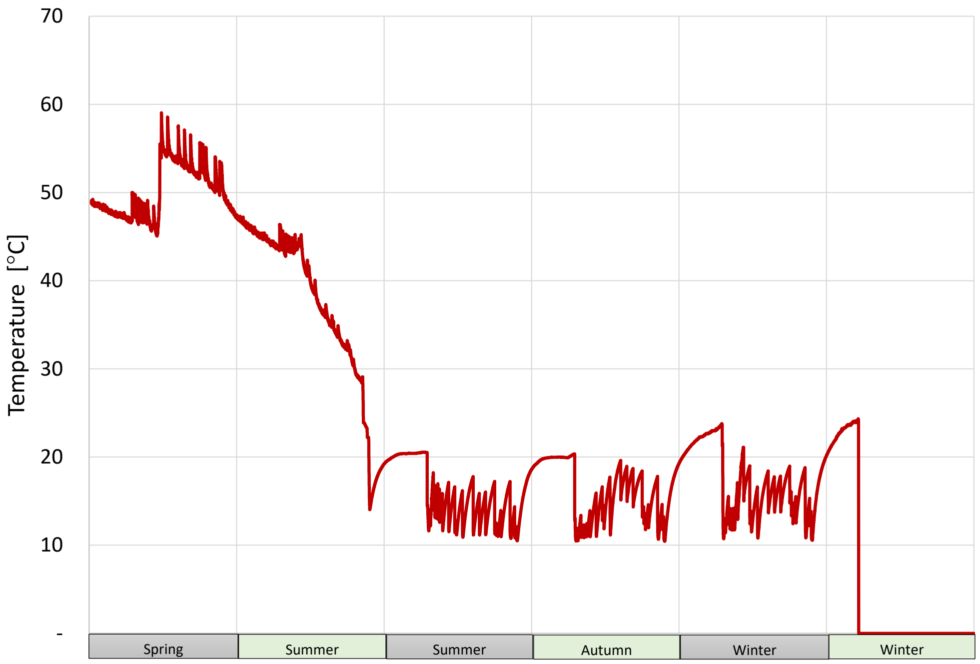

Figure 58. Temperature of the DHW measured after the tank during the 6-day test

In Figure 59 the supply- and return temperature is shown. As can be seen the space heating is working during the whole test but after day 1 based only on the back up heater. For the summer days one can see that the heating is turned off when the outdoor temperature increases.

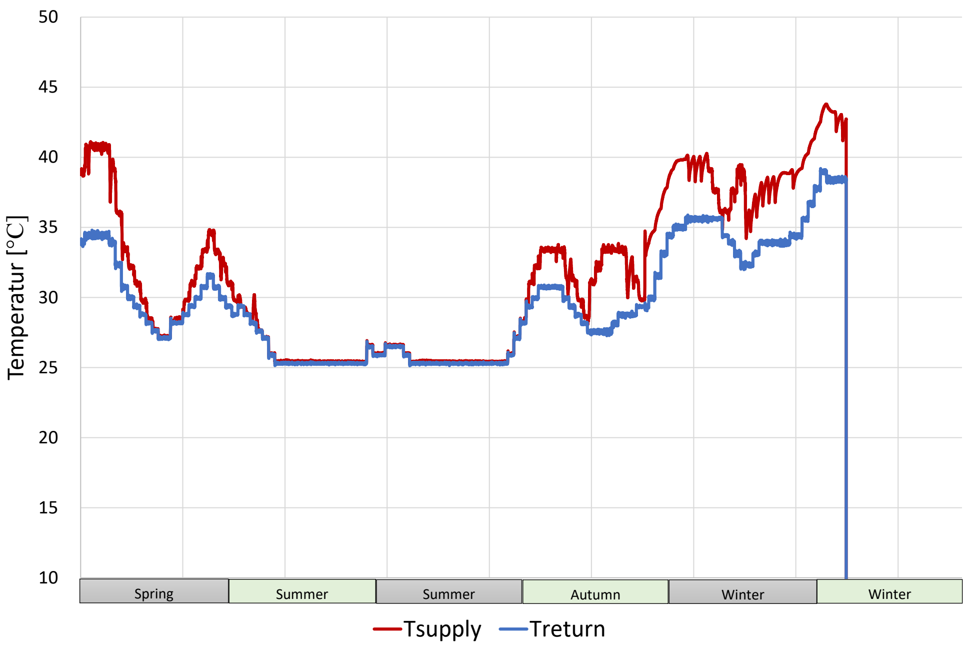

Figure 59. Supply- and return temperature to the radiator rig during the 6-day test

10.6 Prototype of a CCB based on an EAHP

Within the project new control algorithms for an exhaust air heat pump were developed, see chapter 9.3, and implemented (in slightly modified form) in a heat pump, of which some are to be included directly in the products sold on the market shortly. The plan and hope were to be able to test an EAHP in the lab together with a Ferroamp EnergyHub used as inverter which would communicate the PV production to the heat pump controller that then adapts its control to optimize self-consumption. However, the communication between these two units has not worked and this was not solved by the end of the project, so no testing of the full prototype including the implemented algorithms could be performed. The system itself was tested in the lab (but without the advanced control features) using a six-day test sequence based on a “hardware in the loop” [14] and the test data were used to calibrate the model of the PV and EAHP system simulated in the studies presented in chapter 9.3.

10.7 Conclusions Prototype

- A new compensation method for laboratory testing of the functionality (control) and performance of the prototype with focus on the smart control functions was developed within the project. The method includes both:
    - A 24 h test of functions
    - A 6-days system testing
- A prototype of a CCB based on a ground source heat pump (GSHP), a space heating buffer tank and a DHW tank for energy storage, passive cooling and smart control was developed within the project.
- Evaluation of the CCB prototype based on a GSHP in lab shows that the CCB can plan the heat production over the day, based on a varying electricity price or expected production of PV-electricity.
- The 6-days system testing has provided inputs on the needs for further adjustments of the smart the control of the prototype.
- New control algorithms for an exhaust air heat pump (EAHP) were developed and implemented (in slightly modified form) in a heat pump, of which some are to be included directly in the products sold on the market shortly.

11 Discussion

Below follows a discussion about results and other important aspects of a Comfort and Climate Box (CCB).

11.1 Future energy prices

The simulations in this project are based on the electricity prices from 2019 and the results shows that the potential economical savings are rather small, up to a few percent. Moreover, the results show that there are trade-offs between energy efficiency and “smart control”, where the power consumption is moved to, by different measures, time periods when the electricity price is low or to periods when there is an excess of on-site produced electricity by the PV-panels. Increased self-consumptions of on-site produced electricity could easily be used for covering increased heat leakage from a tank or smart control based on electricity prices could result in that the heat pump operates at less favourable conditions for the heat pump, e.g., lower outdoor temperatures during night time when the electricity price is low. Therefore, there must be a clear gain to make before smart control should be activated.

In addition, looking at the life cycle cost based on data from 2019, the savings in lower running costs due the smart control cannot compensate for the extra investments needed. But the energy prices, in Sweden as well as in the rest of Europe, are foreseen to maybe increase but definitely variate more in the future when the amount of electricity form intermittent, renewable sources increases in the electricity mix. The reason for this is an increasing foreseen need for electricity in the future when several industrial sectors as well as the transportation sector will rely on increased electrification in order reach their targets for CO_2 reduction in combination with that fossil-based electricity production will be phased out or down.

How the electricity prices will develop in the future is hard to tell. If the prices we have seen during the autumn and start of the winter 2021 are here to stay or if the prices will go back to more normal levels compared to the past ten years, the future will tell. During 2021 the electricity prices have been both higher and with larger variations compared to earlier years. When this report is written, in the end of December 2021, we have seen a week with price variations up to 4 SEK/kWh over the same day. Most of the days have had price variations of 2-3 SEK/kWh between the highest and the lowest cost over the day. Such large variations in electricity price creates clear incentives for implementation of smart control of heat pumps and will totally change the economic evaluations of the results and the interest for implementing different control functions.

In Figure 60-Figure 62 below the hourly electricity prices from Nord Pool for 2019 is compared with the prices for 2021 for three different months, the graphs also include an assumed increased price volatility up to 200%. 200% was the highest volatility evaluated in the sensitivity analysis (see chapter 9.2.5). As seen in the figures an increased price volatility over the day with 200% seems to be modest compared to the price levels (and variations) during the heating season

2021. But even though a 200% increased volatility of the prices from 2019 looks modest for periods of high electricity prices during 2021, a larger increase in assumed volatility would have led to unrealistically negative prices during periods of low electricity prices in 2019, like the summer month, see Figure 61. Here, already an increased volatility of 200% resulted in assumed negative spot market prices down to -0.5 SEK/kWh. Therefore, higher price volatility was not assumed in the sensitivity analysis.

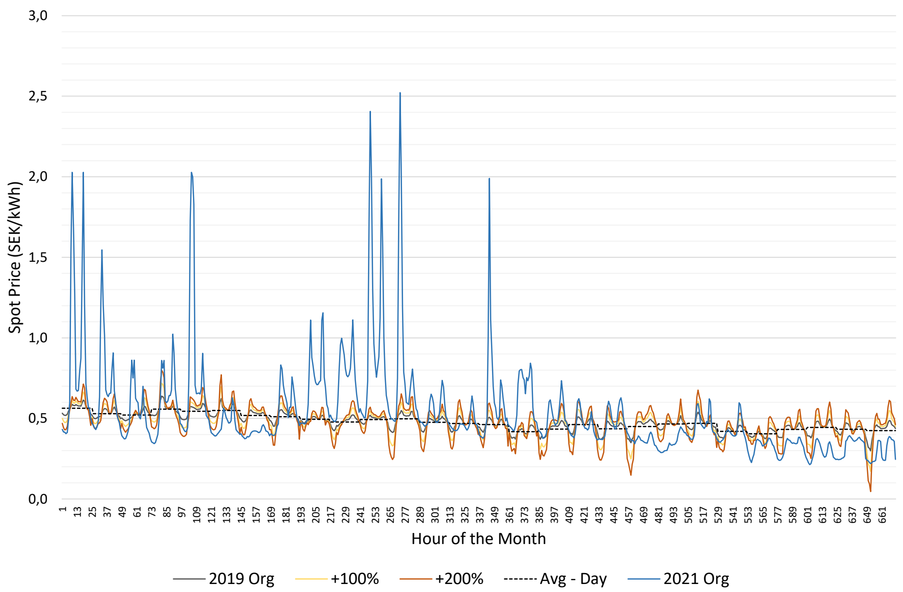

Figure 60. Spot market prices from Nord Pool, SE3 for February 2019 including an increased price volatility of 100% and 200%, compared with Spot market prices for February 2021 [9]

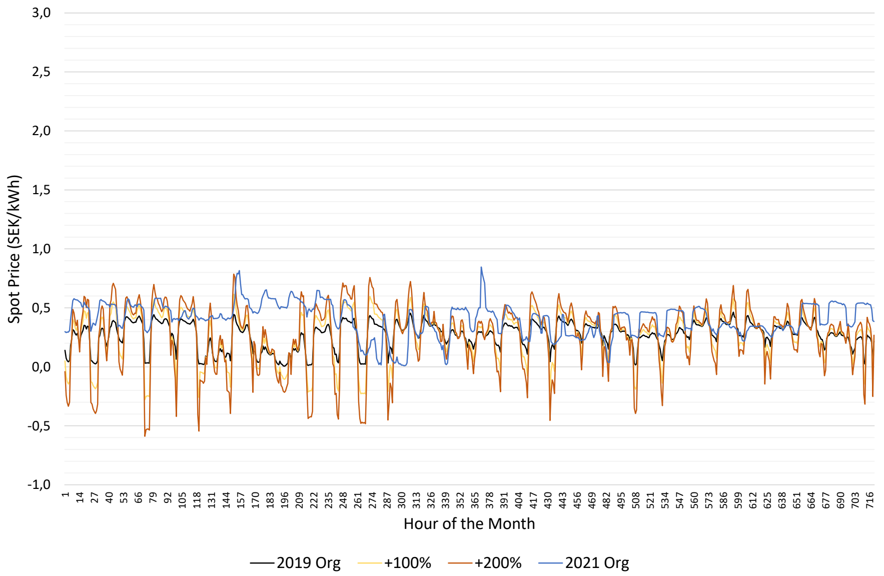

Figure 61. Spot market prices from Nord Pool, SE3 for June 2019 including an increased price volatility of 100% and 200%, compared with Spot market prices for June 2021 [9]

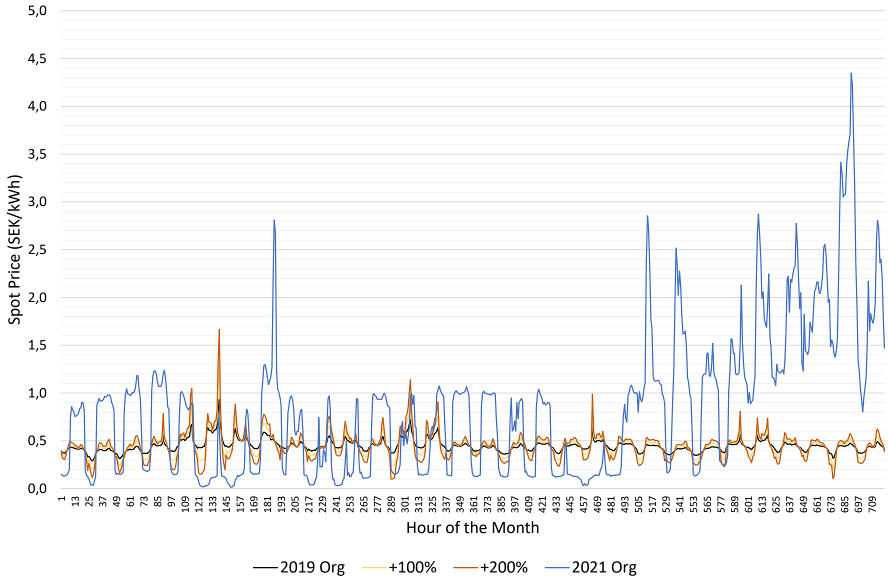

Figure 62. Spot market prices from Nord Pool, SE3 for November 2019 including an increased price volatility of 100% and 200%, compared with Spot market prices for November 2021 [9]

11.2 Simple installation and integrated control

A high penetration of Comfort and Climate Box (CCB) solutions on the market could result in higher share of renewable energy in the energy mix and a more stable electricity grid. However, to get high acceptance and demand from homeowners for Comfort and Climate Box (CCB) solutions it is important that it can offer other values compared to the present heating system, often a heat pump existing on the market today, and that it is working as one uniform product, where all parts are controlled together.

One example where there is a need for the CCB to work automatically without any actions needed from the house owner is concerning the smart control functions for planning the heat production over the day. Examples are price algorithms or algorithms to increase the internal use of solar PV power. They should work automatically and plan the heat production over the day based on input about variations in, for instance, electricity price or solar. Here, the quality of the forecast plays an important role for good results. Regarding electricity prices, Nord Pool's day-ahead market prices are published the day before and thereby the heat pumps operation for the next day can be optimized based on these data. But for providing input about heat demand and production of solar PV power, a weather forecast is needed. There is also a need for forecasts related to user behaviours such as DHW consumption. This is an area for improvements for the development of future CCB's, where this project has not focused. Within this project, the weather conditions for the previous day, was used as prediction for the day ahead, which is a fair enough simplification to make.

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11.3 Simple installation and comfort cooling

Another typical example, where a simple installation is necessary is the function for comfort cooling. Cooling could offer an additional value for the homeowner and should then be an integrated part of the product which works smoothy. Today, there are already existing heat pump products on the market with an included function for passive cooling from the borehole (GSHPs), or direct cooling by operating the compressor (ASHPs or GSHPs), even though they are still relatively rare in the field. It works as an integrated part of the system, when the outdoor temperature is high the heat pump unit automatically shifts to cooling mode and indirect cooling.

What is needed is a good way to distribute the cooling to the building. The most common solution for Swedish conditions today is to use a fan coil for distributing the cold. One or a few fan coils strategically located in the building, can give increased comfort for the rooms with highest need for cooling. An alternative to this is to use the floor heating system for cooling. This is a solution used in other countries but rarely used in Sweden today. To use the floor heating system for cooling, means however a risk that cold floors might lead to lower perceived comfort.

Simulations from the project show that using an indirect system for cooling compared to a direct system more or less halves the available cooling power (from the borehole) with the settings used in the simulations, but the difference in overheated hours for the building (defined as an indoor temperature above 25°C) between the two cases are not that big, neither for a normal villa nor the low energy building. Especially if it is combined with increased ventilation, opening of windows or using a lower set temperature for when to start the start the cooling. The benefit with the indirect system is that one avoids possible problems with condensate on pipes etc. In addition, it makes it easier to use the ordinary heating system for distributing the cold in the building.

11.4 CCB development potential

The result from the simulations has shown that the economical savings of the control functions evaluated are modest with the electricity prices for 2019 in Sweden. The main reason is that the variation in electricity price over the day is small for the year evaluated. But higher fluctuations in electricity price and an increasing use of power tariffs are to be expected in the future. The price structure and potential for PV-electricity varies from country to country. Especially the control algorithms for self-consumption of PV-electricity are today probably more relevant for other parts of the world (or Europe) with more sun and other price structures. But this solution can be of interest also for Swedish homeowners who prioritizes high self-consumption for other reasons than just a short pay-back time, and who finds it satisfying to know that they are using electricity they have produced on-site.

Even if the economical savings in Sweden today are small, it has been of valuable for the heat pump manufacturers to investigate the possibilities with smart control functions and additional storage. Thereby they are now well prepared for the future, when the condition would change and there is substantial saving to make related to the control of the loads over the day.

There is a slowly growing trend in Sweden that grid owners change their business models to be based on the peak capacity outtake during the month instead of electricity consumption. With such a price model, a CCB which can plan the heat production, and power consumption, and avoid consuming during peak hours in a good way have a potential to save money for the owner. Connected to this, one area with large potential for the future is an integrated control including both a CCB and the electric car charging. To be able to avoid that the CCB and the car charging run simultaneously, can offer a large saving potential for the homeowner but also even out peaks for the grid owner. Specially to avoid the use of the backup heater, or that the compressor run at top speed, at the same time as the car is charged.

For policy makers and grid owners it is good to be aware of the possibilities to use a CCB to help even out the electric loads in the grid over the day. With a well-constructed price profile, with high cost during high load hours and low-cost during low load hours, it is technically possible to use CCBs to even out the loads and avoid peaks consumptions in the grid.

11.5 Cybersecurity

The CCB archetype *Flexibility* is built on the assumption that a CCB is connected to the internet, and some of the evaluated control algorithms in the project requires that the CCB is connected and gets information about e.g., electricity prices for its control. With a connected product it is important to consider cyber security aspects. A potential risk for a homeowner with a hacked CCB is in worst case that someone external takes over the control of the heat pump and for instance turns off the heat and/or the production of DHW. There is also a risk of leakage of sensitive data from the CCB. If a large amount of heat pumps or other electrical loads are hacked and controlled together there is also a risk for damage and shutdown of the electric grid.

Connected CCB and other services for these products needs a high security level to prevent the CCB from being hacked. If this still is the case, the CCB should have a control strategy that minimizes the impact of the hacker attack. The CCB need to secure space heating and DHW for the building (within its defined comfort limitations) and first when this is fulfilled allow control via external signals (price or other). Another recommendation is to make sure that the CCB do not response too fast to external control signals to reduce the risk for damage to the electric grid in case of a synchronised attack including many electrical loads.

12 Conclusions

A Comfort and Climate Box (CCB) is defined as a heat pump in combination with energy storage and integrated control. In this Swedish project it has also included control in combination with PV-panels and, for some of the CCB concepts comfort cooling. A CCB can have different focus areas, but this project has in first-hand focused on the archetype “Flexibility”.

The energy storage makes it possible to plan the heat production in time and shift heating, and thereby electric loads, to hours with e.g., low electricity price or high production of solar PV-power. A CCB can be used to shift loads over the day, but it is not a solution for long time storage from one season to another. The project has shown that it is possible to efficiently control the electricity consumption over time using a CCB, including a heat pump, energy storage and integrated control. This has been proven first with simulations and thereafter by laboratory testing of a prototype developed within the project.

The result from the simulations showed that the economical savings of the control functions evaluated are modest with the electricity prices for 2019 in Sweden. The main reason is that the variation in electricity price over the day is small for the year evaluated. However, higher fluctuations in electricity price and an increasing use of power tariffs are to be expected in the future, in Sweden as well as in other parts of Europe.

A CCB includes extra energy storage in addition to the ordinary DHW-tank normally used in today heat pumps. But additional storage results in additional heat losses and the heat losses will decrease the potential energy efficiency. Storage at higher temperature or larger storage volumes lead to larger losses and there is a clear trade-off between the thermal energy storage and increased losses, where the losses consume some of the benefits with the storage. It is therefore recommended to store the heat at as low temperature as possible, e.g. in a DHW preheating tank with a lower temperature than the ordinary DHW-tank, a buffer tank for space heating or to use the building’s thermal inertia to store energy. Moreover, there must be a clear gain to make (e.g. relatively high electricity price volatility, high peal power tariffs or high difference between purchase and sale price of on-site produced electricity), since the “smart control” could result in somewhat lower overall efficiency and interference with safety control of the heat pump.

Since the potential savings in running cost are relatively low (at least for the electricity prices in the level of the ones for 2019), there is a need to keep the investment costs low to get an acceptable life cycle cost. Therefore, it is beneficial to use already existing storage alternatives as long as possible, e.g. the DHW tank or the building’s thermal inertia. Cost for develop new control algorithms on the other hand is a one-time cost for a heat pump manufacturer, when done there are low costs to implement it in each new heat pump. Therefore, the additional investment cost for control can be kept modest.

The results and the outcomes from this project have resulted in that heat pumps manufacturers can be well prepared for the future when the price structure for electricity and power will change – for the benefit for the end-users as well as for the grid operators and utilities. This applies especially for the heat pump manufacturers who have been actively involved in and contributed to this project, but also to other manufacturers, and grid operators and utilities in Sweden as well as abroad, who will be able to take part of the results. Moreover, standardization organisations could benefit from the results from the developed test method for system testing of a CCB.

13 Publication list

Scientifically reviewed articles

1. Psimopoulos et al. LCA and LCC of a stationary battery system versus a DHW tank for energy storage for a single family house with a PV system and a compact exhaust air HP. In manuscript, to be submitted in Energy and Buildings, Jan 2022.
2. Padovani, F., Sommerfeldt, N., Madani, H. Utilizing heat pumps for solar photovoltaic storage in buildings: A system of systems perspective. In manuscript, to be submitted to Energy Strategy Reviews, Jan 2022.

Other publications

1. Participation in IEA Heat Pumping Technology TCP Annex 55 and IEA Energy Storage TCP Annex 34 "Comfort and Climate Box – Speeding up market development for integrating heat pumps and storage packages". This includes for instance:
    - Input based on results from the Swedish CCB project to reports for the Annex.
    - Reports from the Annex will be published on IEA Heat Pumping Technologies website and database during 2022 (Home - HPT - Heat Pumping Technologies).
    - Sweden was responsible for leading the work related to Part VII – Roadmap.
    - Presentations from the Swedish project to the international project group.
    - Participation in the CCB workshop organized at the 13th IEA Heat Pump Conference 2020 (digitally in April 2021 due to Corona), presenting the first draft of the Roadmap for CCB, including drivers, barriers and recommendations to different stakeholders.
2. Article in Kyla&Värme, January 2020

Presentations

3. European Heat Pump Summit, Nürnberg, 2021-10-27
4. Svenska Kyl & Värmepumpdagen 2021, Online/Stockholm, 2021-11-18
5. Webinar on PV and heat pump systems, Webinar organized by Högskolan i Dalarna, 2020-12-16

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15 Appendices

Appendix A:	IEA HPT Annex 55 / ECES Annex 34 “CCB” Task 1 report - Sweden
Appendix B:	Comfort & Climate Box – towards a better integration of heat pumps and storage Final report of the combined Annex 34 (ECES) and Annex 55 (HPT), Part VII – Roadmap (draft version)
Appendix C:	Administrativ bilaga till Slutrapport