Investigation of potentials in thermal energy storage for space heating applications in Sweden

EMMA HUMIRE

GHAZAL FARAMARZI
Abstract

The aim of this study was to investigate the economic and energy-efficiency potentials for configuring thermal energy storage (TES) units in Swedish residential buildings. Consequently, the goal was to carry out economical and energy calculations over two applications of coupling two different types of heat pumps with a TES unit (water tank) for providing space heating in a detached single-family house in Stockholm, Sweden during winter time. The heating systems with the heat pumps and TES unit were modeled and simulated using the software MATLAB. Different criteria were applied to govern when the heat pumps would charge the TES unit, for example one criterion stated that the charging process would only occur if the electricity price was lower than a certain value. The results showed that there were savings both in terms of energy and economy for coupling a TES unit with a heat pump, for both types of heat pumps and regardless of criteria selection. The conclusions of the study is that there is potential for configuring TES units with heat pumps in detached single-family households in Sweden. However, since the models in this study included several simplifications, it is necessary to perform similar simulations with wider and more accurate models.
Sammanfattning


Värmehandel för hushållet räknades fram timvis för den vecka som studerades. Utifrån detta behov bestämdes värmepumpens uteffekt per dag. För timmar där effekten producerad av värmepumpen översteg värmehandels effekten laddades TES-enheter för senare användning vid timmar med värmehandel som översteg effekten producerad av värmepumpen. TES-enheten som var en vattentank dimensionerades utefter det största värmehandeln under veckan.


Foreword

Since February of 2018 we have done research on the topic of thermal energy storage and it has been one of the most interesting areas we have worked with. At the beginning we didn’t know about this technology, the significance of the study or results we would get. However, during the course of the work we have gained a deeper understanding of the topic from hours and hours of reading through articles. In the end we learned that this topic is not only very important for managing energy utilisation in buildings but that it is also a very fun and intriguing topic.

We would like to thank our supervisor Tianhao Xu from the department of ETT at The Royal Institute of Technology in Stockholm, Sweden, for providing us with the best support and guidance during this spring. It has been a pleasure to work with you.

We would also like to thank Joar Bagge, PhD student at the department of Mathematics at The Royal Institute of Technology in Stockholm, Sweden, for helping us deal with MATLAB and LaTeX.
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Abbreviations

**COP** - Coefficient of performance
**PCM** - Phase-change material
**SGBC** - Swedish Green Building Council
**TES** - Thermal energy storage
**UN** - United Nations
**VAT** - Value-added tax
1 Introduction

Of all the environmental challenges the world faces today, the energy consumption and heat supply are of interest since there is room for improvement and development, for example in terms of energy efficiency. In Sweden, the residential and non-residential sector is relevant when discussing energy efficiency. For instance, detached single-family households in Sweden used up to 32.8 TWh for space heating and hot water in 2013, making them the largest consumer in the housing and non-residential sector. (Energimyndigheten, 2015, p.14-15). It should be mentioned that the single-family households are also the largest consumers on the heating market in terms of capital (Värnemärknad Sverige, 2014, p.8). According to statistics from the Swedish Energy Agency, the annual total energy used for heating in single-family households has decreased from 38.6 TWh in 2002 to 31.2 TWh in 2014. (Energimyndigheten, 2014a, p.14) Although the statistics show a decreasing trend of energy consumption the number of houses is growing as well as the population (SCB, 2017) and thus the demand for reliable energy will increase.

One hot topic in the area of energy efficiency in buildings is thermal energy storage (TES). Simply put, the main idea of TES is to temporarily store thermal energy for use at a later point in time, with the help of different mediums such as water and oil (Navarro, et al., 2015, p.527). Overall, there are many different types of TES methods but there are three central methods: sensible, latent and thermochemical storage. With the sensible storage method, the heat storage is basically a temperature difference between the medium and the surroundings, whilst the latent heat storage involves phase change of the storage medium. (Navarro, et al., 2015, p.527). It should be mentioned that the thermochemical storage method is still under investigation and as such is not a fully enough developed method to be applied in buildings (Heier, J., Bales, C. & Martin, V., 2015, p.1322).

TES systems have a lot of benefits, for example the opportunity to decouple the demand and supply and consequently shift the peak hours, make use of the surplus heat and acquire economic benefits (Tomlinson & Kannberg, 1990). Since the cost of electricity rises during high consumption times, i.e. during the day, the economical benefits of using a TES unit would be the amount of money not needed to be invested in electricity during those peak hours. (Gadd & Werner, 2015) Moreover, it is possible to acquire tax reductions and other economical benefits when installing TES units in households (ASHRAE, 2012, p.51.1). For example, in the United States a bill has been passed, which enables investors of thermal energy storage systems to acquire an investment tax credit, which can be seen as a tax reduction. This bill is called The Energy Storage Tax Incentive and Development Act of 2016. (Energy Storage Association, n.d.)

Another environmental-related benefit of TES is that the energy efficiency could contribute to a carbon dioxide emission reduction (Navarro, et al., 2015, p.527). For example, if heat spill is stored for later use then the need to burn fossil fuels for energy is decreased, as proposed by Arce et al. (2015) As a consequence of the storing opportunity there will be a decreased dependency on fossil energy sources at high consumption hours. Furthermore, it is valuable to point out that TES gives the opportunity to a more effective use of renewable energy sources such as solar energies that usually are producing systems during day time. (Heier, Bales & Martin, 2015, p.1308 ) Similarly, TES technology can be used to store the energy produced by wind power when the production of energy exceeds the demand. This is useful as wind power is an intermittently producing system which is dependent on weather conditions. (Liu et al., 2017, p.1-2)

Because of the energy efficiency, emission reductions and economic benefits heat storage systems could be a step to reaching sustainable development in the residential sector. Hence, TES could be important to achieve both international and national sustainable development goals. For example, on an international level TES could be important to achieve the sustainable development goals written by the UN. Goal number seven, called “Clean and Affordable Energy” in the UN document, concerns access to reliable energy services and increasing both energy efficiency and use of renewable energy sources in the global energy systems. As mentioned above, these are goals that could be achieved with the help of TES technology. Furthermore, the climate changes and greenhouse gas emissions are in the focus of goal number 13, “Climate action”. With TES technology there is an opportunity to reduce the emissions in residential buildings and thus, coming one step closer to achieving this global goal. (United Nations, n.d.)

On a national level, the Swedish government has formulated environmental goals in different areas, including the residential and housing sector. Among these goals, called The Environmental Objectives, goal
number 15, “A Good Built Environment”, states that energy in the residential sector should be used in an effective manner by year 2020. (Boverket, n.d.) For example, a TES unit could make use of surplus heat generated in a building during the day by storing it and utilize it during nighttime when the heat demand might be higher. This would thus decrease the need for bought energy. (Heier, Bales, & Martin, 2015, p.1308) The potential energy savings of utilizing a TES unit in a household could be related to one of the indicators used by The Swedish Green Building Council (SGBC). SGBC’s indicator number three, Energianvändning (Energy utilization), concerns the total amount of energy a household purchases for space heating, cooling etc. (SGBC, n.d.) and it is possible that installing a TES unit could affect a house’s grading on that particular indicator. Consequently, it is possible that the installation of TES units in different houses in Sweden could contribute to achieving the Environmental Objective number 15. However, it should be mentioned that this is a topic that must be investigated further, as will be done in this study.

A few studies have been conducted in exploring TES and in particular investigating the potential of implementing TES units in residential buildings. For example Arce et. al. (2011) investigated the energy efficiency potential of TES units in Spain and other selected countries in Europe, not specifically including Sweden. With the help of computer simulations Heier, Bales & Martin (2012) studied the effect of thermal energy storage on heating demand in two single-family houses located in Nordic climate. To this day, no one has conducted an investigation of both the economical and energy efficiency potentials of coupling sensible TES units with heat pumps in detached, single-family households in Sweden. The aim of this project is to investigate the economic and energy-efficiency potentials for configuring thermal energy storage (TES) units in Swedish residential buildings. Therefore, the goal of this project is to perform economical and energy calculations over two different applications of coupling two different types of heat pumps with a TES unit for providing space heating in the case of a detached single-family house in Stockholm, Sweden during winter time.

## 2 Background

Knowledge of the configuration of the heating market and energy prices in Sweden and the energy demand in the residential sector is central to understanding the possible potential of TES units in single-family households. Furthermore, a brief review is given of different international and national directives and goals that demand a change in the way energy is utilized. These could motivate the use of TES systems. A review of different types of thermal energy storage technologies used in buildings is necessary for a better understanding of their advantages and disadvantages. Moreover, there are many different configuration options available for TES units in residential buildings. The coupling of a TES unit with a heat pump is one such configuration that will be central in this study. An understanding of these topics will be crucial to picking an appropriate thermal energy storage system for the detached single-family case studied in this report. These topics will be covered in the following subsections.

### 2.1 The heating market and energy prices in Sweden

One of the largest energy markets in Sweden is the heating market, annually providing 100 TWh to the residential and industrial sector, with a turnover of around 100 billion SEK. Households of various types purchase energy from the heating market for space heating and hot water. The heating market is composed of five different technologies and energy carriers: district heating, heat pumps, electric heating, biomass and oil & gas. District heating is the most widespread technology, meeting more than half of the heating demand on the market. In single-family households electrical heating and heat pumps are the most widely used technologies. (Värmemarknad Sverige, 2014, p.8) According to Energimyndighetens, the average single-and two-family household used 16200 kWh for space heating and warm water in 2016 (Energimyndighetens, 2016, p.9).

As mentioned previously, the single-family households are the largest consumers on the heating market, both in economical terms and the amount of energy consumed (Värmemarknad Sverige, 2014, p.8). For example, the total energy used by detached single-family households amounted to 32.8 TWh for space
heating and hot water in 2013 (Energimyndigheten, 2015, p.14-15). There are several factors which might affect the economical costs for single-family households. For example, the price of district heating will most often be greater for single-family households since the areas in which they are located usually are less dense in terms of people and energy demand, in comparison with large apartment buildings. Furthermore, single-family households are often faced with a larger cost than multi-family households when purchasing energy. (Värmemarknad Sverige, 2014, p.16)

In Sweden, the use of heat pumps for various applications is common in detached single-family households. In 2010, approximately 50% of all single-family households used heat pumps in different configurations. (Boverket, 2013, p.23) The sizes of heat pumps vary greatly depending on factors such as the heat demand of a household. A rule of thumb, according to Svenska Kyl & Värmevärmeföreningen (SKVP), is to dimension the heat pump to cover 50-70% of the greatest heat and power demand during the year. As an example, SKVP mentions that a household consuming 20 000 kWh of electricity for electrical heating for space and water heating has a peak power demand of 8 kW. (SKVP, n.d.) Another example is from Sustainable Energy Utilisation, where it is suggested that a heat pump of 10 kW capacity is typical for space heating and hot water appliances for a single-family household (Jonsson & Boldanowicz, 2005, p.17:3).

The installation costs of heat pumps vary depending on the type of heat pump. According to Vattenfall, for a detached household with a living area of 125 $m^2$ the initial investment cost for a ground source heat pump is 134 000 SEK and for an air-to-water heat pump is 115 000 SEK. (Vattenfall, n.d.b.) (Vattenfall, n.d.c.)

As mentioned previously, knowledge of the energy prices on the heating market and how they vary is important to understanding the potential of TES on the market. For instance, the cost of electricity for households in Sweden varies over the years but one general trend is that the cost has risen (Energimyndigheten, 2017, p.49). For example, during week 9 in 2018 (26/2-4/3) the cost of electricity varied from a minimum cost of 0.36153 kr/kWh, occurring one midnight, to a maximum cost of 2.57341 kr/KWh, occurring one at 8 AM in the morning (Nord Pool, n.d.). This is an example of how the peak and valley prices depending on the time of day.

### 2.2 Energy policies and directives in Europe and Sweden

There are numerous directives and policies that could act as incentives for installing TES units in residential buildings. For example in Europe, The Energy Efficiency Directive states that the reduction of energy use in the EU member countries must amount to 20 % by year 2020 and 30 % by year 2030. Moreover, the directive states that there must a 1.5% decline in the amount energy sold in the EU member countries. (European Commission, n.d.) On a national level, Sweden has issued similar goals called the Environmental Objectives, of which goal number fifteen, “A Good Built Environment”, is comparable. This goal states that energy in the residential sector should be used in an effective manner by year 2020. (Boverket, n.d.) For example by storing surplus heat in a house for use during a later point in time the need for bought energy could decrease (Heier, Bales, & Martin, 2015, p.1308), which in turn could affect the level of fulfillment of these objectives.

In Sweden there are various certification processes that can be used to evaluate and benchmark a house’s energy performance. For example, there is an evaluation and certification system called Miljöbyggnad, given by Sweden Green Building Council. In this system a building is evaluated on fifteen different indicators such as level of radon, ventilation and energy usage. For each indicator the house is graded on a scale of bronze, silver and gold, where bronze is the lowest score and gold is the highest. Indicator number three, Energianvändning (Energy utilization), is governed by the amount of energy that is purchased for space heating, hot water heating etc. As described previously, a TES unit could decrease the need for purchased energy and consequently also affect the score on factor number three, which in turn could affect the building’s overall score in the Miljöbyggnad system. (SGBC, n.d.)
2.3 TES in residential buildings

2.3.1 Classification of TES systems

TES systems in buildings can be classified in two main types, depending on their charging and discharging process. The first type is passive storage, in which the difference of temperature of the ambient and the heat storage is key in the discharging and charging process of the thermal energy storage. Reversely, the second type of storage is active storage and named as such because of the need for supplied work to be able to discharge and charge the storage. Fans and pumps are two examples of appliances used in active storage. The subcategories for the two main types of TES are different sorts of sensible and latent storage systems. (Heier, Bales & Martin, 2015, p.1309)

2.3.2 Sensible and latent heat storage systems

Sensible heat storage is the most widely used storage technique for both heat and cooling applications (Navarro, et al., 2015, p.527). Water, rock, concrete and iron are some examples of storage media used for sensible heat storage, with the water and rock being the most common because of their low-cost and great abundance. (Kakaç, Payçoç, & Yener, 1989, p.132) The most common storage containers for sensible heat storage are tanks of various geometries, with vertically aligned tanks being the most widely used. (ASHRAE, 2012, p.51.4) These tanks come in various sizes, ranging from 100 $dm^3$ to 5 $m^3$ (EASE, n.d.). However there are drawbacks with these sorts of sensible heat storage systems, for example the amount of space that the tanks require, which is of course depending on the amount of heat that is needed to be stored, is often a problem. (De Gracia & Cabeza, 2015)

The most typical technology used in residential buildings today is sensible storage, with water as the storage medium. Water as a medium has a lot of benefits such as easy access, non-expensiveness and non-toxicity. (Heier, Bales & Martin, 2015, p.1322) Furthermore, the large specific heat of water is a thermodynamical property which also makes it suitable and favorable as a sensible heat storage medium. (ASHRAE, 2012, p.51.4) One of the drawbacks of using water as storage medium is its corroding effect on the containment systems, such as pipes etc. Furthermore, due to its freezing point being fairly close to possible low ambient temperatures, there is a risk that the medium could freeze. (Kakaç, Payçoç, & Yener, 1989, p.134) This risk is more prominent in cooling applications using water, such as ventilation, instead of heating applications like hot water and space heating.

In latent storage the mass and heat of fusion of the medium is of importance. The reason is that this method uses phase transition of materials. With the help of latent storage technologies it is possible to store both cold and heat. (Navarro, et al., 2015, p.527) According to previous studies phase changing materials are not the best choice for heat storage in residential buildings because there are only a few number of phase changing materials that have high latent heat in the desired temperature range for buildings. Moreover, there are other drawbacks with phase-change materials (PCMs) such as low heat transfer that cause a limited discharging process. With other words, the system would not be able to supply heat quickly. Another issue with most PCMs is that they are expensive, except for water. However, water is mainly used as a PCM in cooling systems since the low operating temperature of such systems are more compatible with the melting point of water. That means that the latent process is not the optimal process for TES in buildings. (Heier, Bales & Martin, 2015, p.1306)

2.3.3 Coupling of TES with heat pump

It is possible to connect a heat pump to a TES system and this could give several advantages. For example the opportunity to shift the electricity consumption from high demand to low demand hours. (Renaldi, Kiprakis & Friedrich, 2016) A heat pump transforms energy from air, ground or water to heat for residential buildings as well as commercial and industrial buildings (Swedish Energy Agency, 2015). A configuration could be a heat pump coupled with a water tank, where electrical power is provided to the heat pump which in turn heats the water in the tank by using a coil heating exchanger (Renaldi, Kiprakis & Friedrich, 2016).
Heat pumps have an input electrical power and an output thermal power that is shown as a ratio between these two called the coefficient of performance, COP (Renaldi, Kiprakis & Friedrich, 2016). The COP value is an indicator of the system’s efficiency, where higher value means a more effective system (Hesaraki, Holmberg & Haghighat, 2015, p.1203). Moreover, the COP value is dependent on the heat source temperature (Energimyndigheten, 2010, p.6, 12).

Furthermore, it is possible to control the capacity and output of a heat pump with the help of variable-speed drive of its components (Fahlén, 2012). This would allow for greater control of the heat pump capacity beyond switching the heat pump on or off.

The heat pump system, like others, has its advantages and disadvantages. One major benefit of heat pumps is their non-existent pollution levels to the local environment. Furthermore, low upkeep and low expenses during operation are two other advantages to using a heat pump. However, while the running expenses may be low, the initial investment costs are not. (Swedish Energy Agency, 2015)

A case study in 2017 by Yin et al. investigated the potential of integrating a heat pump in a thermal energy storage system. The case study looked closer at a multiple heat source system combining solar heating, a heat pump, and a water tank as an energy storage system, and concluded that such a system combination has a potential to decrease the consumption of electricity by 33% for the whole system. This reduction was compared to a system consisting only of a heat pump. (Yin, et al., 2017) In 2016, Renaldi, Kiprakis & Friedrich investigated the coupling of a heat pump with a thermal energy storage, a hot water tank, as a heating system in a residential building. The study concluded that the running costs of the heat pump could be decreased when connecting the heat pump with the thermal energy storage. (Renaldi, Kiprakis & Friedrich, 2016)

3 Method

The project was divided in two phases: the first consisted of a literature study where background on TES was collected from different databases accessed through KTH Royal Institute of Technology Library (KTHB). The databases used were Primo, Web of Science and ScienceDirect. A database used, though not accessed through KTHB, was Google Scholar. The following search words were central in the database searches: “thermal energy storage”, “sensible heat storage in buildings”, “TES in residential buildings” and “heat pump thermal energy storage”. Apart from the authors’ own research, literature on the topic was provided by the supervisor. The literature provided included articles and books, for example, the 2012 ASHRAE Handbook - HVAC Systems and Equipment.

Information on different types of thermal energy storage systems and configurations with different technologies, such as heat pumps, was collected in order to be able to select an appropriate TES system for the calculations in the second phase.

The second phase of the project concerned the economical and energy-related calculations for the case of a detached single-family household in Stockholm, Sweden during a week in February. The calculations were performed using the computer programs Excel and Matlab. In the following subsections, the procedures used for these calculations and data about the case will be described and presented in chronological order, as they were done during the course of the study. Nearly all of the equations used in the following subsections were retrieved from the book Sustainable Energy Utilisation (Jonsson & Bohdanowicz, 2005, p.3:2, 3:6, 3:11-12, 3:17), unless stated otherwise, and all thermodynamical data was collected from Heat and Mass Transfer Fundamentals & Applications (Çengel & Ghajar, 2015).

3.1 General outline of the case

The case studied was a single-family household located in Sweden. The location was chosen by the authors to be the municipality of Sollentuna in Stockholm. The house was simulated for a week in February 2018, using data for the dates 26/2-4/3. Thermodynamical data for an existing household was provided by the supervisor while heating systems were modeled in this study using Matlab.
The heating system of the household consisted of a heat pump and electrical heaters. Furthermore, two set ups of the heating systems were examined: one where the heat pump was of a ground source type and a second set up where the heat pump was of an air-to-water type. The first set up was named “reference case A” and the second one was named “reference case B”.

In this case study, the possible economical and energy-related savings of adding a TES unit were investigated. Note that the economical calculations did not concern installation or upkeep costs of the heating system, but only electricity costs. The investigation was performed for both set ups of the heating system. The first set up for the heating system with the addition of a TES unit system was called “case A” and respectively “case B” for the second set up. The TES unit used in this study was a sensible heat storage system consisting a water tank coupled with the heat pump in the modeled heating system.

For both case A and B, different criteria were applied for the calculations. The criteria governed how the heating system would charge the TES unit. The criteria considered were the hourly electricity price variation and variation of COP. For case A only the electricity price criterion was considered, while both the electricity price and COP criteria were considered for case B. For case A and B, calculations were performed once with the electricity price criterion and once without. The COP criterion for the air-to-water heat pump was always considered. The cases and criteria selections are summarized in figure 1.

![Figure 1: A flowchart illustrating the different cases and criteria selections for the calculations.](image)

### 3.1.1 Heat demand calculations

As mentioned previously, all of the equations in this subsection are collected from Jonsson & Bohdanowicz (2005). Firstly, the heat demand curve of the household was calculated for the particular week studied. For heat demand calculations in a building there are several factors to take into account. In general, the heating demand can be described as the difference between the heat losses in the building minus the heat gains. The heat gains and losses can in turn be decomposed into different contributing components, as described by equation (1).

\[
Q_{\text{heatdemand}} = Q_{\text{transmission}} + Q_{\text{ventilation}} + Q_{\text{infiltration}} - Q_{\text{solar}} - Q_{\text{int}}
\]  

(1)

The transmission losses, \(Q_{\text{transmission}}\), include heat losses through any exposed surfaces of the building by conduction and convection. Transmission losses occur through walls, glass, ceilings and floor and are thus dependent on the area, the material of the surfaces and the temperature difference of the inside and outside air. The effect of the material and thickness of the surfaces can be summarized by the overall heat transfer coefficient \(U\) and the transmission losses are calculated using the equation (2).

\[
Q_{\text{transmission}} = UA(t_{IN} - t_{OUT})
\]  

(2)

The data for the outdoor temperature used for the calculations were retrieved from a website called Temperatur.nu. The site provides data that can be used for free for studies and research. (Temperatur.nu, n.d.)
The data was picked for a week in late February in 2018, for the dates 26/2 to 4/3, in a municipality in Stockholm called Sollentuna. The lowest temperature during this week was -20.5 deg C and the highest temperature was -1.0 deg C. The temperature data can be found in Appendix 1.

The indoor environment was assumed to be homogenous, which meant that the temperature of the walls, roof and all other surfaces of the house were the same temperature as the desired indoor temperature at 21 deg C. The indoor temperature was also assumed to be constant. In table 1 the information about the overall heat transfer coefficient and areas of the different house components for the single family house in Sweden is shown.

```
<table>
<thead>
<tr>
<th>Walls</th>
<th>Roof</th>
<th>Floor</th>
<th>Windows</th>
<th>Door</th>
</tr>
</thead>
<tbody>
<tr>
<td>U [W/Km²]</td>
<td>0.6</td>
<td>0.29</td>
<td>0.28</td>
<td>2.43</td>
</tr>
<tr>
<td>A [m²]</td>
<td>100</td>
<td>160</td>
<td>125</td>
<td>28</td>
</tr>
</tbody>
</table>
```

Furthermore, heat losses through the floor can be taken into account when calculating the heat demand of a house, which is shown in equation (3). It is very similar to the equation (2), describing general transmission losses, $Q_{\text{transmission}}$, with a slight modification where a term for $t_{\text{OUT,AVG}}$ is added. This term represents the annual mean outdoor temperature for the area where the building is located. In this study, the average annual temperature for Sollentuna was 6.1 deg C (Temperatur.nu, n.d.).

$$Q_{\text{floor}} = U A (t_{\text{IN}} - (t_{\text{OUT,AVG}} + 3))$$ (3)

As with most houses there is a ventilation system which gives rise to ventilation losses, $Q_{\text{ventilation}}$, due to the heat exchange of the indoor air with the outside air. For calculations of ventilation losses there are several quantities that are important, such as the density ($\rho$) and the specific heat ($C_p$) of the indoor air as well as the ventilation level ($V$). The ventilation level chosen for this study was 0.35 l/s per m² floor area, which is the lowest ventilation level according to Boverket (2015, p.156). The ventilation losses can be calculated using equation (4).

$$Q_{\text{ventilation}} = V \rho C_p (t_{\text{IN}} - t_{\text{OUT}})$$ (4)

All thermodynamic data for the indoor air was retrieved from the book “Heat and Mass Transfer Fundamentals & Applications”. The quantities used were density and specific heat taken at indoor temperature, 21 deg C. All properties were read at atmospheric pressure. The properties for air which were used in this study are gathered in table 2. (Çengel & Ghajar, 2015, p.924)

```
Table 2: Summary of all air properties gathered and used in the study.

<table>
<thead>
<tr>
<th></th>
<th>Density $\rho [kg/m^3]$</th>
<th>Specific heat $C_p [kJ/kgK]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (21 deg C)</td>
<td>1.204</td>
<td>1.007</td>
</tr>
</tbody>
</table>
```

Heat losses arising from air leakage through cracks in the building structure are usually called infiltration heat losses, $Q_{\text{infiltration}}$. However, in this study the losses from infiltration were neglected for simplicity. Heat gain from solar irradiation, $Q_{\text{solar}}$, arise as the heat from the sun flows into the house through the windows. The heat gain is thus dependent on the area of the windows, the type of windows and the amount of solar irradiance. The orientation of the house will also impact the heat transfer since the calculations for the solar heat gains must be performed for windows in facing different directions. (Jonsson & Boldanowicz, 2005, p.3:17). However, since the solar irradiance during winter time in Stockholm is low this term was neglected in this study. (SMHI, 2015)
For residential buildings the internal heat gains, $Q_{int}$, which include the heat generation from the human body and electrical devices, are relatively small (ASHRAE, 2013, p.17.1). Thus, the internal gains for the single-family household were neglected in this study.

The final equation used for calculating the heat demand of the household is shown by equation (5).

$$Q_{heat\text{demand}} = Q_{\text{transmission}} + Q_{floor} + Q_{\text{ventilation}}$$ (5)

### 3.1.2 Modelling of heating systems for the reference scenarios

Secondly, the heating systems for reference case A and B were modelled. In order to understand the electricity demand of the heat pumps and make reasonable assumptions for the COP values of the two types of heat pumps, a further study on the theory behind the COP calculations for heat pumps was performed.

For a heat pump, as mentioned previously, the efficiency of the system can be shown by the coefficient of performance, COP. Equation (6) shows the relation between output $Q_1$ of the heat pump and input electrical power, $E$, into the heat pump:

$$COP = \frac{Q_1}{E}$$ (6)

COP can also be defined in terms low and high temperatures of the heat pump (Havtun, 2014, p.13). For a ground source heat pump that collects heat from below the earth’s surface, the low temperature would be a few degrees lower than the temperature of the ground and the high temperature would be a few degrees higher than the hot water temperature produced by the heat pump. The high temperature of an air-to-water heat pump would be the temperature of the water that will be used for heating in the household (for example in radiators) and the low temperature would be the outdoor temperature. The following equation, from Ekroth & Granryd (2006, p.131, 137), gives the maximum theoretical value of COP which is for a reversible process without losses.

$$COP = \frac{t_{\text{HIGH}}}{t_{\text{HIGH}} - t_{\text{LOW}}}$$ (7)

According to Energi- och klimatrådgivningen, the temperature of the ground is almost constant during the whole year (Energi-och klimatrådgivningen, 2017). Therefore the COP value of the ground source heat pump was considered constant in this study since the COP is dependent on the ground temperature, which is the low temperature side of the heat pump.

The ground source heat pump chosen in this study is a product called “Diplomat Inverter”. The product has variable-speed drive. The 3-12 kW-size model of the heat pump was chosen. (Therminia Värnepumpar, n.d.) Table 3 shows information about this product that was gathered from Therminia Värnepumpar (n.d.) and used in this study.

<table>
<thead>
<tr>
<th>Table 3: Summary of case A with reference scenario</th>
<th>Reference Case A</th>
<th>Case A</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>COP [-]</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Capacity [kW]</td>
<td>3-12</td>
<td>3-12</td>
</tr>
</tbody>
</table>

According to data from Energimyndigheten, the COP of an air-to-water heat pump is dependent on the outside temperature and the outlet temperature of the heat pump. The results showed that for low outside temperature the COP values decreased. (Energimyndigheten, 2014b) Therefore, in this study the variation for COP of the air-to-water heat pump was taken into consideration.
The air-to-water heat pump chosen in this study is an air-to-water heat pump called “Aeromax Plus”. The product has variable-speed drive. The 12 kW-size model of the heat pump was chosen. (Kingspan, 2011, p.6, 14) Table 4 shows information about this product that was gathered from Kingspan (2011) and used in this study.

<table>
<thead>
<tr>
<th>TES</th>
<th>Reference Case B</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP [-]</td>
<td>Max 3.94</td>
<td>Max 3.94</td>
</tr>
</tbody>
</table>

In the product sheet for the heat pump “Aeromax Plus” measured output and input values of the heat pump at different outdoor temperatures were provided. By interpolating and extrapolating these data points, a function for the variation of the COP for the air-to-water heat pump was created. This was done in Matlab using linear, piecewise interpolation and extrapolation. It was performed with Matlab’s built-in function \textit{Interp1}. The values of COP achieved using this procedure can be seen in figure 2.

The average heat demand was calculated for each day and the capacity of the heat pump was set to these calculated values. This meant that the capacity of the heat pump varied with each day. In the reference scenarios when the power produced by the heat pump exceeded the heat demand, the excess amount of power from the heat pump was considered to be lost from the system. For all hours, the heat pump covered as much as possible of the heat demand. Electrical heaters were back up for the hours when the heat demand exceeded the capacity of the heat pump. The COP value of electrical heaters can be in the range of 0.8-0.99 (Stafor, n.d.). The COP value of the electrical heaters in study was chosen to be 1.

3.1.3 Dimensioning of TES

After the heat demand curve was calculated and modelling of the heating systems for the reference scenarios was performed, the size of the TES unit was calculated. The thermal energy storage water tank was dimensioned from the largest peak in the heat demand curve of the household that exceeded the heat pump capacity. This peak equaled a certain amount of energy, \(Q_{\text{dim}}\) in kilowatthours. \(Q_{\text{dim}}\) equaled the area

\[
\begin{align*}
\text{Figure 2: Interpolated and extrapolated values of COP based on data points from product sheet of heat pump “Aeromax Plus”}
\end{align*}
\]
under the heat demand curve minus the capacity of the heat pump. The area of the peak was calculated using trapezoidal numerical integration. It was done using Matlab’s built-in function Trapz. \(Q_{\text{dim}}\) needed to be converted into the unit kilojoules. The unit conversion was performed by multiplying \(Q_{\text{dim}}\) with 3600 seconds and \(Q_{\text{dimkJ}}\) was acquired. The mass of water needed in the tank to be able to store this amount of energy was calculated using the equation (8). The heat storage was assumed to be adiabatic, i.e. the water tank had no heat losses to the environment.

\[
Q_{\text{dimkJ}} = mc_p\Delta T
\]  

(8)

Where \(m\) is the mass of water, \(c_p\) the specific heat of water and \(\Delta T\) the difference in inlet and outlet temperature of the water tank. In 2016, Renaldi, Kiprakis and Friedrich performed calculations on a set up similar to this study, coupling a heat pump with a water tank. In that study, \(\Delta T\) was set to 10 Kelvin (Renaldi, Kiprakis & Friedrich, 2016). Due to the similarities of the heating system set up, \(\Delta T\) was assumed to 10 Kelvin in this study. The inlet temperature of the water tank was set to 35 deg C as this was the outlet temperature of the air-to-water heat pump for the specific values of COP chosen (Kingspan, 2011, p.7). This meant that the outlet temperature of the water tank was 45 deg C.

Finally, the volume \(v\) of water could be calculated from equation (9), which uses the mass and density of water.

\[
v = \frac{m}{\rho}
\]

(9)

All thermodynamic data for water in the TES tank was retrieved from the book “Heat and Mass Transfer Fundamentals & Applications”. The quantities used were density and specific heat. All properties were read at atmospheric pressure. The properties of water were taken at an average value in the temperature interval 35-45 deg C, i.e. the average of the chosen inlet and outlet temperature of the water tank, and are summarized in table 5. (Cengel & Ghajar, 2015, p.918)

<table>
<thead>
<tr>
<th></th>
<th>Density (\rho) [(\text{kg/m}^3)]</th>
<th>Specific heat (C_p) [(\text{kJ/kgK})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (40 deg C)</td>
<td>992.1</td>
<td>4.179</td>
</tr>
</tbody>
</table>

### 3.1.4 Coupling of TES with heat pump and criteria selection

As mentioned previously in case A, a ground source heat pump was used and in case B an air-to-water heat pump was used. The heat pump in each case heated the water in the tank using a coil heat exchanger. The power produced by the heat pump during the valley hours was used to charge the TES unit. The amount of energy stored in the TES unit was then used in hours with a heat demand that exceeded the power produced by the heat pump. Valley hours were defined differently in the calculations using different criteria.

In one criteria selection, valley hours were defined as hours whenever the output of the heat pump exceeded the heat demand (i.e. there was a surplus of heat) and the electricity price dropped below the average electricity price for the week studied. In the second criteria selection, valley hours were defined as hours whenever the output of the heat pump exceeded the heat demand, regardless of the electricity price. For both criteria selection, a COP criterion was applied to the air-to-water heat pump. This criterion defined valley hours as hours whenever the COP value of the air-to-water heat pump exceeded the average value of the COP for the whole week. There was no such criterion for the ground source heat pump since the COP value of that heat pump was considered to be constant.

Data of electricity prices for the week studied was retrieved from Nord Pool (Nord Pool, n.d.). These values do not include taxes. According to Vattenfall the tax on electricity including value-added tax is 0.4138 SEK/kWh for 2018 (Vattenfall, n.d.a). The taxes were then added to the hourly electricity prices from Nord Pool and the values can be found in Appendix 2. Then an average electricity price was calculated to be approximately 0.956 SEK/kWh.
3.1.5 Economical calculations

For this part of calculation the hourly price for electricity including taxes was used, see Appendix 2. For both
reference scenarios the hourly electricity cost for the household was calculated in different ways depending
on the heat demand. If the heat demand exceeded the capacity of the heat pump, the electricity cost was
calculated as the cost for electricity needed for the heat pump and electricity purchased for the electrical
heaters to cover the gap. If the capacity of the heat pump exceeded the heat demand, the only cost was the
electricity needed for the heat pump. The total electricity bill for the household that week was the sum of
all hourly electricity costs.

In both scenarios with a TES unit installed, the electricity cost was once again calculated differently
depending on the heat demand and the amount of energy stored in the TES unit. When the heat demand
exceeded the total heat produced by the heat pump and energy stored in the water tank, the hourly cost
was the electricity needed for the heat pump and the additional electricity for the electrical heaters to cover
the gap. Otherwise the hourly price was just the electricity needed for the heat pump.

3.1.6 Energy savings calculations

In this part of the calculations, the hourly energy demand was analysed. For case A, with and without the
electricity price criterion applied, energy was stored in the TES-unit during valley hours. The amount of
energy from the TES unit which was used in peak hours, to cover the gap between the demand and supply
of the heat pump, was then summarised for the week studied. Note that this was not necessarily all of the
energy that was stored in the TES.

The amount of electricity needed for the heat pump to charge the TES unit with that amount of
energy could be calculated by dividing the used amount of energy by the COP value of the ground source
heat pump, according to equation 6. For comparison with the reference case A, the amount of electricity
needed by the electrical heaters to cover this energy demand was equal to the energy demand. This was
because the electrical heaters had a COP of 1. Thus, the savings in electricity consumption were examined
when comparing the cases with their respective reference cases. Note that whenever the term “electricity
consumption for peaks” is used in the study, this is referring to the peaks of heat demand above the heat
pump’s capacity that are covered by the TES unit and would in the reference cases be covered by electrical
heaters.

For case B, with and without the electricity price criterion applied, the same strategy was used
but the only difference was that the COP value had an hourly variation. The amount of electricity needed
for the heat pump to charge the TES unit with that amount of energy could be calculated by dividing the
used amount of energy by the COP values of the air-to-water heat pump, according to equation 6. For
comparison with the reference case B, the amount of electricity needed by the electrical heaters to cover this
energy demand was equal to the energy demand. This was because the electrical heaters had a COP of 1.

4 Results

4.1 Household heat demand

The heat demand curve of the household and outdoor temperature for the week studied is shown in figure
3. The heat demand curve has a periodical look, which is expected since the heat demand is dependent on
the outdoor temperature, which varies in a similar way. The largest heat demand during the whole week is
around 10.45 kW and appears at approximately hour 72. The lowest heat demand is approximately 5.8 kW
and occurs in the later part of the week, around hour 158, where the outdoor temperature is approximately
-1 degrees. There are two large peaks in the heat demand, both of which exceed a heat demand of 10 kW.
The first peak exceeding 10 kW occurs approximately between hours 70 to 75, where the mean outdoor
temperature is -19 degrees, whilst the second one occurs between hours 125 to 130 with an average outdoor
temperature around -18 degrees. As it could be seen in the graphs these peaks with the lowest temperatures
during the week.
Figure 3: Variation of the household’s heat demand and the outdoor temperature during the week.

4.2 TES unit

The red curve in figure 4 shows the heat pump output. The areas between the heat demand and heat pump for hours when energy demand exceeds heat pump, is the amount of energy that is desired to be covered by the thermal energy storage unit. The shaded area shows the area of the biggest peak, which in this case was used to dimension the TES unit. Table 6 shows the maximum capacity of the tank to be approximately 18 kWh, which is equal to the value of the shaded area. To store this amount of energy in the TES unit the tank would need to be able to contain approximately 1,56 m³, or 1561.6 litres, of water.

Figure 4: Variation of the heat demand and heat pump capacity during the week. The TES unit was dimensioned from the area of the peak marked with blue lines.
### Table 6: Capacity and dimensions of the TES unit (water tank)

<table>
<thead>
<tr>
<th>Maximum capacity [kWh]</th>
<th>Maximum water mass [kg]</th>
<th>Maximum water volume [dm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.9848</td>
<td>1549.3</td>
<td>1561.6</td>
</tr>
</tbody>
</table>

#### 4.3 Ground source heat pump

##### 4.3.1 Case A with reference scenario - with electricity price criterion

In figure 5 a summary of the week for case A, with the electricity price criterion applied, is shown. The black line shows the amount of accumulated energy in the TES unit in kilowatthours and how it changes over the course of the week. The green line shows the hourly variation of the electricity price, including tax and VAT, for the week studied.

As can be seen in figure 5, the TES unit is for the first time charged by the heat pump during hour 10. During this time the capacity of the heat pump exceeds the heat demand of the household and the electricity price drops below the average electricity price for the week, 0.956 SEK/kWh. The TES then discharges around hour 20. This is because the heat demand of the household exceeds the capacity of the heat pump during this time. The energy from the TES is used to cover as much as possible of the heat demand that the heat pump is unable to cover. The same pattern is seen for the rest of the week, as expected from the modelling of the TES system with the heat pump.

In the middle of the week between hours 75 to 110 the heat pump does not charge the TES unit due to the high electricity price during these hours. As it is shown in figure 5 there is a maximum electricity price of around 3 SEK/kWh occurring at hour 80. Later in the week studied there is a high amount of energy that is stored in the TES unit. Low electricity price and heat pump capacity exceeding the heat demand of the household in these hours is the reason for this high amount of storage. However the amount of energy stored in the TES unit does not exceed the maximum capacity for the water tank. As it can be seen in figure 5 the maximum energy stored in the TES unit is approximately 15 kWh.

![Accumulated energy in TES relative electricity price, heat pump and heat demand](image)

**Figure 5:** Variation over the week of accumulated energy in the TES unit relative the electricity price, heat pump and heat demand of the household for case A with electricity price criterion applied.

In figure 6 two graphs are shown: the blue graph is the electricity cost during each hour for the reference scenario and the dashed line is the electricity cost during each hour for case A, with electricity price...
criterion applied. The economical savings for the week studied is the difference between these two graphs. That means for hours where the electricity cost for these two scenarios is equal the graphs overlap and there are no economical savings.

For example, the largest cost during the week occurs around hour 80 and there are no savings around this hour for case A, with the electricity price criterion. Around hour 80 is also where the electricity price is at its highest, as seen in figure 5. The savings occur when the TES unit is discharging. For example, there are savings around hour 25, 50, 70, 120 and 150.

It is valuable to note that for the reference scenario with no TES system, during hours with a lower heat demand than the power produced by the heat pump, the same amount of electricity was consumed for the heat pump operation as case A. The excess amount of power was in case A used to charge the TES unit but was lost in the reference scenario. This is applied for case B as well.

**Figure 6:** The households’ electricity costs each hour for reference case A and case A with electricity price criterion applied.

### 4.3.2 Case A with reference scenario - without electricity price criterion

In figure 7 a summary of the week for case A, without the electricity price criterion applied, is shown. As can be seen the TES unit is charged more often in comparison to the figure 5. This is due to neglected electricity criterion here. The heat pump is charging the TES unit whenever the heat demand is lower than the power produced by the heat pump. For example, in contrast to case A with the electricity criterion applied, the heat pump now charges the TES unit around hours 75 to 110.

It is noted that the amount of energy stored in the TES unit does not exceed the maximum capacity for the water tank. As it can be seen in figure 7 the maximum energy stored in the TES unit is approximately 16 kWh.
As can be seen in figure 8 there are savings in case A, without electricity price criterion applied, in comparison to reference case A. The savings occur around the same hours as for case A with the electricity price criterion applied. However, the savings are larger and there are now savings occurring around hour 100, which did not happen for case A with the electricity price criterion applied. Furthermore, there are still no savings around hour 80 where the electricity cost is the highest during the week.

**Figure 8:** The households’ electricity costs each hour for reference case A and case A without electricity price criterion applied.
4.3.3 Energy and economical savings case A

In table 7 a summary for the total electricity cost and the electricity consumption for peaks for case A and the reference scenario are gathered. In both criteria selections for case A the results show that there are economical and energy saving opportunities. The savings are higher for the case without electricity price criterion, for both electricity cost and electricity consumption for peaks. This was because without the electricity criterion applied, the heat pump could charge the TES unit more often and a higher amount of energy was stored in the TES unit. This means that the TES system was able to shift more peaks in the heat demand.

<table>
<thead>
<tr>
<th></th>
<th>Electricity cost [SEK]</th>
<th>Electricity consumption for peaks [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case A</td>
<td>312.8392</td>
<td>32.0683</td>
</tr>
<tr>
<td>Case A - with electricity price criterion</td>
<td>286.1032</td>
<td>6.4137</td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td><strong>26.7359</strong></td>
<td><strong>25.6546</strong></td>
</tr>
<tr>
<td>Reference case A</td>
<td>312.8392</td>
<td>47.9521</td>
</tr>
<tr>
<td>Case A - without electricity price criterion</td>
<td>271.6598</td>
<td>9.5904</td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td><strong>41.1793</strong></td>
<td><strong>38.3617</strong></td>
</tr>
</tbody>
</table>

4.4 Air-to-water heat pump

4.4.1 Case B with reference scenario - with electricity price criterion

In figure 9 a summary of the week for case B, with the electricity price and COP variation criteria applied, is shown. The black line shows the amount of accumulated energy in the TES unit in kilowatthours and how it changes over the course of the week. The green line shows the hourly variation of the electricity price, including tax and VAT, for the week studied. The yellow line shows the hourly variation of COP value of the air-to-water heat pump.

As can be seen in figure 9, the TES unit is for the first time charged by the heat pump during hour 10. During this time the capacity of the heat pump exceeds the heat demand of the household, the electricity price drops below the average electricity price, 0.956 SEK/kWh, and the COP value is above the average COP value, 2.9433, for the week. The TES then discharges around hour 20. This is because the heat demand of the household exceeds the capacity of the heat pump during this time. The same pattern is seen for the rest of the week, as expected from the modelling of the TES system with the heat pump.

Similar to case A with electricity price criterion applied, the heat pump does not charge the TES unit in the middle of the week between hours 75 to 110. This is mainly because of the high electricity price during those hours, as well as the COP value occasionally dropping below 2.9433. As shown in figure 9 there is a maximum electricity price of around 3 SEK/kWh occurring at hour 80. Later in the week studied there is a high amount of energy that is stored in the TES unit. Low electricity price, COP above the average value and heat pump capacity exceeding the heat demand of the household in these hours is the reason for this high amount of storage. However the amount of energy stored in the TES unit does not exceed the maximum capacity for the water tank. As it can be seen in figure 9 the maximum energy stored in TES unit during the week is approximately 15 kWh.
Figure 9: Variation over the week of accumulated energy in the TES unit relative the electricity price, heat pump and heat demand of the household for case B with electricity price criterion applied.

In figure 10 two graphs are shown; the blue graph is the electricity cost during each hour for the reference scenario and the dashed line is the electricity cost during each hour for case B, with electricity price criterion applied. The economical savings for the week studied is the difference between these two graphs. That means for hours where the electricity cost for these two scenarios is equal the graphs overlap and there are no economical savings. These graphs overlap each other more often in comparison to the case A with the electricity price criterion applied. Which means the total economical savings is less in this case.

Similar to case A the largest cost during the week occurs around hour 80 and there are no savings around this hour for case B, with the electricity price criterion. Around hour 80 is also where the electricity price is at its highest, as seen in 9. The savings occur when the TES unit is discharging. For example, there are savings around hour 25, 70, 120 and 150.
4.4.2 Case B with reference scenario - without electricity price criterion

In figure 11 a summary of the week for case B, without the electricity price criterion applied, is shown. As can be seen the TES unit is charged more often in comparison to the figure 9. This is due to the neglected electricity criterion here. The heat pump is charging the TES unit whenever the heat demand is lower than the power produced by the heat pump and the COP value is above the average value for the week studied. For example, in contrast to case B with the electricity criterion applied, the heat pump now charges the TES unit around hours 82 to 110. However, the heat pump still does not charge the TES unit around hours 75-81. This because of the COP value of the air-to-water heat pump falling below the average COP value for the week.

It is noted that the amount of energy stored in the TES unit does not exceed the maximum capacity for the water tank. As it can be seen in figure 11 the maximum energy stored in TES unit is approximately 16 kWh.
Figure 11: Variation over the week of accumulated energy in the TES unit relative the electricity price, heat pump and heat demand of the household for case B without electricity price criterion applied.

As can be seen in figure 12 there are savings in case B, without electricity price criterion applied, in comparison to reference case B. The savings occur around the same hours as for case B with the electricity price criterion applied. However, the savings are larger and there are now savings occurring around hour 100, which did not happen for case B with the electricity price criterion applied. Furthermore, there are still no savings around hour 80 where the electricity cost is the highest during the week.

Figure 12: The households’ electricity costs each hour for reference case B and case B without electricity price criterion applied.
4.4.3 Energy and economical savings case B

In the table 8 a summary for the total electricity cost and the electricity consumption for peaks for case B and the reference scenario are gathered. In both criteria selections for case B the results show that there are electricity and energy saving opportunities. The savings are higher for the case without electricity price criterion, for both electricity cost and electricity consumption for peaks. This was because without the electricity criterion applied, the heat pump could charge the TES unit more often and a higher amount of energy was stored in the TES unit. This means that the TES system was able to shift more peaks in the heat demand.

Table 8: Energy and economical savings for case B

<table>
<thead>
<tr>
<th></th>
<th>Electricity cost [SEK]</th>
<th>Electricity consumption for peaks [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case B</td>
<td>494.4364</td>
<td>28.6171</td>
</tr>
<tr>
<td>Case B - with electricity price criterion</td>
<td>470.5759</td>
<td>9.9719</td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td>23.8603</td>
<td>18.6451</td>
</tr>
<tr>
<td>Reference case B</td>
<td>494.4364</td>
<td>42.5603</td>
</tr>
<tr>
<td>Case B - without electricity price criterion</td>
<td>457.7076</td>
<td>14.8800</td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td>36.7287</td>
<td>27.6803</td>
</tr>
</tbody>
</table>

4.5 Summary

All of the cases showed that there are savings both in terms of economy and energy, both with and without the electricity price criterion applied. In table 9 the results in terms of maximum and minimum savings have been summarized. It shows that case A without electricity price criterion, which includes a ground source heat pump and a TES unit, gives the maximum saving both economical and energy-wise. The minimum savings are for case B with electricity price criterion, which includes an air-to-water heat pump and a TES unit. This is expected since the COP values of the air-to-water heat pump are smaller than the ground source heat pump and because case B is most limited with the electricity price criterion applied. Similarly, the results for case A without the electricity price criterion applied are expected since the charging of the TES unit is not limited by anything except heat demand and heat pump capacity for the household. However, it is also noted that for both case A and B, the savings are maximized when the electricity price criterion is neglected.

Table 9: Energy and economical savings for case A

<table>
<thead>
<tr>
<th></th>
<th>Economy [SEK]</th>
<th>Electricity [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum savings scenario</td>
<td>Case A - without electricity price criterion</td>
<td>Case A - without electricity price criterion</td>
</tr>
<tr>
<td>Minimum savings scenario</td>
<td>Case B - with electricity price criterion</td>
<td>Case B - with electricity price criterion</td>
</tr>
</tbody>
</table>

5 Discussion

All of the cases indicated that there is a savings potential, both with and without the electricity price criterion applied. The results showed that case A, without the electricity criterion applied, gave the most amount of savings in terms of both energy and economy. Case B, with the electricity criterion applied, gave the least amount of savings both in terms of energy and economy. For both case A and B, the savings were maximized when the electricity price criterion was neglected.

One thing that all of the results had in common was that at the end of the week the TES unit never completely discharged to zero. There was approximately 14 kWh left in the TES unit at the very last hour of the week for each of the cases. This could indicate that the TES system with the heat pump
configuration is not effectively used at the end of the week since there is unused energy left in the tank. However, depending on the heat demand the week following the one examined in this study. For example, this unused storage could be useful if there is a high heat demand the coming week.

For both case A and B the savings were maximized when the electricity price criterion was neglected, as mentioned previously. However, case A gave larger savings when comparing the two cases without the electricity price criterion applied. The main difference between the two cases was the type of heat pump used and their COP values. In case A a ground source heat pump was used and in case B an air-to-water heat pump was used. The ground source heat pump in this study was assumed to have a constant COP value of 5 while the air-to-water heat pump was assumed to have a mean COP value is 2.9433. This means that for the same amount of electricity more power was produced in case A with the ground source heat pump since the output of a heat pump is proportional to the COP value. It is very likely that this has had an impact on the results and should be kept in mind when comparing the two cases with each other.

Another parameter that could have had an impact on the results is the COP criterion, which was only and always applied to case B. This criterion limited the charging possibilities of the air-to-water heat pump, in comparison to the ground source heat pump, as the air-to-water heat pump would charge only if the COP value was high enough. The impact of the COP criterion can be seen when comparing the black graphs in figures 5 and 9 and figures 7 and 11; in all of the graphs for case B the TES was charged less than in case A. Thus, the TES system in case B was able to shift fewer hours than the TES system in case A.

A general comparison between the ground source heat pump and the air-to-water heat pump indicate that due to the higher COP value the ground source heat pump (case A) is a better option if the goal is to maximize the savings. However, it should be noted that the initial investment cost, which have been neglected in this study, for a ground source heat pump in a single-family household is higher than the initial investment cost for an air-to-water heat pump. Thus, the choice the heat pump is complex and not always based on one factor, like the COP value.

The graphs in figure 6, 8, 10 and 12, show the difference in hourly electricity costs between each reference case and their respective case. These graphs show that there are indeed economical savings at specific hours during the week. More hours with economical savings occurred when the electricity price criterion was neglected. This applied for both case A and case B. For example, for both cases with the electricity price criterion neglected, there were more hours with economical savings which can be explained with the fact that the heat pump was able to charge the TES unit more freely without the electricity price criterion. Consequently, this allowed the TES unit to cover more peaks in the heat demand.

Even though both cases, with and without the electricity price criterion applied, indicated that there are savings in terms of both economy and energy, the calculations without the electricity price criterion applied might be more realistic. In reality, a surplus output from the heat pump might be the only criterion for the TES charging process to commence.

Furthermore, another important aspect is the magnitude of the savings. The largest savings acquired in this study were 41.1793 SEK and 38.3617 kWh. Now, these figures could have a large impact when considering both a larger time and spatial perspective; for one household these savings may be influential when considering a time span of an entire year. Moreover, these savings may be even more influential when extending the spatial perspective to include an entire neighbourhood of households. The economical savings may be of more concern to each private consumer whilst the energy savings could be in everyone’s interest when considering environmentally related objectives such as the The Energy Efficiency Directive.

The thermal energy storage technique used in this study was sensible storage with a tank as a storage container and water as the storage medium. The water tank was calculated to have a maximum volume capacity of approximately 1561.6 liter of water. This size is among the common size for these types of tanks, which as mentioned previously could be in a range of 100 dm$^3$ to 5m$^3$. Thus, it is possible that the water tank in this study could be suitable for a single-family household, at least in terms of space.

In 2017 Yin et al. performed a study in which energy savings calculations were performed for electricity consumption in a case similar to the cases in this study with the exception that Yin et al. also coupled solar cells with the heating system. The result from Yin et al. indicates saving opportunities for a winter day. In this study a weekly saving during wintertime for two main setups of the heating systems with different criteria selections has been calculated and the results shows savings opportunities. The results
show different amount of savings depending on the heat pump type due to theirs different COP value and also the different criteria applied. Regardless of criteria selections both studies indicate saving potential for thermal energy applications in residential buildings.

In a study performed by Renaldi, Kiprakis & Friedrich in 2016 a similar heating system configuration was studied in the United Kingdom. In that study the initial cost for the heating system was considered in the economical calculations, in contrast to this study. Renaldi, Kiprakis & Friedrich’s study indicate an economical savings potential in using TES units in residential buildings. Their result harmonizes with the results yielded in this study.

5.1 Sources of error

The study has several limitations and sources of error. Firstly, considering the limitations of the model. In this study it has been assumed that exactly the amount of energy stored in the TES unit can be used whenever needed in the future, without heat losses from the water tank. In reality there are losses from the water tank and thus it is not fully accurate to do this assumption. On the other hand, the results show that the stored energy usually will be used during a one day period except for the last hours of the week when the storage is high because of the low heat demand. The heat losses might be more significant in the case of a more long term storage, longer than one day.

Furthermore, the TES system in this study is based on data from the past, i.e. the calculations were performed for a particular week in the past but not in real-time. Thus, the heat demand of the household for that particular week was already known and the capacity of the heat pump could on a daily basis be set to the average heat demand of the particular day. For this system to work in reality, prediction based on previous data about the outdoor temperature would be necessary.

Another assumption is the heat gain from the sun that was not considered in the heat demand calculations. Even though the solar irradiation is fairly low during wintertime in Sweden, it would be more correct to include the heat gain from the sun as it is nonzero and therefore could impact the results. Furthermore, the internal heat gains from appliances and humans in the household were neglected. As mentioned previously, the internal heat gains in single-family households are usually negligible and were neglected in this study. However, it would be more accurate to include this term in the heat demand calculations.

Moreover, the COP values for the air-to-water heat pump have been calculated by extrapolating and interpolating data values from the heat pump’s product sheet. A linear relation was assumed, which might not be the case in reality. Thus, the calculated COP values of the air-to-water heat pump could be a source of error. Furthermore, the assumption that the ground source heat pump had a constant COP could also induce errors since there might be small variations in the temperature below ground, which is the low temperature side of the heat pump.

In this study a week during late February in Sweden was analysed, but to more thoroughly examine the economical and energy potentials of installing a TES unit system in residential households other seasons should be analysed too. This could change the result due to higher temperatures and solar heat gain during summer and spring time. However, there might be a potential for installing a TES unit in residential households in Sweden because of the cold climate in North causing a high heat demand in households.

Another important point when analysing other seasons, other than temperature variation, is the electricity price variation which could impact the result of the economical potential calculations. Disregarding the installation and upkeep costs, this study indicates that there could be economical benefit. However, to have a more accurate and reliable result these calculations should be performed for several seasons and include more thorough economical calculations that cover initial costs, upkeep costs and apply a payback method.

5.2 Sustainability relevance

As mentioned previously, goal number fifteen in Environmental Objectives, “A Good Built Environment”, states that energy in the residential sector should be used in an effective manner by year 2020. This study
indicates that there could be a potential for more effective use of energy in residential buildings with the help of TES units. This illustrates the significance of this study, as TES systems could aid in achieving this Environmental Objective and achieve sustainable use of energy in the residential sector.

The results showed that there were energy savings in heating applications when coupling a heat pump with a TES unit; a lower amount of electricity would be purchased by the household compared to the case with no TES unit. This decrease in energy demand could impact the house’s score on SGBC’s assessment in the certification system Miljöbyggnad, where a lower energy demand would yield a higher score. This could have several possible effects, a higher score in Miljöbyggnad could for example increase the economical value of the house.

Another important results is that the TES unit system could give an opportunity to use the renewable energy sources more efficient. For example the ground source heat pump uses the ground temperature for heating the household which is a renewable source. Normally, when the energy demand is lower than the power produced by the heat pump some of the output power from the heat pump is going lost but with a heat pump and a TES unit configuration this output power could charge the TES unit. This amount of energy stored in TES could then be used in the future for household heating when the heat demand exceeds the capacity of the heat pump. This is a step forward in sustainable development.

6 Conclusions

The aim of this project was to show if there are economic and energy-efficiency potentials for configuring thermal energy storage units in single family houses in Sweden. With the help of economic and energy calculations this study has produced results that indicate that there are both economic and energy-efficiency potentials for a configuration of a TES unit with a heat pump.

The results show that there were savings for case A with the electricity price criterion applied, which included a ground source heat pump coupled with a TES unit. In economic terms, these savings equaled 26.7359 and the savings in electricity consumptions for peaks equaled 25.6546 kWh. Case B, with the electricity price criterion applied, which included an air-to-water heat pump coupled with a TES unit, yielded the lowest amount of savings in both economic terms and electricity consumption for peaks. The savings for case B with the electricity price criterion applied were 23.8603 SEK and 18.6451 kWh respectively.

It was found that the savings were maximized for case A without the electricity price criterion applied, where a ground source heat pump was coupled with a TES unit. In economic terms, these savings equaled 41.1793 SEK and the savings in electricity consumptions for peaks equaled 38.3617 kWh. Case B, without the electricity price criterion applied also yielded savings, both in terms of economy and electricity consumption for peaks. The savings for case B without the electricity price criterion applied were 36.7287 SEK and 27.6803 kWh respectively.

Furthermore, the results indicate that there is a potential for configuring TES units even when disregarding the electricity price criterion for charging the TES unit with the heat pump. Neglecting the electricity price criterion may even yield more savings than applying the criterion.

Finally, there is a need for further research in the field of thermal energy storage applications for residential buildings. More accurate calculations and models need to be applied, as well as a consideration for seasonal variation.

7 Reference list


8 Appendices

8.1 Appendix 1. Hourly outdoor temperatures in Sollentuna for each day in degrees Celsius

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8.2 Appendix 2. Hourly electricity prices including taxes for each day in SEK/kWh

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8.3 Appendix 3. Matlab code for case A with reference case

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### Reference Case A and Case A (ground source HP)

#### Table of Contents

- Hourly outdoor temperature and electricity prices ........................................................... 1
- Thermodynamical data of household .................................................................................. 1
- Heat demand calculations .................................................................................................. 2
- Reference Case A ................................................................................................................. 3
- Dimensioning of TES (water tank) ..................................................................................... 3
- Case A ............................................................................................................................... 4
- Energy and economical savings .......................................................................................... 7

---

### Hourly outdoor temperature and electricity prices

```
Tout = xlsread('Tout.xls'); % hourly outdoor temperature [C]
Elcost = xlsread('Electricitycost.xls'); % hourly electricity cost [SEK/kWh]
```

### Thermodynamical data of household

```
Uwalls = 0.6/1000; % [kW/(K*m^2)]
Awalls = 100; % [m^2]

Uroof = 0.29/1000; % [kW/(K*m^2)]
Aroof = 160; % [m^2]

Ufloor = 0.28/1000; % [kW/(K*m^2)]
Afloor = 125; % [m^2]

Uwindows = 2.34/1000; % [kW/(K*m^2)]
Awindows = 28; % [m^2]

Udoor = 3/1000; % [kW/(K*m^2)]
Adoor = 4; % [m^2]

% Thermodynamical data of air at T = 21 C
rhoair = 1.324; % [kg/m^3]
Cpair = 1.006; % [kJ/(kg*K)]

% Thermodynamical data of water at Tavg = (TinTES + TouTES) /2 [C]
Cph2o = 4.179; % [kJ/(kg*K)]
rhoh2o = 992.1; % [kg/m^3]
```
% Ventilation flow V: 0.35 litres/s and square metre floor area
V = (0.35*Afloor)/(10^3); %[m^3/s]

% Indoor temperature Tin: desired constant indoor temperature
Tin = 21; %[C]

% Average annual outdoor temperature
Toutavg = 6.1; %[C]

% Heat pump data
COP = 5; %[-] coefficient of performance of HP. For ground source HP
it is assumed to be constant here.

Heat demand calculations

Qheatdemand = []; % vector to store heat demand
hour = [1:length(Tout)]; % produces a vector containing all the hours
of the week

for index = 1:length(hour) % for-loop for calculating the heat demand
    Qheatdemand(index) = V*rhoair*Cpair*(Tin-Tout(index)) + (Tin-
Tout(index))*((Uwalls*Awalls) + ...
+ (Uwindows*Awindows) + (Uroof*Aroof) + (Udoor*Adoor)) +
(Ufloor*Afloor)*(Tin - (Toutavg + 3));
end

figure
plot(hour, Qheatdemand, 'b', hour, Tout)
title('Household heat demand and outdoor temperature')
hold on
xlabel('Hours [h]')
legend('Heat demand [kW]', 'Outdoor temperature [deg C]')
grid on
grid minor

QHP = []; % vector to store output of heat pump
ElHP = []; % vector to store electricity need of heat pump
for day=1:7 % for-loop to calculate the average heat demand per day
    Day = Qheatdemand((1:24) + (day-1)*24);
    QavgDay = mean(Day);
    QHP = [QHP QavgDay*ones(1,24)];
end
ElHP = QHP/COP; % [kW] electricity needed for the heat pump
Reference Case A and Case A (ground source HP)

Reference Case A

CostRefA = []; % vector to store the hourly cost of electricity
for index = 1:length(hour)
    if Qheatdemand(index) > QHP(index)
        CostRefA(index) = ElHP(index)*Elcost(index) + (Qheatdemand(index)-QHP(index))*Elcost(index);
    else
        CostRefA(index) = ElHP(index)*Elcost(index);
    end
end

Dimensioning of TES (water tank)

The following is a procedure to find the hours/x values for the largest peak of the week. The peak is divided into two smaller areas. These x values are later used by function trapz to calculate the total area of the peak.

limit1 = QHP(24*4.5);
limit2 = QHP(24*5.5);
I1 = find(Qheatdemand>limit1);
I2 = find(Qheatdemand==limit2);
a = 117;
b = 121;
c = 121;
d = 132;
Reference Case A and Case A (ground source HP)

Area1 = trapz(hour(a:b), Qheatdemand(a:b)) - (b-a)*limit1;
Area2 = trapz(hour(c:d), Qheatdemand(c:d)) - (d-c)*limit2;
Qdim = Area1 + Area2;

% We know 1 Wh is 3600 J. We convert Qshift [kWh] to joules
QdimkJ = Qdim*3600; \(\text{[kJ]}\)

% TES temperature design
TinTES = 25; \(\text{[C]}\) inlet temperature
ToutTES = 35; \(\text{[C]}\) outlet temperature
deltaT = ToutTES - TinTES; \(\text{[C]}\)

% We know Qdim = mass*(specific heat)*(temperature difference) for the TES
mH2O = QdimkJ/(Cph2o*deltaT); \(\text{[kg]}\) amount of water needed to store Qshift
VH2O = (mH2O/rhoh2o)*1000; \(\text{[litres]}\) volume of water needed to store Qshift

Case A

Elcostmax = mean(Elcost); \(\text{[SEK/kWh]}\) limit for what is classified as "high" electricity cost per hour

CostA = []; \% vector to store the hourly cost of electricity
TES = []; \% vector to store the TES charge
UsedA = []; \% vector to store the amount of energy taken from the TES

for index = 1:length(hour) \% for-loop for running the TES-HP system
    surplus = (QHP(index) - Qheatdemand(index)); \% the difference between the QHP and Qheatload
    if Qheatdemand(index) > QHP(index) \% HP doesnt cover heat demand
        if index == 1 \| TES(index-1) == 0 \% First hour OR TES is empty
            TES(index) = 0;
            CostA(index) = ElHP(index)*Elcost(index) + (-surplus)*Elcost(index);
        elseif TES(index-1) >= (-surplus) \% TES is able to cover rest that HP doesnt
            TES(index) = TES(index-1)-(-surplus);
            UsedA(index) = (-surplus);\% TES is able to cover rest that HP doesnt.
            CostA(index) = ElHP(index)*Elcost(index);
        elseif TES(index-1) < (-surplus) \% TES is unable to cover the rest that HP doesnt, buy electricity
            TES(index) = 0;
            UsedA(index) = TES(index-1);
            CostA(index) = ElHP(index)*Elcost(index) + ((-surplus)-TES(index-1))*Elcost(index);
        end
    elseif Qheatdemand(index) <= QHP(index) \% HP covers heat demand either perfectly or with surplus/excess
        UsedA(index) = TES(index-1);
        CostA(index) = ElHP(index)*Elcost(index) + ((-surplus)-TES(index-1))*Elcost(index);
    end
end
Reference Case A and
Case A (ground source HP)

if Elcost(index) <= Elcostmax % want to charge TES [REMOVE
    THIS ROW WHEN NEGLECTING THE ELECTRICITY PRICE CRITERION]
    if index == 1 % if first hour
        TES(index) = surplus;
    else % for all other hours
        TES(index) = surplus + TES(index-1);
    end
    if TES(index) > Qdim % this is to check if the energy we
        have stored is not larger than possible (Qdim)
        TES(index) = Qdim
    end
    CostA(index) = ElHP(index)*Elcost(index);
else %[REMOVE ROW 146-149 WHEN NEGLECTING THE ELECTRICITY
    PRICE CRITERION]
    TES(index) = TES(index-1); % we neither charge nor use TES
    CostA(index) = ElHP(index)*Elcost(index);
end
else
    error('this shouldnt happen') % to detect errors
end

figure
plot(hour, Qheatdemand, 'b', hour, QHP, 'r', hour, TES, 'k', hour,
    Elcost, 'g')
hold on
grid on
grid minor
legend( 'Heat demand [kW]', 'Heat pump [kW]', 'Accumulated energy in
    TES [kWh]', 'Electricity price [SEK/kWh]')
xlabel('Hours [h]')
title('Accumulated energy in TES relative electricity price, heat pump
    and heat demand')

figure
plot(CostRefA)
hold on
plot(CostA, '--')
legend('Electricity cost reference case A', 'Electricity cost case A')
xlabel('Hours [h]')
title('Electricity cost for case A with reference scenario - with
    electricity price criterion')
grid on
grid minor
Reference Case A and Case A (ground source HP)

**Accumulated energy in TES relative electricity price, heat pump and heat demand**

- Heat demand [kW]
- Heat pump [kW]
- Accumulated energy in TES [kWh]
- Electricity price [SEK/kWh]

**Electricity cost for case A with reference scenario - with electricity price criterion**

- Electricity cost reference case A
- Electricity cost case A
Energy and economical savings

Economical

\[
\text{TotCostRefA} = \text{sum(CostRefA)}; \quad [\text{SEK}] \quad \text{total cost for reference case A}
\]
\[
\text{TotCostA} = \text{sum(CostA)}; \quad [\text{SEK}] \quad \text{total cost of case A}
\]
\[
\text{SavingsA} = \text{TotCostRefA} - \text{TotCostA} \quad [\text{SEK}] \quad \text{difference between case A and reference case A}.
\]

% Energy
\[
\text{TESusedA} = \text{sum(UsedA)}; \quad [\text{J}] \quad \text{the total amount of energy that was used by the TES during the whole week}
\]
\[
\text{ElTESA} = \text{TESusedA}/\text{COP}; \quad [\text{W}] \quad \text{the electricity used by TES}
\]
\[
\text{ElrefA} = \text{TESusedA}; \quad [\text{W}] \quad \text{this is what the energy would amount to if electricity was used}
\]
\[
\text{ESavingsA} = \text{ElrefA} - \text{ElTESA} \quad [\text{W}] \quad \text{savings in purchased electricity}
\]

\[
\text{SavingsA} = 26.7359
\]

\[
\text{ESavingsA} = 25.6546
\]

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Appendix 4. Matlab code for case B with reference case

Reference case B and Case B (air source heat pump)

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Hourly outdoor temperature and electricity prices

Tout = xlsread(’Tout.xls’); % hourly outdoor temperature [C]
Elcost = xlsread(’Electricitycost.xls’); % hourly electricity cost [SEK/kWh]

Thermodynamical data of household

Uwalls = 0.6/1000; % [kW/(K*m^2)]
Awalls = 100; % [m^2]
Uroof = 0.29/1000; % [kW/(K*m^2)]
Aroof = 160; % [m^2]
Ufloor = 0.28/1000; % [kW/(K*m^2)]
Afloor = 125; % [m^2]
Uwindows = 2.34/1000; % [kW/(K*m^2)]
Awindows = 28; % [m^2]
Udoor = 3/1000; % [kW/(K*m^2)]
Adoor = 4; % [m^2]

% Thermodynamical data of air at T = 21 C
rha = 1.324; % [kg/m^3]
Cp = 1.006; % [kJ/(kg*K)]

% Thermodynamical data of water at Tavg = (TinTES + TouTES) /2 [C]
Cph2o = 4.179; % [kJ/(kg*K)]
rhoh2o = 992.1; % [kg/m^3]

% Ventilation flow V: 0.35 litres/s and square metre floor area
V = (0.35*Afloor)/(10^3); \([m^3/s]\)

% Indoor temperature Tin: desired constant indoor temperature
Tin = 21; \([C]\)

% Average annual outdoor temperature
Toutavg = 6.1; \([C]\)

% Heat pump
% In this case the COP of the heat pump will not be constant. It
% varies
% with the outside temperature. COP values for the heat pump will be
% interpolated/extrapolated with the help of data points from the
% chosen
% heat pump product sheet

**Heat demand calculations**

Qheatdemand = []; % vector to store heat demand
hour = [1:length(Tout)]; % produces a vector containing all the hours
of the week

for index = 1:length(hour) % for-loop for calculating the heat demand
    Qheatdemand(index) = V*rhoair*Cpair*(Tin-Tout(index)) + (Tin-
    Tout(index))*((Uwalls*Awalls) + ...
    + (Uwindows*Awindows) + (Uroof*Aroof) + (Udoor*Adoor)) +
    (Ufloor*Afloor)*(Tin - (Toutavg + 3));
end

figure
plot(hour, Qheatdemand, 'b', hour, Tout)
title('Household heat demand and outdoor temperature')
hold on
xlabel('Hours [h]')
legend('Heat demand [kW]', 'Outdoor temperature [deg C]')
grid on
grid minor

QHP = []; % vector to store output of heat pump
ElHP = []; % vector to store electricity need of heat pump

for day=1:7 % for-loop to calculate the average heat demand per day
    Day = Qheatdemand((1:24) + (day-1)*24);
    QavgDay = mean(Day);
    QHP = [QHP QavgDay*ones(1,24)];
end

COP = []; % for-loop to calculate the COP value of the HP at different
hours and outdoor temperatures

for index = 1:length(hour)
    COPproduct = [3.69 3.15 3.1 4.06]; % COP values at temperatures
    corresponding to Tlow; data from product sheet
    Tlow = [-3 0 2 7]; % outdoor temperature; data from product sheet
input = Tout(index); % the current temperature at which the COP will be evaluated
COP(index) = interp1(Tlow,COPproduct,input,'linear','extrap');
end
ElHP = QHP./COP; % [kW] electricity needed for the heat pump

Reference Case B

CostRefB = []; % vector to store the hourly cost of electricity
for index = 1:length(hour)
    if Qheatdemand(index) > QHP(index)
        CostRefB(index) = ElHP(index)*Elcost(index) + (Qheatdemand(index)-QHP(index))*Elcost(index);
    else
        CostRefB(index) = ElHP(index)*Elcost(index);
    end
end

Dimensioning of TES (water tank)

The following is a procedure to find the hours/x values for the largest peak of the week. The peak is divided into two smaller areas. These x values are lated use by function trapz to calculate the total area of the peak.

limit1 = QHP(24*4.5);
limit2 = QHP(24*5.5);
I1 = find(Qheatdemand>limit1);
I2 = find(QHP==limit2);
a = 117;
b = 121;
c = 121;
d = 132;
Area1 = trapz(hour(a:b), Qheatdemand(a:b)) - (b-a)*limit1;
Area2 = trapz(hour(c:d), Qheatdemand(c:d)) - (d-c)*limit2;
Qdim = Area1 + Area2; % [kWh]

% We know 1 Wh is 3600 J. We convert Qshift [kWh] to joules
QdimkJ = Qdim*3600; % [kJ]

% TES temperature design
TinTES = 25; % [°C] inlet temperature
ToutTES = 35; % [°C] outlet temperature
deltaT = ToutTES - TinTES; % [°C]

% We know Qdim = mass*(specific heat)*(temperature difference) for the TES
mH20 = QdimkJ/(Cph2o*deltaT); % [kg] amount of water needed to store Qshift
VH20 = (mH20/rhoh2o)*1000; % [litres] volume of water needed to store Qshift

Case B

Elcostmax = mean(Elcost); % [SEK/kWh] limit for what is classified as "high" electricity cost per hour
COPmin = mean(COP); % [-] limit for what is classified as "high" COP. Anything above and including COPmin is considered "high".

CostB = []; % vector to store the hourly cost of electricity
TES = []; % vector to store the TES charge
UsedB = []; % vector to store the amount of energy taken from the TES

for index = 1:length(hour) % for-loop for running the TES-HP system
    surplus = (QHP(index) - Qheatdemand(index)); % the difference between the QHP and Qheatload
    if Qheatdemand(index) > QHP(index) % HP doesn't cover heat demand
        if index == 1 || TES(index-1) == 0 % First hour OR TES is empty
            TES(index) = 0;
            CostB(index) = ElHP(index)*Elcost(index) + (-surplus)*Elcost(index);
        elseif TES(index-1) >= (-surplus) % TES is able to cover rest that HP doesn't
            TES(index) = TES(index-1)-(-surplus);
            UsedB(index) = (-surplus);
            CostB(index) = ElHP(index)*Elcost(index);
        elseif TES(index-1) < (-surplus) % TES is unable to cover the rest that HP doesn't, buy electricity
            TES(index) = (-surplus);
            UsedB(index) = (-surplus);
            CostB(index) = ElHP(index)*Elcost(index);  
        end
    end
end
Reference case B and Case B (air source heat pump)

$$\text{TES}(\text{index}) = 0;$$
$$\text{UsedB}(\text{index}) = \text{TES}(\text{index}-1);$$
$$\text{CostB}(\text{index}) = \text{ElHP}(\text{index}) \times \text{Elcost}(\text{index}) + ((-\text{surplus}) - \text{TES}(\text{index}-1)) \times \text{Elcost}(\text{index});$$

end

elseif \ Qheatdemand(\text{index}) \leq QHP(\text{index}) \% \ HP \ covers \ heat \ demand\ either \ perfectly \ or \ surplus/excess

if \ \text{Elcost}(\text{index}) \leq \text{Elcostmax} \ & \ COP(\text{index}) \geq \text{COPmin}; \% \ want\ to\ charge\ TES\ \ [\text{REMOVE} \ "\text{Elcost}(\text{index}) \leq \text{Elcostmax}" \ \text{WHEN \ NEGLECTING \ THE \ ELECTRICITY \ PRICE \ CRITERION}]

if \ \text{index} = 1 \% \ if \ first \ hour
$$\text{TES}(\text{index}) = \text{surplus};$$
else \% \ for \ all \ other \ hours
$$\text{TES}(\text{index}) = \text{surplus} + \text{TES}(\text{index}-1);$$
end

if \ \text{TES}(\text{index}) > Qdim \% \ this \ is \ to \ check \ if \ the \ energy \ we
have \ stored \ is \ not \ larger \ than \ possible \ (Qdim)
$$\text{TES}(\text{index}) = Qdim$$
end

\text{CostB}(\text{index}) = \text{ElHP}(\text{index}) \times \text{Elcost}(\text{index});$$

else
$$\text{TES}(\text{index}) = \text{TES}(\text{index}-1);$$ \% \ we \ neither \ charge \ nor \ use \ TES
$$\text{CostB}(\text{index}) = \text{ElHP}(\text{index}) \times \text{Elcost}(\text{index});$$

end

else
\text{error}(\"\text{this \ shouldnt \ happen}\") \% \ to \ detect \ errors
end

date
plot(hour, Qheatdemand, 'b', hour, QHP, 'r', hour, TES, 'k', hour, Elcost, 'g', hour, COP)
hold on
grid on
legend('Heat demand [kW]', 'Heat pump [kW]', 'Accumulated energy in TES [kWh]', 'Electricity price [SEK/kWh]', 'COP [-]')
xlabel('Hours [h]

title('Accumulated energy in TES relative electricity price, COP heat pump and heat demand')

figure
plot(CostRefB)
hold on
plot(CostB, '--')
legend('Electricity cost reference case B [SEK]', 'Electricity cost case B [SEK]')
xlabel('Hours [h]
title('Electricity cost for case B with reference scenario - with electricity price criterion')
grid on
grid minor
Reference case B and Case B (air source heat pump)

Cumulated energy in TES relative electricity price, COP heat pump and heat demand

Electricity cost for case B with reference scenario - with electricity price criterion
Reference case B and Case B (air source heat pump)

Energy and economical savings

Economical

\[
\text{TotCostRefB} = \text{sum(CostRefB)} \quad [\text{SEK}] \text{ total cost for reference case B}
\]

\[
\text{TotCostB} = \text{sum(CostB)} \quad [\text{SEK}] \text{ total cost of case B}
\]

\[
\text{SavingsB} = \text{TotCostRefB} - \text{TotCostB} \quad [\text{SEK}] \text{ difference between case B and reference case B}
\]

% Energy
\[
\text{ElTESB} = \text{sum((UsedB./COP))} \quad \% \text{ the electricity used by TES}
\]

\[
\text{ElrefB} = \text{sum(UsedB)} \quad \% \text{ this is what the energy would amount to if electricity was used}
\]

\[
\text{ESavingsB} = \text{ElrefB} - \text{ElTESB} \quad \% \text{ savings in purchased electricity}
\]

\[
\text{TotCostRefB} = 494.4362
\]

\[
\text{TotCostB} = 470.5759
\]

\[
\text{SavingsB} = 23.8603
\]

\[
\text{ESavingsB} = 18.6451
\]

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