Heating Energy Performance & LCC Analysis on Renovation Proposals of a Multi-Family Apartment Cluster

Stevson Sonny Widjaja, Yinxin Liu

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and numbers of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. Numbers of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 programs and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international program provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Jouri Kanters (Energy and Building Design)

Supervisor: Henrik Davidsson (Energy and Building Design), Erik Johansson (Energy and Building Design)

Keywords: Building energy consumption, building renovation, building envelop, heat pump, individual substation, life cycle cost

Thesis: EEBD – AEBM01 / 20

Abstract

The study was carried out to assess the energy performance of the buildings in a cluster located in Lund. The buildings were the projects of million homes program, built in the 1960s, and are in great need of renovation. Five retrofit techniques were proposed in the study. Improving the building envelop with insulation and windows, adding exhaust air heat pump, combining exhaust air heat pump, insulation, and windows, changing energy source to a ground source heat pump, and increasing district heating substation numbers for each building are considered in the study.

The study's goal is to assess the energy performance of the buildings with retrofitting strategies. Also, the life cycle cost analysis was carried out afterward to see the economic feasibility of each strategy. The results show that all the techniques help to decrease the total heating energy demand of the whole cluster. For the economic analysis, which strategy is more feasible depends on the period of time. It shows that regarding a 35-year period, the ground source heat pump has the most savings. And with a 50-year period, the combination of exhaust air heat pump and improved building envelop has the most savings.

Acknowledgments

We would like to express gratitude to our supervisors Henrik Davidsson, Erik Johansson, and Rafael Campamà Pizarro in the department of Energy and Building Design at Lund University for the support and guidance throughout the thesis study.

Thanks to Jesper Svärd from LKF, Lunds Kommunala Fastigheter AB, for providing the technical data, Andreas Rudenå, and Toivo Säwén at Strusoft for the cooperation with us. Also sincere thanks to Johnny Svensson for the help regarding the ground source heat pump.

Many thanks also to our classmates and Jonas Manuel Gremmelspacher, Yuchen Yang, and Akram Abdul Hamid for helping us with the simulation related study.

Finally, we would like to express special thanks to our families for encouragement and support during the whole master's program. Also, thanks to every friend of ours for always being together with us.

Abbreviation

ACH	Air changes per hour
AHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BBR	Boverkets byggregler
EAHP	Exhaust air heat pump
DH	District heating
DHW	Domestic hot water
EPBD	European performance in buildings directive
EU	European Union
GSHP	Ground source heat pump
HVAC	Heating, ventilation, and air conditioning
LCC	Life cycle cost
LKF	Lunds Kommunala Fastigheter AB
NPV	Net present value
ppl	People

Notation

ΔT	Temperature difference (K)
λ	Heat Conductivity (W/m·K)
ρ	Density (kg/m³)
d	Thickness (m)
C_P	Specific heat of the air (J/(kg·K))
k	Insulation thermal conductivity (W/m/K)
h_s	Insulation to air heat surface heat transfer coefficient (W/m2/K)
F	Future value (SEK)
i	Interest rate (%)
P	Present value (SEK)
N	The time period (year)
g_r	Growth rate(%)
kWh	Kilowatt-hour
U-value	Thermal Conductance (W/m^2·K)
G-value	Solar energy transmittance

Table of Contents

1. Introduction

A very significant goal of the European Union is to reduce building energy. Over 40 % energy consumption of the European Union was accounted for building energy (European Commission, 2011). According to EPBD (Energy Performance of Building Directive), the renovations of existing buildings give a chance to take cost-effective measures to improve the building performance (EN, 2010). Every 30 to 40 years is the period of the old building's major renovation, the opportunity of enhancing building energy performance is considered seriously (Liu *et al.*, 2014). With retrofitting strategies, heating energy demand could be decreased. In Sweden, over 30 % of heat demand was covered by district heating (Swedish Energy Agency, 2014). To produce demanded energy, an alternative way was proposed in the thesis, a heat pump coupled with district heating, which has a potential to be a highly efficient heat source. In the past two decades, the heat pump has become a developed heating supply technology in Sweden. Sweden has relatively high numbers of heat pumps installed in the world, with around 1.5 million heat pumps operated(Fernando *et al.*, 2004). The main reason is that Sweden has a cold climate and a relatively low electricity price. 50 % to 60 % of heating demand is estimated to be covered by heat pumps during the coldest day (Jonasson, 2019). Heat pump water heating systems have much more heat supply than conventional electric heaters with the same amount of energy (Hepbasli and Kalinci, 2009). This project assesses the air source heat pump and ground source heat pump.

1.1. Background

Within the IEA Energy in Buildings and Communities Program, Annex 75 is an international (mainly European) task group aiming at cost-effective building renovation at district level combining energy efficiency and renewable energy. Within Annex 75 there is a subtask called case studies which among other things aims to investigate factors influencing the choice for a cost-effective strategy applied in a real case. The study case of the thesis is one of the Annex 75 projects.

1.1.1. Retrofitting Techniques

The retrofitting measures of the buildings could be divided into two main categories. Firstly, improving building envelopes could help to reduce heat loss and increase airtightness. Replacement of windows and the addition of insulation are included in it. Secondly, the improvement of energy supply systems helps to get way larger use of renewable energy (Verbeeck and Hens, 2005). Ground source heat pump and exhaust air heat pump system were considered in the study.

The implementation of multiple district heating substations was also studied to see how much heat loss could be reduced.

1.1.1.1. Insulation

Adding insulation helps to reduce the U-value of the walls and reduce the cost of heating energy need during the heating season. The study by Morelli et al. (2011) shows that, when insulation was added on the inner side of the walls of a multifamily building with a brick façade, the energy-saving could be up to 72 % for the entire building. Another study by Valdbjorn et al. (2012) analyzed the energy-efficient strategies for the insulation improvement of a building with a solid wall, it demonstrated that

62 % of the heat loss could be reduced when the insulation was added on the roof and the façade and the windows were replaced with better-performing windows.

Heat losses through the envelop decreased when the insulation thickness was increased. The study carried out by Daouas et al. (2011) showed a result that the decrease of the yearly transmission load through the walls was fast when the thickness was small and goes gradually with larger values. The study carried out by Akyüz et al. (2017) found a similar result that with the increase of the insulation thickness, the heat loss showed a significant decrease and decreased significantly with thinner thickness. As for the 120 mm insulation and above, the heat loss decrement rate gradually lowered.

1.1.1.2. Window

In a building, windows help to capture the heat from the sun and keep the heat inside the rooms during the heating season. Aldawoud et al. (2017) had conducted a study on heating energy consumption with regards to window types. It showed that, based on the energy performance result, the heating energy consumption greatly depends on the glazing types. Comparing the single-pane, double-pane, and triple-pane glazing windows, the triple-pane glazing has the best energy performance.

1.1.1.3. EAHP

An exhaust air source heat pump is a machine that transfers heat from exhaust air to water by applying a refrigeration cycle. In the heating mode, the refrigerant extracts heat from exhaust air and turns to gas, the compressor compresses the gas to high temperature and increases the pressure of the refrigerant. Then the indoor coil releases heat to space heating and domestic hot water, the refrigerant condenses back into the liquid phase to complete a cycle. The overall trend today towards exhaust air heat pump is that because it can supply heat need for space heating and domestic hot water simultaneously, it also recovers 2- 3 times more energy than air to air exchanger (Fehrm, Reiners, and Ungemach, 2002). From the exhaust air, the system can get 3 to 4 times of heating energy as much as electricity energy use (Zhang, Wang, and Wu, 2007). The study by Johansson et al. (2009) showed that, in new buildings with higher airtightness, an exhaust air heat pump can cover 60 % to 90 % of the total heating energy consumption.

1.1.1.4. GSHP

Sweden has made use of geothermal energy for decades since half-century ago, during the 1990s the technology of ground source heat pump developed rapidly, and Sweden took a leading role. It is also the most common heat pump nowadays in Sweden. A vertical borehole extracting heat from the ground is the most typical way.

Sweden was rated as the top three leading countries in geothermal energy use regarding installed units and capacity, energy extracted, etc (Lund and Boyd, 2015). Sales for larger ground source heat pumps for multifamily houses have been growing steadily during the last few years. Ground source heat pump sales, with capacity >10kW, has been doubled since 2013 (Gehlin and Andersson, 2016).

1.1.1.5. Individual Substations

Adalberth et al. (2016) conducted a study on reducing culverts from the central substation to other buildings on a district level, in order to reduce the heat loss externally to the ground. The study showed that, in the Linero project, the energy saving is approximately 7 kWh/m^2 and the payback period is 3 years after the renovation when the external culverts were reduced by 40 %.

1.1.2. Problem Motivation

1.1.2.1. Climate Change

Some targets have been set by the EU to reduce greenhouse gas emissions continuously till 2050. For the year 2020, three key targets have been set by the EU leaders and enacted in legislation. Renewable energy sources should be used for at least 20 % of the EU energy total consumption and as for energy efficiency, a 20 % improvement rate should also be achieved. The national emission reduction targets cover 55 % of total EU emissions which are housing, agriculture, waste, and transport excluding aviation. The national renewable energy targets vary based on different starting points for renewables production and the ability to increase, for Sweden is 49 % (EC, 2016). The targets of climate and energy framework in 2030 include the reduction of at least 40 % of greenhouse gas emissions, the sharing of at least 32 % of renewable energy, and the improvement of 32.5 % of energy efficiency` (European Commission, 2014). The long-term strategy set for 2050 aims to reach net-zero greenhouse gas emissions with an economic wise. Between 80 % to 100 % of greenhouse gas reduction should be achieved by 2050. It has been reported that 75 % of the residential and service buildings were built before energy performance standards existed and most of the buildings must be renovated. Sustainable and renewable energy-efficient products, such as heat pumps and better insulation materials, are considered as the desired renovated strategies. (European Commission, 2018).

In Sweden, the long-term climate goal is that there will be no greenhouse gas emissions by 2045. According to the statistics of the Swedish Energy Agency, the residential and service buildings accounted for more than 30 % of total energy use, which means that a huge amount of energy could be saved by renovating these buildings (*Swedish Energy Agency, 2019*).

1.1.2.2. Million Homes Program

In the 1960s and early 1970s, many large-scale housing areas were built in European countries. And the buildings have relatively low technical quality (Turkington *et al.*, 2004). To arrange the housing shortage, the million homes program was initiated by the Swedish Parliament. Approximately 1.4 million houses were built and two-thirds of which were apartment buildings. In some countries, a major way to deal with the old buildings was demolition, while in Sweden it is mainly focused on retrofitting the buildings instead of tearing them down (Ferrari, 2012). The main owner of the million homes program was municipality companies. The companies own around 650 thousand multi-family apartments, and half of them were owned by municipal housing companies (Lind, 2015).

It has been 50-60 years since the dwellings were built, the installations of the buildings are now coming to the technical ending of life. Nowadays a new ventilation system could be installed at a low cost and meet the residential building's living standards. Many of the buildings have problems with the damaged facades. The constructions of the buildings were built before the high request of airtightness and insulation, hence the heat loss in terms of the building envelop is considerable (Högberg, Lind and Grange, 2009).

1.2. Objective

The first objective of the study is to perform case study research by assessing the heating energy performance of a cluster when the aforementioned energy retrofitting measures are applied to the building envelope and the energy supply systems. The second objective is to determine the economic feasibility of the retrofitting techniques, concerning the Life Cycle Cost.

1.3. Scope

The study was intended to investigate the energy performance of the property before and after renovation, focusing on decreasing energy consumption when insulation is added on the existing walls, and windows are replaced by better ones. Besides, individual district heating substation, and applying an exhaust air source heat pump as an energy source will be investigated to find out the most cost-effective or energy-efficient option. The replacement of district heating to the ground source heat pump will also be analyzed. Further analysis was carried out corresponding to the economic feasibility through Life Cycle Cost, where energy, material, and equipment cost will be accounted for.

1.4. Research Questions

The thesis was carried out to solve the following questions:

1. How is the energy-saving potential when the retrofitting techniques are applied?
2. Comparing several techniques to find out, which one has the best performance of energy-saving?
3. Which technique applied has the highest economic feasibility?
4. Which strategy is the most cost-effective in the long term?

1.5. Limitation

The study from Bagge et al. (2015) shows that domestic hot water flow changed in seconds. In the study, hot water usage was based on hourly flow during weekdays from May to August, to keep an identical period of space heating and the weather data. The results would have been more accurate if the domestic hot water use was evaluated in a shorter time period.

In the parametric study of the insulation thickness needed, five different thicknesses of insulation were considered in the study in terms of the energy consumption simulation and Life Cycle Cost analysis. If more thicknesses were considered the result might have been benefitted more from another thickness. Moreover, the study of the optimum insulation thickness did not consider the thermal comfort in this study. When more insulation is added on the envelope of a building, there might be some more overheating hours in summer since the heat inside the building Is preserved better. However, it can be solved easily by opening the windows since this building is a residential building.

Besides, the airtightness of the existing building could not be measured. This is because there was not enough time to carry out sensitivity analysis and the lack of instruments to do a blower door test. Thus, a study of the airtightness of residential buildings was used as a reference.

Water pump sizing is based on the water flow to space heating and DHW. Regarding heat pump installation, the replacement and electricity use of water pumps were not considered in this case. The duct system and water pipe connected with the heat pump were also regarded as a limitation in the study. The heat pump was sized with the highest capacity, which means the size of the heat pump did not vary in the case study. Regarding the combination of energy use and the life cycle cost, it would be possible to get more efficient results with a smaller size of the heat pump.

For the LCC analysis, the cost of the transportations was not included since the limitation of time was not enough to study the location of the suppliers of the materials. Moreover, since it was considered as minor expenses compared to the total area of the façade, the initial renovation expenses of the added insulation did not include the extra area due to the embedding of the insulation. Likewise, the recurring cost of the subscription of the district heating was not included in the LCC analysis due to the same reason. Compared to the annual district heating expenses, the cost of the subscription is very small, which is around 1795 SEK annually.

Besides, the economic parameters chosen for the LCC analysis is one of the most determining factors for the results. Different rate of the interest, the inflation, the price change of the material and the energy, as well as the wage, leads to the different result of the LCC analysis, such as the payback time and the accumulative net saving. However, variations of economic parameters were not included in this project due to the time provided.

2. Methodology

The study was carried out based on the simulation programs and measured data. The measurements were provided by LKF (Lunds Kommuns Fastighets AB), including the CAD files of the buildings and monthly heating demand. The data was used to validate the simulation result. In the meantime, the excel hand calculation method was also used to prove the simulation result.

2.1. Overview

In this section, the existing conditions of the buildings are illustrated, including the location, ventilation, building envelope and energy performance, etc. The renovation proposals and the workflow of the study are also illustrated.

2.1.1. Existing Building

The case buildings for this project are located in Klostergården in Lund, Sweden. The buildings are owned by municipal housing company LKF and are in great need of renovation. Lund is in the south of Sweden, the location is shown in Figure 1.

Figure 1 The location of Lund from Google Maps

2.1.1.1. General Information

The cluster consists of 2 high rise buildings and 1 low rise building. The high-rise buildings are rectangular, and the low-rise building is in an "L" shape. The short high-rise building is A1, the long high-rise building is A2 and the "L" shape building is A3. The view of three buildings is shown in Figure 2.

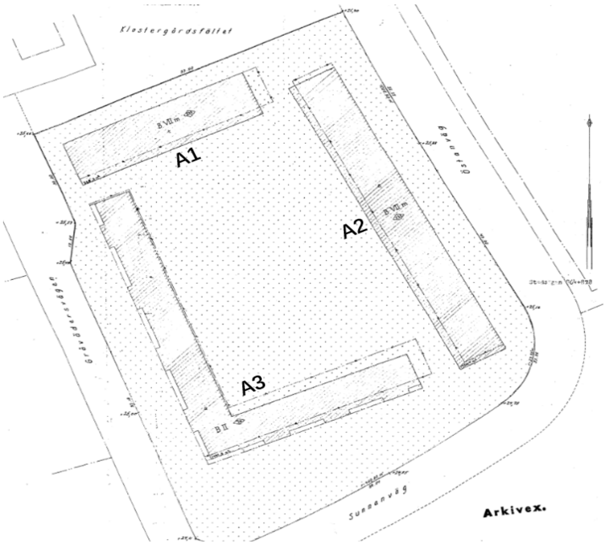


Figure 2 The site plan of the cluster from LKF

The high-rise buildings have 9 floors above the ground and 1 basement each. The low-rise building has 2 floors above the ground and 1 basement. There are 3, 5, and 7 staircases in A1, A2, and A3, respectively. The height of each floor is 2.5m. The layout of the A1 building is shown in Figure 3, the other two buildings have a similar layout as the A1 building.

Figure 3 The layout of the A1 building, 1st floor.

The ventilation system is an exhaust air system, the air intakes by the apartment windows can help to get fresh air due to the pressure difference created by exhaust air devices. Since the maintenance and cleaning service was not enough, the current ventilation condition is lower than the requirements. As low comfort due to the ventilation condition was not considered in the study, ventilation was set as the lowest requirement in the simulation regarding BBR standard (National Board of Housing, 2018), 0.35 l/s per m^2 of floor area.

The existing window is shown in Figure 4. It is double-pane glazing with a huge air gap in between, but the air gap is connected directly to the outdoor air. As a result, the U-value of the window changes depends on the outdoor air temperature. In winter, the outdoor air comes into the air gap and sweeps the heat on the surface of the inner glazing, increasing the U-Value by acting as a chimney that transports the heat out of the building. In summer, since the outdoor air temperature is not as low as in winter, the chimney effect is weakened. Considering that, since the U-value of single-pane window and double pane window are approximately 6 W/m^2K and 3 W/m^2K respectively, the window in this study case was considered as 4.7 W/m^2K (*Aspire Bifolds Surrey, 2020*).

Figure 4 The window of the existing building

The general information on the buildings is shown in Table 1. Stories above the ground consist of apartments, with the fan room on the top floor. The basements consist of bicycle storage rooms, equipment rooms, and laundry rooms. Basements were considered a heated area in this case.

Table 1 General information about the studies buildings

	Existing	Unit
Building number	3	Unit
Number of Apartment floor	20	Floor
Number of Basement floor	3	Floor
Heated Floor Area	24 530	m^2
Envelope Area	13 830	m^2
Glazing Area	3 580	m^2
Roof Area	3 149	m^2
Heating Setpoint of Apartment	21	°C
Heating Setpoint of Basement	18	°C
Ventilation AFS 2009	0.35	$l/s{\cdot}m^2$
Heat Recovery	-	-
HVAC System	Exhaust Air System	-

The room number and the occupant of each building are shown in Table 2.

Table 2 Number of rooms and occupants of the existing building

Building	Room number	Occupant
A1	72	201
A2	170	380
A3	28	100

2.1.1.2. Existing Construction

Figure 5 shows A1's southeast-facing façade. The walls of the apartment floor are the blue facades shown in Figure 6. The red part is the basement wall, and the yellow part is the reinforced wall. On the top, the green construction is the wall of the 9th floor, extension floors from the previous renovation.

Figure 5 The façade of the building A1

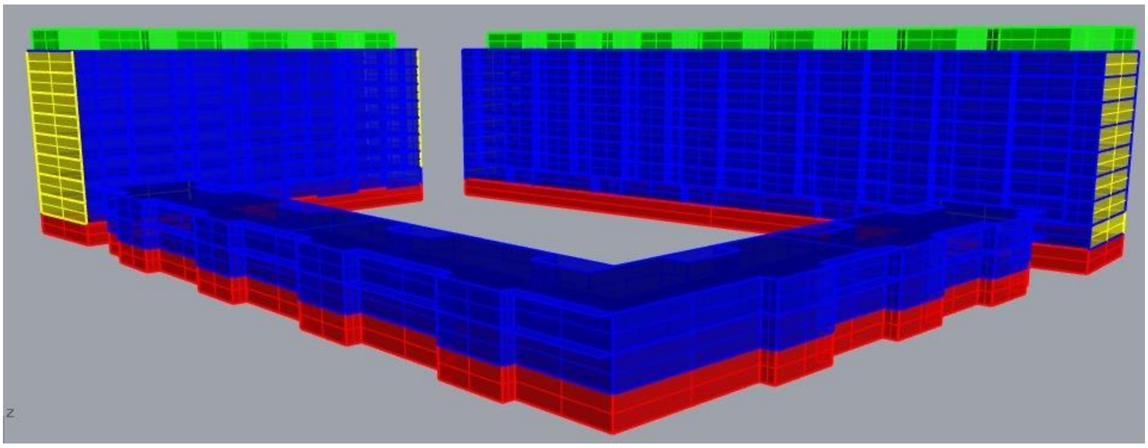


Figure 6 The construction of the buildings

Layers of the basement wall are shown in Figure 7. External reinforced concrete is the outermost layer, and a wood wool panel is used as the interior finishing. The wood wool panel acts as an insulation and the U-value of the basement wall is 1.25 W/(m^{2}K).

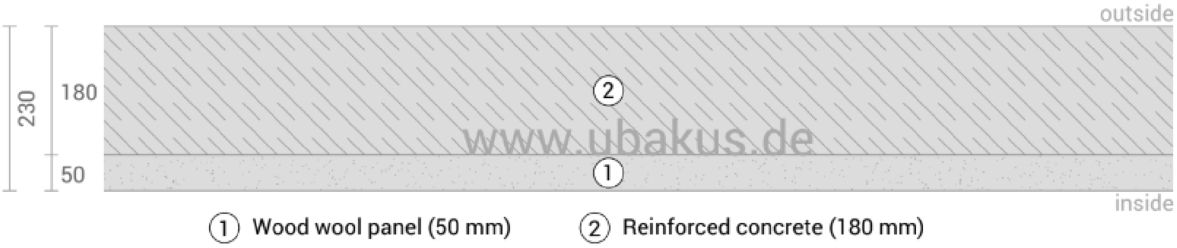


Figure 7 The construction assemblies of the existing basement wall

The reinforced wall of the apartment floor is composed of brick, with a mineral wool insulation layer and reinforced concrete. The interior surface is a gypsum board. The U-value of the reinforced wall is 0.308 W/(m^{2}K), shown in Figure 8.

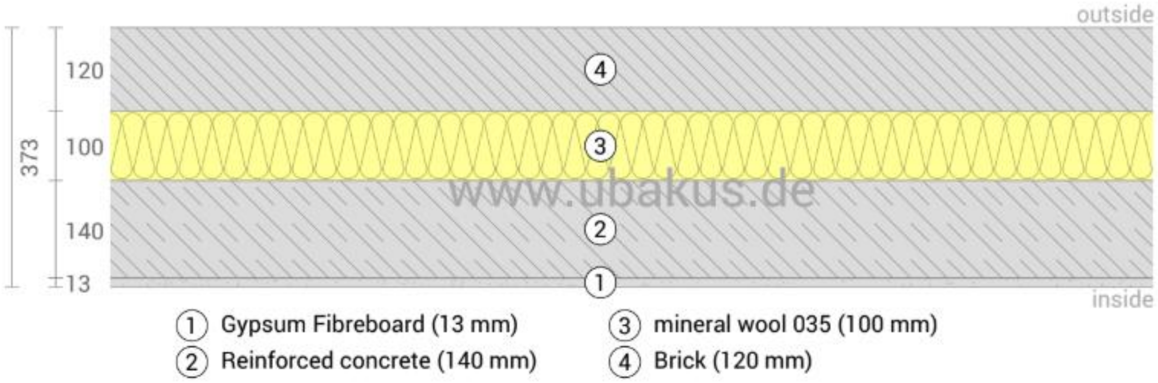


Figure 8 The construction assemblies of the existing reinforced wall of the apartment floor

Figure 9 illustrates the construction layers of the apartment floor. Same as the reinforced wall, the exterior layer is composed of brick and insulation layer. The difference between them is that this wall does not have reinforced concrete layer, the insulation layer is directly followed by the interior gypsum board and the U-value of this wall is 0.314 W/(m^{2}K).

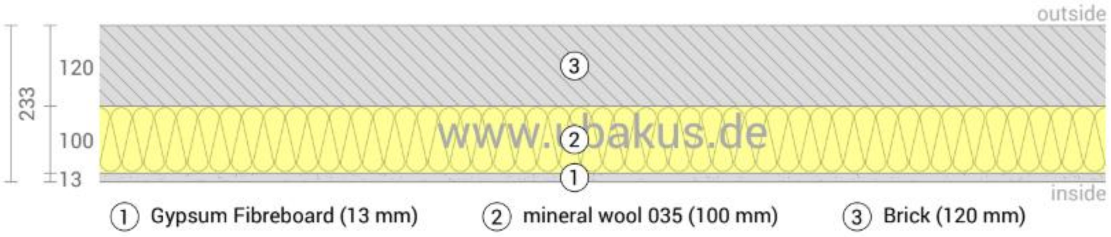


Figure 9 The construction assemblies of the existing wall of the apartment floor

As for the construction assemblies of the roof, the intermediate floor, and the wall of the 9th floor, they are listed in Appendix C.

2.1.1.3. Energy Performance of Existing Building

The energy report given by LFK has the energy usage data of 5 years, from 2014 to 2018 (see Appendix A). The energy supply system, for now, is a district heating system to provide space heating and domestic hot water energy needs. There is an air source heat pump system used in the existing building previously, but it is considered as not working anymore since it is in a bad condition. However, the air source heat pump was still considered in the report from 2014 to 2018. As COP of the heat pump was not given, the typical COP of the air source heat pump is considered at the range of 3.2 to 4.5 (Fischer and Madani, 2017). Considering that the quality of the heat pump is not good, the lowest COP of 3.2 was chosen. The energy performance of the existing building is shown in Table 3 and the result is the average value of the 5 years.

Table 3 The energy use of the cluster (from 2014 to 2018)

	Existing Building	Unit
Average Electricity Use for Air Heat Pump in 5 Years	8.8	kWh/y/m^2
COP	3.2	-
Average Heating Energy supplied by Air Heat Pump in 5 Years	28.0	kWh/y/m^2
Average District Heating Use in 5 Years	107.3	kWh/y/m^2
Total Heating Energy Need	135.4	kWh/y/m^2

2.1.2. Retrofitting Proposals

Case 0 represents the existing condition of the building. As for the retrofitting proposals, there are 5 branches in total. The Case 1 series is the improvement of the building envelop, including adding insulation and changing windows. From A to E are the same windows with 5 different insulation thicknesses. Case 2 is using the exhaust air heat pump as the bivalent heat source. Case 3 series is the combination of Case 1 and Case 2, applying exhaust air heat pump to the retrofitted buildings after Case 1. Case 4 is replacing the district heating with the ground source heat pump. And the last, Case 5 is having multiple substations in each building to reduce the underground heat loss. All the cases are shown in Table 4.

Table 4 The renovation proposals

	Renovation Proposals
Case 0	-
Case 1A	Adding 120mm of Wall Insulation & Applying triple-pane window
Case 1B	Adding 160mm of Wall Insulation & Applying triple-pane window
Case 1C	Adding 200mm of Wall Insulation & Applying triple-pane window
Case 1D	Adding 240mm of Wall Insulation & Applying triple-pane window
Case 1E	Adding 280mm of Wall Insulation & Applying triple-pane window
Case 2	Using EAHP
Case 3A	Combination between Case 1A and 2
Case 3B	Combination between Case 1B and 2
Case 3C	Combination between Case 1C and 2
Case 3D	Combination between Case 1D and 2
Case 3E	Combination between Case 1E and 2
Case 4	Using GSHP
Case 5	Having individual substations

2.1.3. Workflow

The workflow was as illustrated in Figure 10 as a flat project process. The starting stage was a literature review and the assessment of the existing buildings that then resulted in some renovation ideas. This step was then continued by making the 3D model of the buildings and a hand calculation of the heating energy use of the existing buildings. A preliminary heating energy simulation was then conducted for the existing buildings. The result obtained from that simulation was then compared to the result from the hand calculation of the heating energy need, the heat loss through the underground pipes and the DHW heating energy need, as well as the annual energy report from the owner of the buildings to validate the energy simulation result. After that, the hourly heating energy result from the simulation was studied together with the design of the energy supply ideas. At the end of the stage, the calculation of the heating energy need was merged with the calculation of the heating energy supplied by the energy supply systems, such as the EAHP (exhaust air heat pump) and the GSHP (ground source heat pump), and the calculation of the impact of the implementation of individual substations.

Finally, the LCC analysis was done by firstly finding the price of the materials, the labor wage, and the maintenances and the data obtained from the suppliers. After that, the economic feasibility was assessed over 35 and 50 years to compare and find the most profitable renovation techniques.

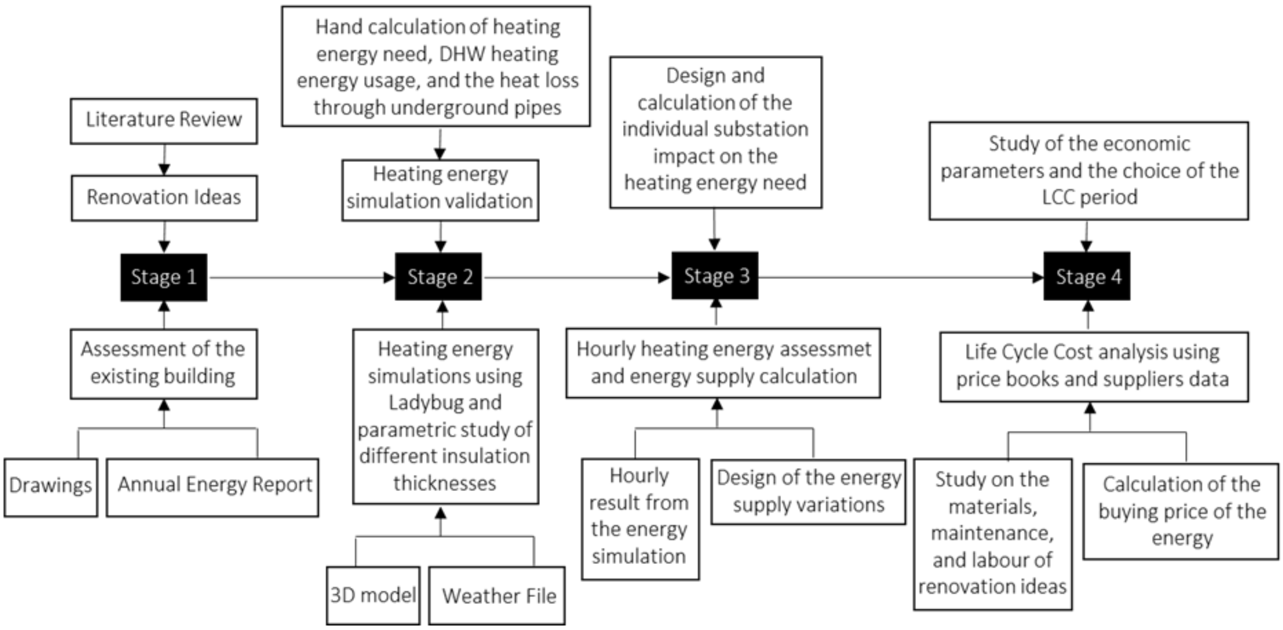


Figure 10 The workflow of the project

2.2. Software

Many software was used in the thesis for energy consumption simulation and data analysis. They are *Autodesk AutoCAD, Sketchup, Rhinoceros, Grasshopper, Ladybug, DIVA,* and *EnergyPlus.*

2.3. Hand Calculation

2.3.1. Excel Calculation

The excel calculation is the teaching material of EEBD (LTH AEBF10). The annual energy need result is based on the input parameters, which include the area, the transmission, U-value of the window, wall, roof, floor, and ground. Also, the average outdoor temperature of Lund, ventilation, and infiltration are applied as the inputs. Energy consumption calculation is based on the following formulas:

$$R = \frac{\lambda}{d} \tag{1}$$

$$R_{tot} = R_1 + R_2 + \cdots + R_n \tag{2}$$

$$U = \frac{1}{R_{tot}} \tag{3}$$

$$Q_{trans} = U \cdot A \tag{4}$$

And,

U: U-value, the thermal transmittance (W/(m^2·K))

R: the thermal resistance of the material (m^2·K/W)

λ: the conductivity (W/(m·K))

d: the thickness (m)

Q_{trans}: the heat transmission loss. (W/K)

A: the area (m^2)

In the ventilation sheet, the heating need through ventilation was calculated, the ventilation does not have heat recovery.

$$Q_{vent} = \rho \cdot C_P \cdot q_{vent} + \rho \cdot C_P \cdot q_{leakage} \tag{5}$$

And,

Q_{vent}: the ventilation heat loss (W/K)

ρ: the density of the air (kg/m^3)

C_P: the specific heat of the air (J/(kg·K))

q_{vent}: the intentional ventilation (l/(s·m2))

$q_{leakage}$: the leakage infiltration (l/(s·m2))

In the result sheet, the total energy need was calculated

$$Q_{annual} = (Q_{trans} + Q_{vent}) \cdot (T_{indoor} - T_{outdoor\ average}) \cdot 24 \times \frac{365}{1000} \tag{6}$$

And,

Q_{annual}: annual total heating energy need (kWh/year)

T_{indoor}: the indoor temperature (°C)

$T_{outdoor\ average}$: the average outdoor temperature (°C)

2.3.2. DHW Calculation

Bagge et al. (2015) carried out a study on daily domestic hot water use. The study divides occupants into three groups, high users, middle users, and low users. The research period was divided into weekdays and holidays from November to February, May to August, and the rest months during the year. Since in this study DHW was considered for average use, the middle user profile was chosen as the studied profile. Also, for middle users, the hourly usage does not vary too much at different times of the year, weekday usage from May to August was studied. The hourly values were exported and the daily usage profile was redrawn in excel, shown in Figure 11.

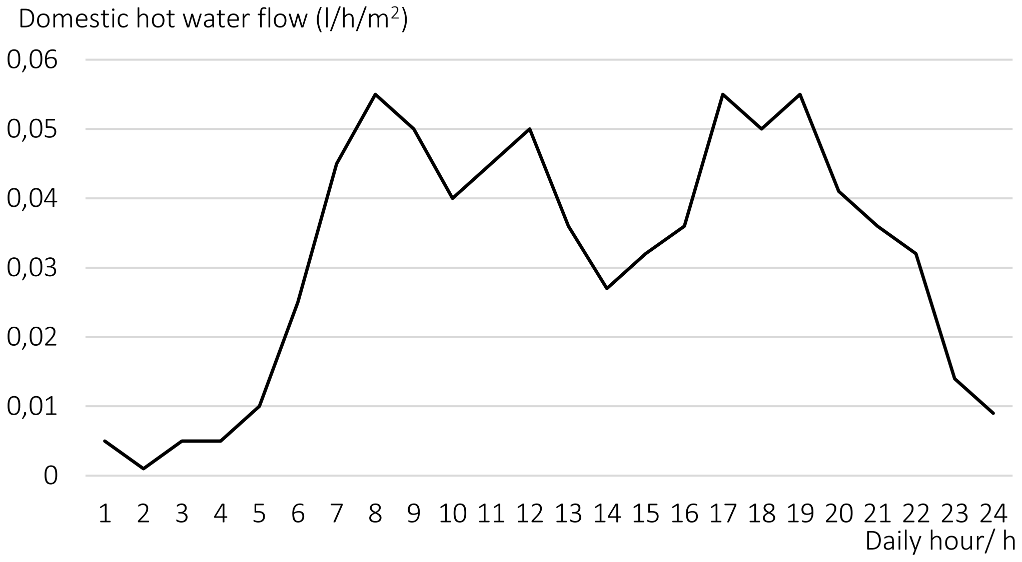


Figure 11 Daily usage of DHW

2.3.3. Heat Loss through Piping Calculation

As one of the retrofitting techniques, multiple substations will help to reduce the heat loss in the culverts underground. To calculate how much energy is losing in the culverts connected to the buildings, heat loss through the pipes was calculated. The concrete description of the heat loss calculation study is stated in 3.6.1. Figure 12 shows the pipe section. Heat loss was calculated following the equations (Samir, 2012):

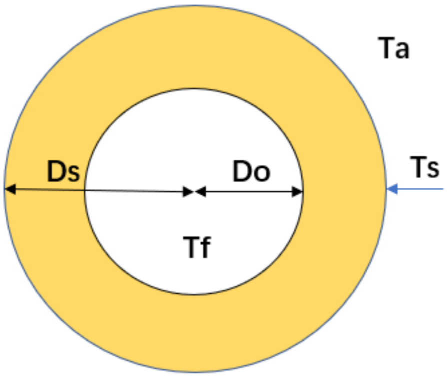


Figure 12 The section of the pipe

$$q = \frac{\pi(T_f - T_a)}{\frac{ln\frac{D_s}{D_O}}{2k} + \frac{1}{h_s D_s}} \tag{7}$$

$$T_s = T_f - q\frac{ln\frac{D_s}{D_O}}{2\pi k} \tag{8}$$

$$h_s = 13.79 + 0.032\Delta T - 40.86D_S + 97.3D_S^2 - 0.01\Delta T D_S \tag{9}$$

And,

q : the heat flow rate through the pipe and insulation, heat loss (W/m)

T_s : the temperature at the surface of the insulation (K)

T_f : the fluid temperature inside the pipe (K).

T_a : the ambient temperature (K).

D_O : the pipe diameter (m)

D_s : the outside diameter of the insulated pipe (m)

k : insulation thermal conductivity (W/m/K)

ΔT : the temperature difference between the insulation surface and the ambient air (K)

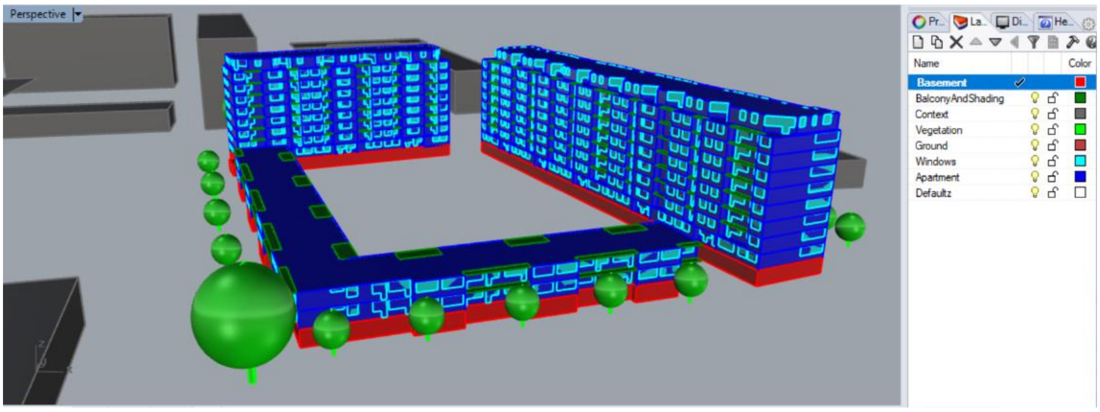
h_s : the insulation to air heat surface heat transfer coefficient (W/m^2/K)

q in the equations is the heat loss through the pipes, which is needed to calculate the total heat loss underground.

2.4. Energy Simulation

2.4.1. Modeling

The 3D modeling of the buildings and the surrounding was done in *Rhinoceros version 5.0*. Figure 13 shows how the layers of the 3D modeling canvas were divided to ease the modification of the material once it is linked to the simulation engine.



Name			Color
Basement	✓		🟥
BalconyAndShading			🟩
Context			⬛
Vegetation			🟩
Ground			🟥
Windows			🟦
Apartment			🟦
Defaultz			☐

Figure 13 The 3D model and layer management in Rhino

As was explained before in Figure 6, the apartment floors and the basement floors were given blue and red as the color of the layers respectively. The heated floors of the building were divided into those 2 layers because two of them have a different heating setpoint, schedule, occupancy rate, building envelope material, and thus, dividing them from the modeling phase will speed up the arrangement in the energy simulation process.

On the surface of the walls that were created inside those layers, some rectangular light-blue planes were laid, acting as the glazing. The technical properties of desired windows were then set to those surfaces in the energy simulation process later.

As shown in Figure 13, the balconies and the shadings were put in a different layer, which shows as dark-green in color, than the layers of the basement floors and the apartment floors. These balconies and shadings, even though they are parts of the buildings, are not supposed to be interpolated as the heated floor area since they are located on the outer side of the building envelope. However, they were made in the 3D modeling since they had a big impact on shading the building envelope from direct sunray or on reflecting them instead.

As to model the surroundings, a layer called ´*Context*´ and ´*Vegetation*´ were made, which are grey and light-green in color respectively. The first one contained the surrounding buildings that might shade the studied buildings, and the other one contained the vegetation around the building that most probably had an impact on the heating energy demand of the building since they obstruct the sunray going directly into the building through the glazing on the building envelope as illustrated in Figure 14.

Besides, a huge planar surface was put into the model as a ground surface to give a clear boundary level of the floors under the ground, which were the basement floors, and the floors on top of the ground level. Moreover, the modeled ground had also a pivotal role as a reflection surface of the sun rays hitting the ground. This reflected sunray might have been passed on to the building envelope and influence the heating energy demand of the building.

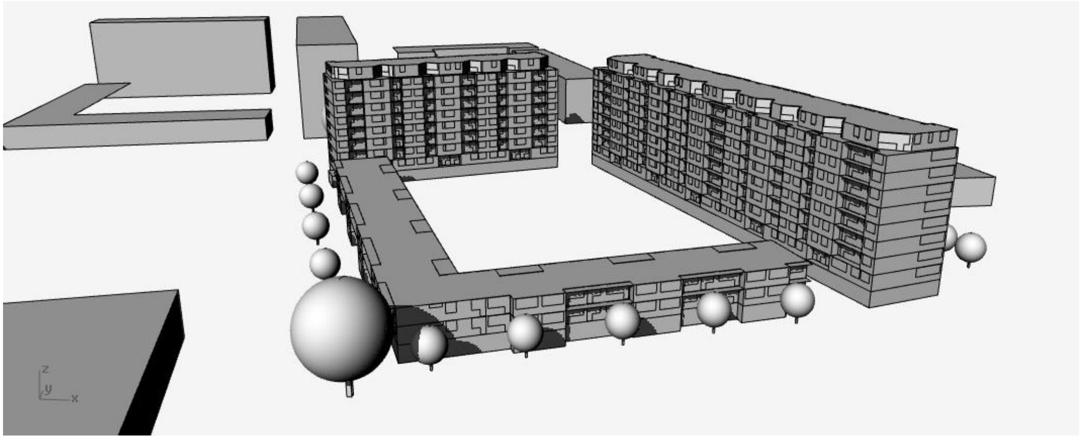


Figure 14 The 3D model of the buildings in shaded view in Rhino

2.4.2. Energy Simulation Engine

2.4.2.1. Constant Parameters

The constant parameters set in the energy simulation are listed in Table 5 below. It consists of the simulation inputs that were not changed for different cases. The area of the total heated floor, building envelope, glazing, and the roof were obtained from the 3D modeling process based on the drawings of the buildings.

The schedule of the infiltration, ventilation, occupancy, lighting, and equipment for the apartment and the basement floors were defined by the *Honeybee Zone Program* schedule. Likewise, the number of the density of the occupancy, the lighting, and the equipment of the basement and apartment floors was also obtained from the *Honeybee Zone Program (Appendix B*). These settings were chosen due to the reason that the corresponding desired data could not be obtained from the owner of the cluster. This Ho*neybee Zone Program* is based on the *Open Studio* standards (NREL, 2017) that was built based on many research studies, prototypes, and other established standards, such as *ASHRAE*. As for the rest of the inputs, such as the heating setpoint, the U-Value, and the heat recovery system, they were specified based on the existing building condition.

Based on the *BBR* standard(National Board of Housing, 2018), the ventilation flow rate was set to 0.35 l/s per m^2 of the heated floor area. This ventilation flow rate does not depend on the occupancy level and should be supplied continuously to ensure the change of air in each room in a residential building. Based on a research of apartment buildings done in Norway(Rønneseth, Sandberg and Sartori, 2019), the infiltration rate of the basement was set to 4 ACH or 0.003 m^3/s per m^2 at 50 Pa pressure difference of heated floor area.

Table 5 The constant parameters of the energy simulation

List of Constant Parameters	Energy Simulation	Unit
	Case 0 and Variation A - E	
Heated Floor Area	24 532	m^2
Building Envelope Area	13 829	m^2
Glazing Area	3 580	m^2
Roof Area	3 149	m^2
Infiltration Schedule	Honeybee Zone Program Schedule	h
Ventilation Schedule		h
Occupancy Schedule		h
Lighting Schedule		h
Equipment Schedule		h
Heating Setpoint of Apartment	21	°C
Heating Setpoint of Basement	18	°C
Infiltration of Basement	4	ACH
	3	l/(m^2·s) at 50Pa
Ventilation	0.35	l/s·m^2
Occupancy of Apartment	0.032	ppl/m^2
Occupancy of Basement	0.02	ppl/m^2
Lighting Density of Apartment	11.84	W/m^2
Lighting Density of Basement	16.1	W/m^2
Equipment Load of Apartment	3.9	W/m^2
Equipment Load of Basement	2.9	W/m^2
U-Value of 9th-Floor Wall	0.19	W/m^2·K
U-Value of Roof	0.11	W/m^2·K
U-Value of Intermediate Floor	0.31	W/m^2·K
U-Value of Slab on Ground	0.13	W/m^2·K
Heat Recovery System	-	-

2.4.2.2. Variable Parameters

The inputs that were changed in the energy simulations were the U-value of the walls, as well as the U-Value, G-Value, and the VT of the window. As listed in Table 6, 120 mm of insulation was added to the existing building for variation A. The thickness was then increased by 40 mm gradually for the rest of the variations. Besides, the windows were replaced with triple-pane windows that have lower U-Value, G-Value, and VT, resulting in the decrement of the infiltration rate. The parameters are shown in Table 6.

Table 6 The variable parameters of the energy simulation

List of Variable Parameters	Energy Simulation						Unit
	Case 0	Variation A	Variation B	Variation C	Variation D	Variation E	
Infiltration Rate of Apartment floors	4	0.8	0.8	0.8	0.8	0.8	ACH
	3	0.6	0.6	0.6	0.6	0.6	l/(s·m2) at 50 Pa
Thickness of Added Insulation	0	120	160	200	240	280	mm
U-Value of Basement Wall	1.25	0.27	0.22	0.14	0.12	0.1	W/m^2·K
U-Value of Wall	0.31	0.15	0.13	0.11	0.1	0.09	W/m^2·K
U-Value of Window	4.7	0.8	0.8	0.8	0.8	0.8	W/m^2·K
G-Value of Window	0.87	0.7	0.7	0.7	0.7	0.7	-
VT of Window	0.89	0.74	0.74	0.74	0.74	0.74	-

2.4.3. Weather Data

Figure 15 shows the hourly outdoor dry-bulb temperature of Lund. The temperature differs from -11.4 °C in January to 26.9 °C in July. The mean temperature during the whole year is 8.7 °C. In the energy simulation, the hourly outdoor air temperature was used as the input data. In excel calculation the average temperature was used.

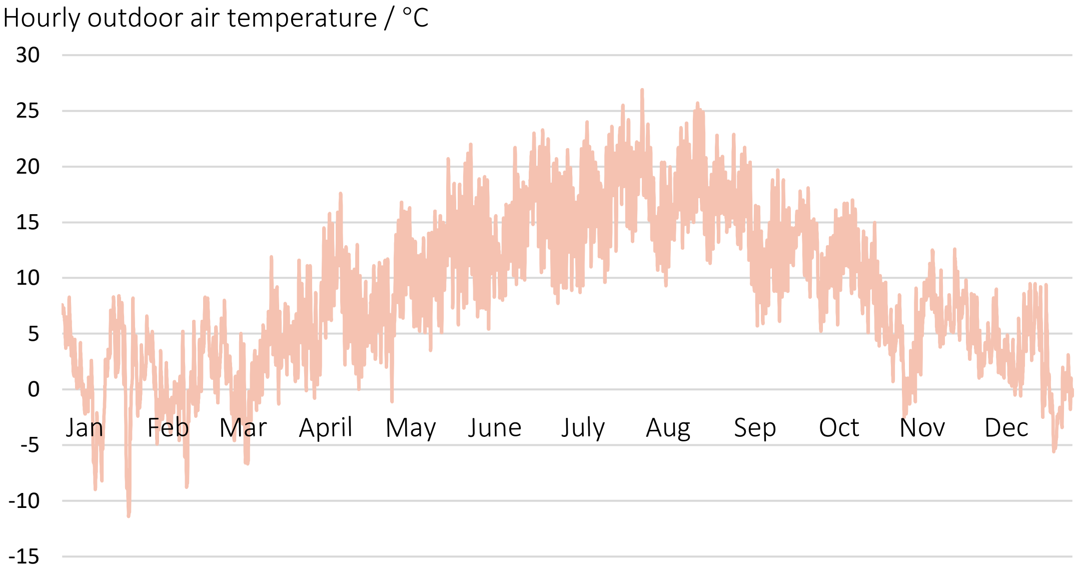


Figure 15 The weather data, the ambient temperature of Lund, EPW file

2.4.4. Energy Simulation Validation

To make sure that the energy simulation worked properly, a validation on the energy simulation result was conducted by comparing the annual heating energy need of the building from the energy simulation, the hand calculation done with *Excel* program, and the annual heating energy use report from the existing building.

For the case of the existing buildings, Case 0, the results obtained from the calculation of the DHW and the heat loss through the underground pipes were added to the result of the air heating energy use calculation done with the energy simulation and *Excel*. The total annual heating energy use of the whole cluster was then obtained and divided by the total heated floor area. Finally, the annual heating energy demand per heated area obtained was compared in Table 13.

2.5. LCC Analysis

The economic feasibility of the renovation techniques was calculated through the LCC analysis of a 35-year and 50-year period. The period for the LCC calculation should be sufficiently long to reflect the development of the initial renovation cost and the impact of the annual cost, such as the maintenance cost. Thus, the 35-year and 50-year period, which are widely used to assess the LCC analysis (Joshi, 2010)(III and Smith, 1998), were chosen. The initial cost of the renovation, annual heating energy cost, annual saving on heating energy cost, annual maintenance cost, and point-in-time maintenance cost were included in the LCC analysis calculation. To have the same perspective about the value of the costs, the cost of the point-in-time maintenances were calculated by using equation (10) to see the future value of the costs that is shaped by the price change rate, and then calculated back with equation (11) to the present value shaped by the interest rate. As for the annual heating energy cost, annual saving on heating energy cost, and the annual maintenance cost, they were calculated with equation (12) and (13). At the end, the total expenses due to the renovation, that consists of the initial costs of the renovation, annual heating energy cost, annual maintenance cost, and the point-in-time maintenance costs were subtracted with the annual saving on the heating energy expenses over a period of time to get the net present value (NPV). The condition where the present value of the total expenses due to the renovation is equal to the present value of the saving on the heating energy expenses is called the breakeven point (BEP) and the time when that condition is met is called the payback time.

$$F = P(1+i)^N \tag{10}$$

$$P = F(1+i)^{-N} \tag{11}$$

$$A_1 = P(1+i)^1 \tag{12}$$

$$P = A_1 \frac{1-(1+g_r)^N(1+i)^{-N}}{i-g_r} \tag{13}$$

And,

F: future value (SEK)

P: present value (SEK)

i: interest rate

N: the time period (year)

g_r: growth rate

To be able to perform the aforementioned calculation, interest rate, and the growth rate of the energy and material price are listed below in Table 7. This growth rate is also commonly called the price change rate. The growth rate of the wage, the inflation, and the price of the electricity energy was calculated by determining the average value based on the growth rate in Sweden over 10 years from 2010 to 2019 (*Trading Economics, 2020*)(*World Wide Inflation Data, 2020*)(*Statista, 2018*). As for the growth rate of the price of the district heating energy, the average value based on the master plan of a future growth rate of the district heating price owned by a district heating supplier company in Sweden is used (Öresundskraft, 2020). The growth rate of the maintenance cost and the material price were set to 0 because of the lack of the corresponding information and the fact that it vastly varies.

Table 7 Interest rate and growth rate of energy and material price

Economic Parameters	Nominal	Real
Wages Growth Rate (%)	2.55	1.45
Interest Rate (%)	0	-1.1
Growth Rate of Electricity (%)	0.53	-0.57
Growth Rate of District Heating (%)	1.7	0.6
Growth Rate of Window Components (%)	0	-1.1
Growth Rate of EAHP Components (%)	0	-1.1
Growth Rate of GSHP Components (%)	0	-1.1
Growth Rate of Insulation Components (%)	0	-1.1
Inflation (%)	1.1	

With regard to the labor cost, an hourly fixed cost of 206 SEK was used. Other information about the duration of each task, was collected from a book called *Sektionsfakta-ROT* by *Wikells Byggberäkningar*(Wikells, 2019a). On top of that, an overhead charge on the wage cost of 272 % was added. This overhead charge covered other costs needed for the renovation to be done, such as the cost of workplace organization, supervising, insurance, machinery used, and many more. The prices of the materials and the cost of maintenances were mainly obtained from the same book and one other book called *Sektionsfakta-VVS*(Wikells, 2019b) as well as the suppliers.

2.5.1. Price of Energy

2.5.1.1. Price of District Heating

The price of the district heating energy that was used in this project is the hourly price of the district heating energy that was built based on the data from a company called Öresundskraft (Öresundskraft, 2020). The price varied depending on the season. The hourly price of the heating energy in winter and summer is 0.89 SEK/ kWh and 0.12 SEK/ kWh respectively, while the price in fall and spring is 0.5 SEK/ kWh. This hourly price is valid only for individual use in apartment buildings and it includes the tax. The annual average price of the district heating is 0.56 SEK per kWh of energy.

2.5.1.2. Price of Electricity

The hourly price of the electric energy used in this project was calculated based on the data from the Nord Pool spot price of electricity(NORDPOOL, 2019). However, the price found there is only one of the components of the total amount that must be paid. The energy tax, the value-added tax, the cost of green electricity certificate, and the electricity transfer fee were then added to that to form the total hourly electricity cost (Lindahl *et al.*, 2019). The annual average price of the electricity is 1.17 SEK for each kWh of energy.

2.6. Retrofitting Cases

2.6.1. Case 1

The thermal properties of building envelope, such as window, wall, roof, and ground floor, has a significant impact on the heating energy use of a building (Mangan and Oral, 2016). In this case, 5 different thicknesses of insulation, from 120 mm to 280 mm with an increment of 40 mm, are applied to the walls of both the basement floors and the apartment floors. Along with that, triple-pane windows that have better performance in keeping the heat inside the building are applied to replace the old windows of the existing building.

2.6.1.1. Window

The triple-pane windows applied have a U-value of 0.8 W/m^{2}K, a G-value of 0.7, and 0.74 VT. (Olympic Glass, 2020) These windows use low emissivity glasses, a frame that is made of timber with aluminum cladding, and 18 mm to 20 mm cavities between each glass that are filled with argon gas that is proved to be able to decrease the heat overall heat transfer by around 25 % in comparison with the air-filled gap(Ahmadi and Yousefi, 2009). This application improves the U-value of the window to almost one-sixth of that of the old one, while the G-value and VT reduce for 0.17 and 0.15 respectively (*Table 8*).

Table 8 The thermal properties and visual transmittance of the existing and the triple-pane window

	Old Window	Triple Pane Window	Unit
U-Value of Window	4.7	0.8	W/m^2·K
SHGC of Window	0.87	0.7	-
VT of Window	0.89	0.74	-

2.6.1.2. Insulation

2.6.1.2.1. Insulation of Apartment Floor Wall

The application of the additional insulation layers is conducted on the outer side of the walls of the apartment floors, for both the ordinary walls and the reinforced walls. Thus, the EPS that has a λ-value of 0.035 W/mK is chosen since it is rigid and easy to apply. Before putting the EPS in place (*Figure 16* and *Figure 17*), an adhesive mortar is applied on the surface of the existing wall. Fixing anchors are drilled into the existing wall to keep the EPS in place, and mortar that is reinforced with glass fiber mesh is then placed on top of the insulation layers. As the finishing, primer, and weather-resistive rendering mortar are placed on the outermost side of the additional layers(GEARS, 2013).

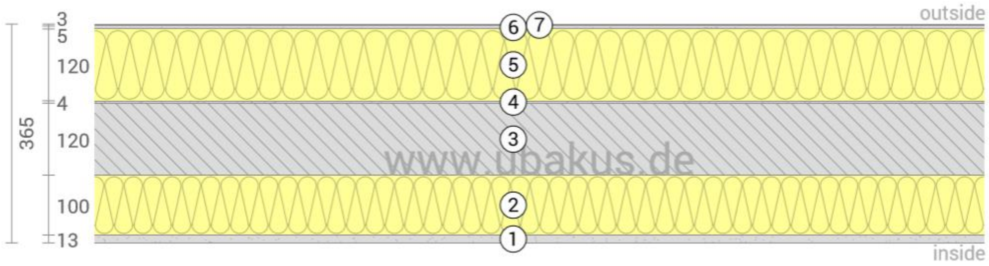


Figure 16 The construction assemblies of the retrofitted wall of the apartment floor. Gypsum board (1), mineral wool (2), brick (3), adhesive (4), EPS (5), fiber-reinforced mortar (6), finishing primer/mortar (7).

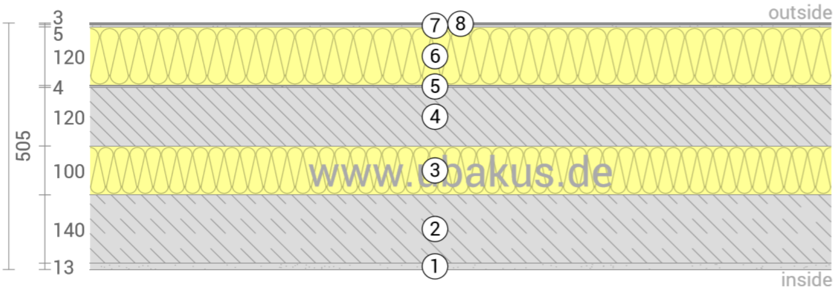


Figure 17 The construction assemblies of the retrofitted reinforced wall of the apartment floor. Gypsum fibreboard (1), reinforced concrete (2), mineral wool (3), brick (4), adhesive (5), fiber-reinforced mortar (6), finishing primer/mortar (7).

The change of U-value, thermal capacity, and the total thickness of the ordinary wall and reinforced wall are shown in *Table 9*. And the thermal properties of each layer of the apartment wall are listed in Appendix C.

Table 9 The thermal properties of the walls and the reinforced walls of the apartment floors

Ordinary Walls	Case 0	Variation A	Variation B	Variation C	Variation D	Variation E	Unit
U-Value	0.31	0.15	0.13	0.11	0.1	0.09	W/m²·K
Heat Capacity	258	278	279	280	282	283	kJ/m²·K
Added EPS	0	120	160	200	240	280	mm
Total Thickness	233	365	405	445	485	525	mm
Reinforced Walls							
U-Value	0.31	0.15	0.13	0.11	0.1	0.09	W/m²·K
Hear Capacity	554	574	575	576	577	578	kJ/m²·K
Added EPS	0	120	160	200	240	280	mm
Total Thickness	373	505	545	585	625	665	mm

2.6.1.2.2. Insulation of Basement Floor Wall

On the other hand, the application of the additional insulation layers on the basement floors is conducted on the inner side of the wall. The newly added layers consist of leveling mortar, timber studs that have a role as a construction system of the insulation(Pullen, 2018), mineral wool insulation material that has λ-value of 0.035 W/mK, vapor retarder with sd-value of 10m, and plasterboards as the innermost layer of the basement wall (*Figure 18*).

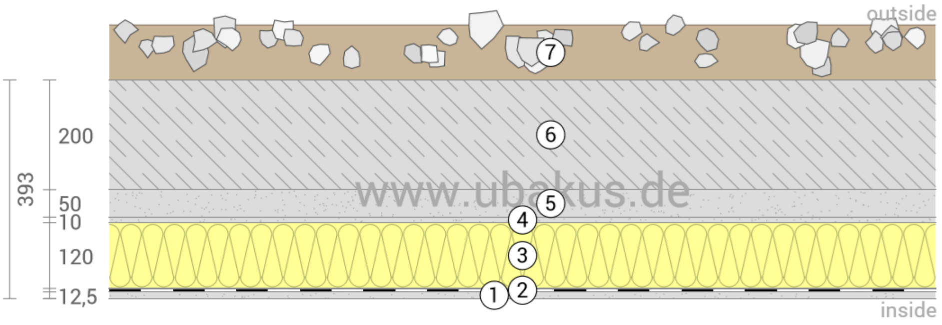


Figure 18 The construction assemblies of the basement wall. Plasterboard (1), vapor retarder (2), MW (3), leveling mortar (4), wood wool panel (5), reinforced concrete (6).

Likewise, the thickness of the insulation was increased gradually from 120 mm to 280 mm with 40 mm increment for the Case 1a until the Case 1e. The change of U-value, thermal capacity, and the total thickness of the basement wall are shown in *Table 10* . And the thermal properties of each layer of the basement wall are listed in Appendix C.

Table 10 The thermal properties of the basement walls

Basement Walls	Case 0	Variation A	Variation B	Variation C	Variation D	Variation E	Unit
U-Value	1.25	0.27	0.22	0.14	0.12	0.1	W/m²·K
Heat Capacity	421	486	486	487	488	488	kJ/m²·K
Added MW	0	120	160	200	240	280	mm
Total Thickness	230	393	433	473	513	553	mm

2.6.1.3. Airtightness

According to a Norwegian study (Rønneseth, Sandberg and Sartori, 2019), apartment buildings that were built between 1960 – 1970 had an infiltration rate of 6 ACH at 50 Pa when they were newly built. However, since the existing building that is studied in this project underwent a mild renovation before, the ACH was set to 4 ACH. Moreover, it was studied that If the building undergoes an intermediate level renovation between 2010 to 2020, such as replacing the window and insulating the wall, the infiltration rate will reduce to around 0.8 ACH at 50 Pa (Rønneseth, Sandberg and Sartori, 2019). The improvement of the airtightness of Case 1a until Case 1e is shown in Table 6.

2.6.2. Case 2

2.6.2.1. EAHP Design

The EAHP was chosen from NIBE. Green Master HP is an exhaust air unit with an integrated heat pump that recovers heat from exhaust air. It works in buildings with exhaust air ventilation systems that do not currently recycle indoor air. The product cools the exhaust air from about 21 °C to around 0 °C and produces both space heating and domestic hot water. The temperature difference of the water heated by the EAHP is 10 °C.

The supply and return temperature of the existing district heating system is 45 °C and 60 °C, the process 2 in *Figure 19*. The cold water is 10 °C and was designed to be heated to 55 °C, which is the process 3. After the renovation, mixed with the 55 °C water from EAHP, the return temperature of the district heating will increase to 52 °C, shown in process 4. The abandoned energy from the exhaust air is used for heating the return water of the space heating system and DHW system. Thus, district heating energy will be less needed. *Figure 19* explained the procedure of the system.

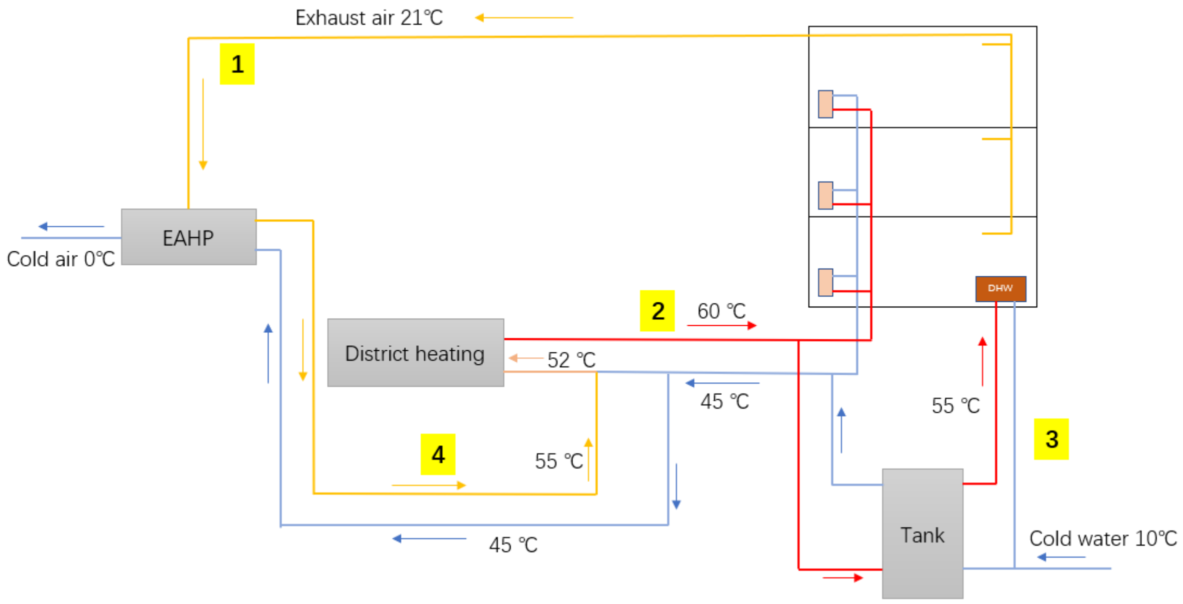


Figure 19 Functional progress of the EAHP

The EAHP was dimensioned in the software. The lifetime of the heat pump is 20 years(Green Match, 2020). The chosen products were shown in *Table 11*.

Table 11 The EAHP design

Building	Exahust air flow /m3/s	Heat pump capacity/ kW	Product
A1	2.52	75.6	3 x F1355-28 + F1155-16
A2	4.61	134.4	6 x F1355-28
A3	1.46	46.2	F1355-28 + 2 x F1155-16

For the DHW tank, the design and the dimension are from the company Thermia. There are three sizes of the water tank, 300 l, 500 l, and 750 l. A1 has 4 of 750 l tanks and 2 of 300 l tanks, A2 has 6 of 750 l tanks and 2 of 500 l tanks, and A3 has 2 of 750 l tanks and a 300 l tank.

2.6.3. Case 3

Case 3 is the combination of Case 1 and Case 2. The technologies used in Case 3 are adding insulation and changing windows, with EAHP providing part of the energy need. The design is the same as Case1 and Case2.

2.6.4. Case 4

2.6.4.1. GSHP Design

The ground source heat pump system was designed by the company Thermia, a Swedish company that manufactures a heat pump system. The groundwater was considered as the energy source and the system produces both space heating and domestic hot water. The system design was based on the peak load, apartment rooms, heated area, and energy demand of the cluster. Each building has a separate heat pump system. The working process of the heat pump for building A1 was shown in *Figure 20*. Process 1 is the water after extracting energy from the groundwater and being sent to the heat pumps. Process 2 and 3 show the supply and return water of space heating. The red line is hot water and the blue line is return water. Between process 2 and process 3 is the water tank of the space heating. Process 4 shows the domestic hot water supply, the green line is the cold water and the orange line is the hot water. There was a heat exchanger in the hot water tank, the heat source of domestic hot water heating is the supply water from the heat pump. The district heating system will be completely replaced by the GSHP in this case, the energy source is only groundwater.

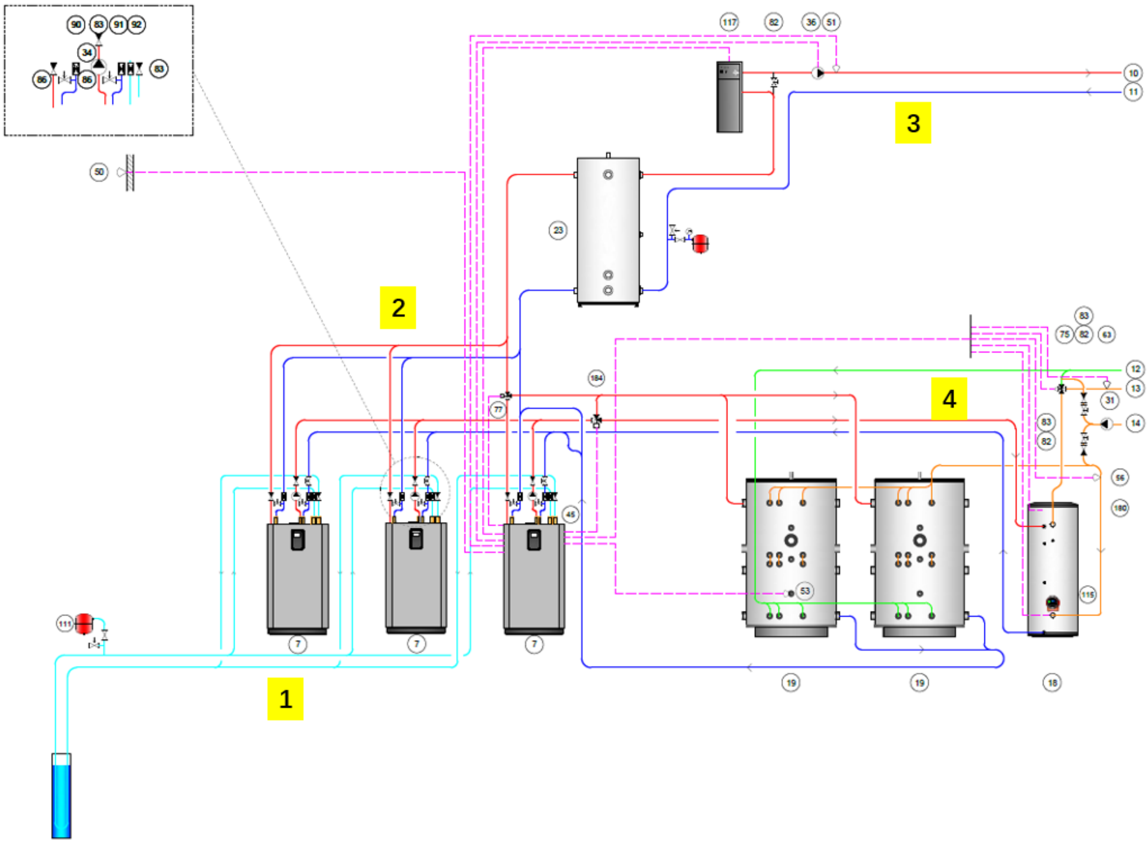


Figure 20 Functional process of GSHP

The district heating energy use will be converted to electricity use based on the COP of the products. As each building has its heat pump system, the COP is different from each other. The products info is shown in *Table 12*

Table 12 The GSHP design

Building	COP	Electricity kWh/y	Product
A1	3.33	258660	3 x MEGA XL HGW
A2	3.19	486590	5 x MEGA XL HGW
A3	3.53	138880	2 x MEGA XL HGW

2.6.5. Case 5

2.6.5.1. Individual Substation Design

For the current condition, the substation connected with the primary network was in the basement of the A2 building. Regarding the district heating of the other two buildings in the property, both are connected to the main substation with the culverts from A2 to A1 and A1 to A3, shown in Figure 21(left).

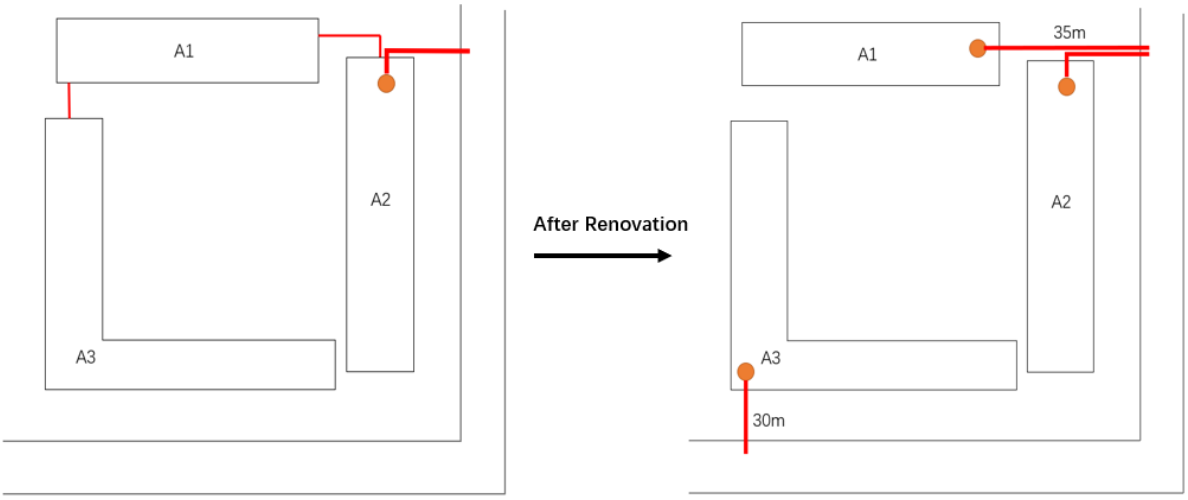


Figure 21 Existing status of the district heating system (left) and after renovation (right)

The pipes in the buildings were well insulated with 30 mm insulation with aluminum coating, the material of the insulation is mineral wool, shown in *Figure 22*. The hot water circulation loss (VVC loss) in the culvert and buildings inside is predicted to be the significant section. VVC loss has been investigated internally inside the buildings and externally in the culvert.

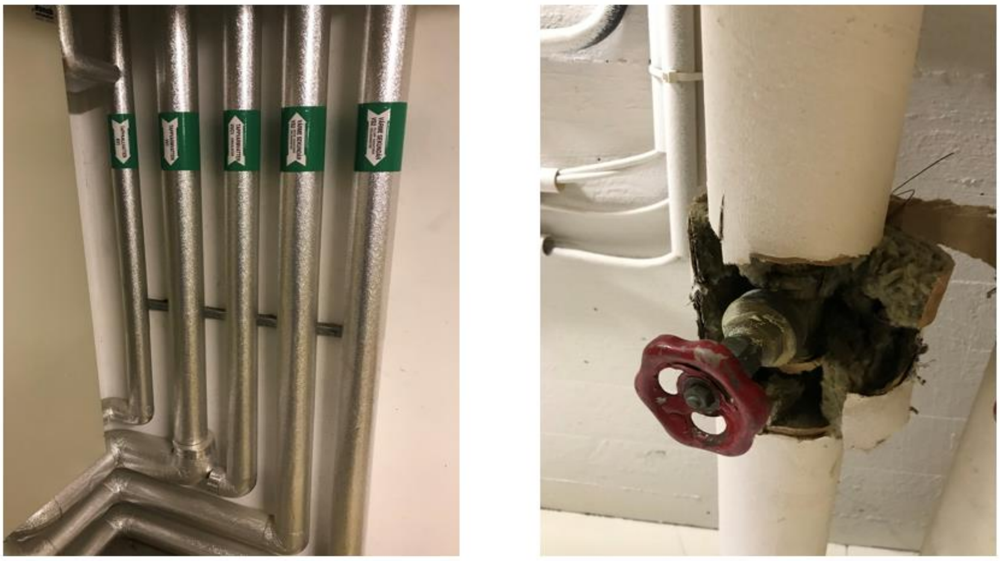


Figure 22 The vertical pipes and the material of the insulation (visible around the valve)

1) VVC loss in the external culvert

Hourly values for district heating use in the summertime from May to August for 24h were provided from LKF. The lowest value was at 7/25 02-03, with the outside temperature above 19 °C, which is why the space heating is not used. The lowest read power is 30kW, at this time occupants barely use hot water; thus the read power has been considered as the pure hot water circulation loss.

2) VVC loss inside the buildings

The piping inside the buildings has thermal insulation of 30 mm. The outer dimensions of the pipes are 15 mm, 18 mm, and 20 mm respectively. To get the heat losses in the 3 buildings, the pipe lengths were calculated.

Figure 21 (right) illustrates the district heating system after renovation, the substations will be increased from only one in the whole property to one for each building. All the buildings will be connected to the primary network.

The length of the new culverts from A1 and A3 buildings to the primary network is also shown in Figure 21(right). As the primary network drawing is not available, the length is the assumption.

The new heat exchangers for each substation were designed based on the product data from Wikells Sektionfakta(Wikells, 2019b). The products are 400 kW, 750 kW, and 250 kW for A1, A2, and A3 building. respectively. The calculation results of the pipe diameters and heat loss calculation are shown in the result section.

3. Results

3.1. Case 0

3.1.1. Heating Energy Performance and Supply

As Table 13 shows below, the annual heating energy demand of the existing building gotten from the energy simulation, and the excel calculation were 138 kWh/m^2 and 153.9 kWh/m^2 respectively. Compared to the number from the annual report of the existing building, which was 135.4kWh/m^2 Table 3), the result from the energy simulation was close. However, as was expected, the result from the hand calculation done with *Excel* showed a noticeable difference. As previously explained, the hand calculation conducted was a static calculation, while the energy simulation was a dynamic one. Instead of using average outdoor air temperature, the outdoor air temperature varied every hour in the energy simulation calculation. Besides, the schedule of the ventilation was 24 hours a day in the hand calculation, while it was based on the *Honeybee Zone Program* in the energy simulation program. Thus, the results from the simulation program were considered closer to the energy use report of the existing building and thus, the heating energy performance of the rest of the cases was simulated with the same script and basic settings in the simulation program.

Table 13 The comparison between the result of the energy simulation and the hand calculation

	Energy Simulation	Hand Calculation	Unit
Air Heating Energy Need	2 507 376	2 895 562	kWh/y
DHW Energy Need	396 437	396 437	kWh/y
Heat Loss through Underground Pipes	482 413	482 413	kWh/y
Heated Floor Area	24 532		m^2
Total Heating Energy Need	138	154	kWh/y/m^2

Based on the simulation result of the heating energy need for air heating, the heating energy calculation of the DHW use, and the heat loss through the underground pipes, the annual heating energy use and the peak load of each existing building in the cluster is shown in Table 14.

Table 14 The annual heating energy need and the peak load of the existing building

Case 0	A1	A2	A3	Unit
Annual Heating Energy Need	139	138	137	kWh/m^2
Peak Load	424	773	250	kW

Annually, the heating energy need for the air heating, DHW, and the heat loss through the underground piping system is around 2500 MWh, 400,000 kWh, and 500,000 kWh respectively (See *Figure 25*). Since the existing building condition was assumed to have no ASHP system, the entire heating energy need illustrated below is supplied thoroughly by the district heating.

3.1.2. Annual Heating Energy Expenses

Based on the hourly calculation of the heating use and the price of the heating energy supplied by the district heating, the annual expenses on heating energy use was calculated to be around 2 549 500 SEK. These expenses were mainly dominated by the expenses on air heating for 80 %, while the expenses on the DHW heating energy use and the heat loss through the underground pipes contributed roughly the same. Obviously, the energy expenses on the heat loss through the underground pipes shown in *Figure 26* is noticeable since it comprises the annual heating energy cost as much as the DHW.

3.2. Case 1

3.2.1. Heating Energy Performance and Supply

Giving additional insulation to the existing building wall, both on the outer side and the inner side of the walls has been proved to give a huge impact on heat energy saving. As a matter of fact, this improvement has been identified as one of the most significant impacts on reducing the heat loss of a building. This is due to the fact that this technique will reduce the thermal bridges, for instance at the connection between the roof and the wall construction as well as the connection between walls and floor slabs(Troi and Bastian, 2015). According to Building Research Establishment Ltd., an appliance of external wall insulation also improves the airtightness by sealing air leakage pathways. (BRE, 2018) Replacing the old windows with the new ones that have lower U-value also enhances the airtightness in the building when it is done properly. Moreover, a combination of having an airtight building envelope and replacing the window is a good solution to reduce the heating energy use in a building, as they serve the biggest proportion of heat loss due to insufficient airtightness of the building envelope(Troi and Bastian, 2015).

Due to the renovation of the walls and the windows in Case 1, the annual heating energy need, and the peak load of building A1, A2, A3 showed a significant improvement. When the 120 mm of insulation is applied (Case 1A), the heating energy use of building A1 and building A2 was reduced to around 40 % of the existing one and the same figure decreased to around 48 % for the building A3. As opposed to, Figure 23 shows that the same figure has insignificant decrement as the insulation thickness was increased gradually for the rest of the cases. This is due to the rest of the heat loss is not caused by the heat transmission through the wall and the time lag aspect on the wall.

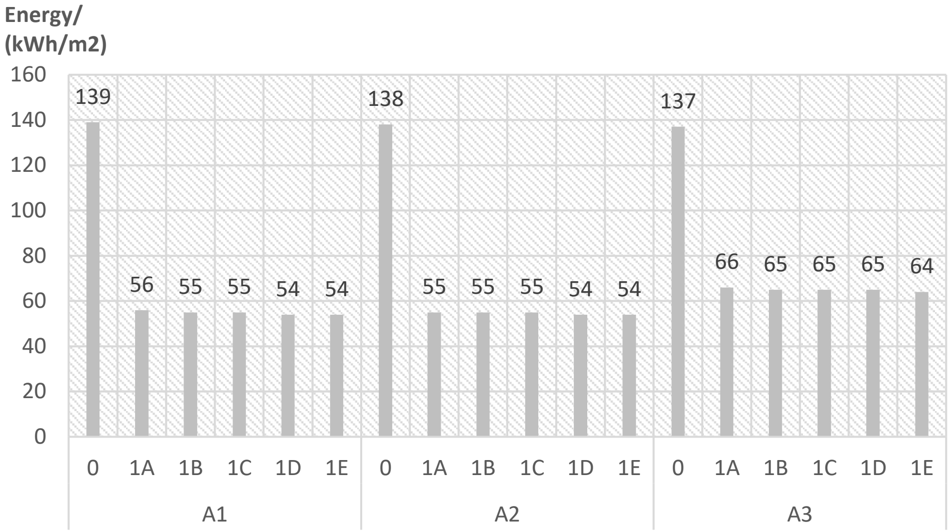


Figure 23 The annual heating energy demand of Case 0 and Case 1

Likewise, the peak load of the buildings also decreased for around half of the existing's when 120 mm of insulation was introduced in Case 1A. Along with that, Figure 24 also depicts the infinitesimal decrement for the rest of the cases due to the same reason as the trend seen in Figure 23 for all of the buildings.

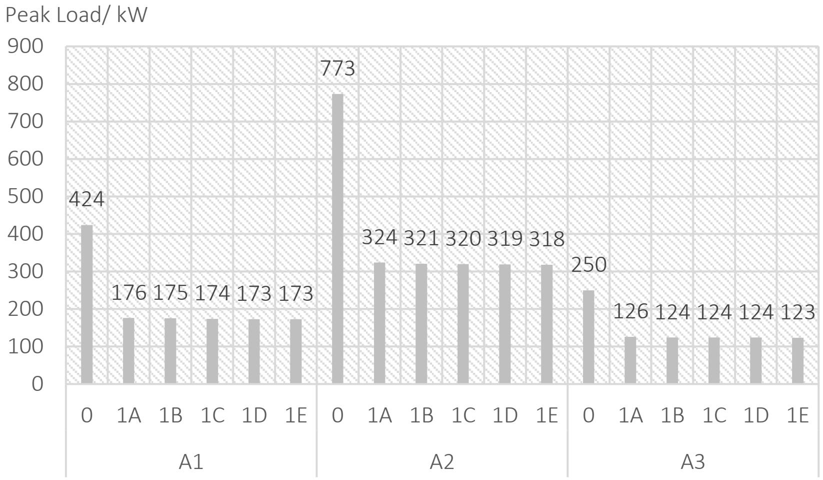


Figure 24 The peak load of Case 0 and Case 1

As for the energy supply for Case 1, the heating energy need is thoroughly supplied by district heating. The annual heating energy need supplied by the district heating is shown in Figure 25. This heating energy use comprises of the heating energy used to heat up the air in the building, DHW heating energy consumption, and the heat that dissipates through the piping systems underground used to transfer the heating among the buildings. In Case 0, the total heating energy use of the buildings is dominated by the air heating, while both the DHW consumption and the heat loss through the piping system constitute only 25 % of it. As for the rest of the cases, the air heating energy consumption decreases significantly that the proportion of the figures are relatively the same. However, as it was expected, the decrement of the heating need for air heating is negligible when the insulation thickness was continuously raised.

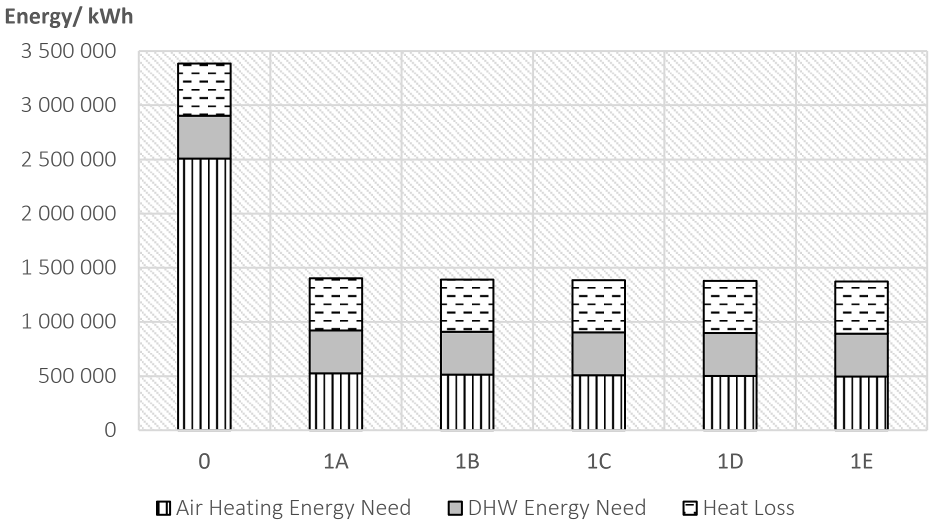


Figure 25 The annual air and DHW heating energy demand as well as the heat loss through the underground pipes of the Case 0 and Case 1

3.2.2. LCC Analysis

3.2.2.1. Energy Expenses

The annual expenses on the heating energy for Case 1 are depicted in Figure 26. The expenses staggeringly decreased to only around 950,000 SEK a year as the triple-pane windows and 120 mm of insulation were applied to the existing case. However, the number of expenses used for supplying DHW energy need and the heat loss remained the same.

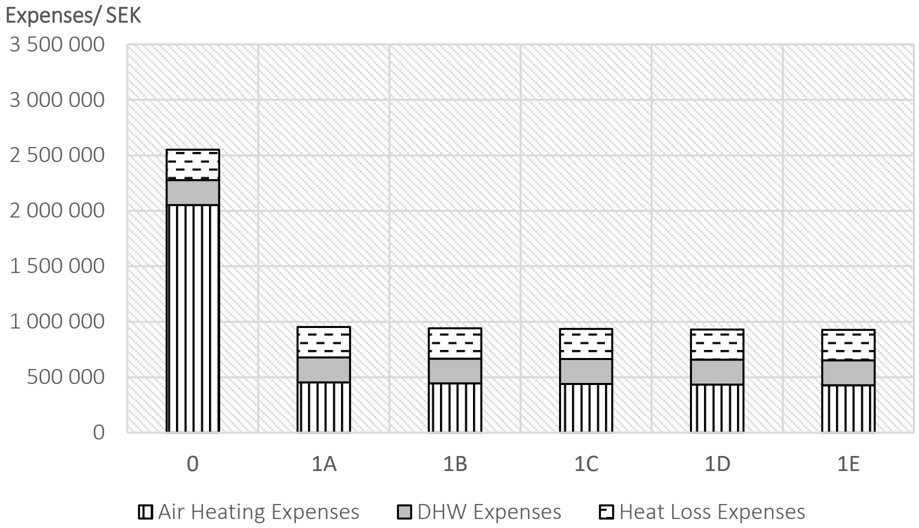


Figure 26 The annual expenses on air and DHW heating energy demand as well as the heat loss through the underground pipes of the Case 0 and Case 1

3.2.2.2. Renovation Expenses

Figure 27 shows that the renovation fixed cost increased along with the increment of the insulation thickness. The amount of the total renovation cost comprises the window cost as the biggest proportion, scaffolding rent cost, and the installation cost of the insulation.

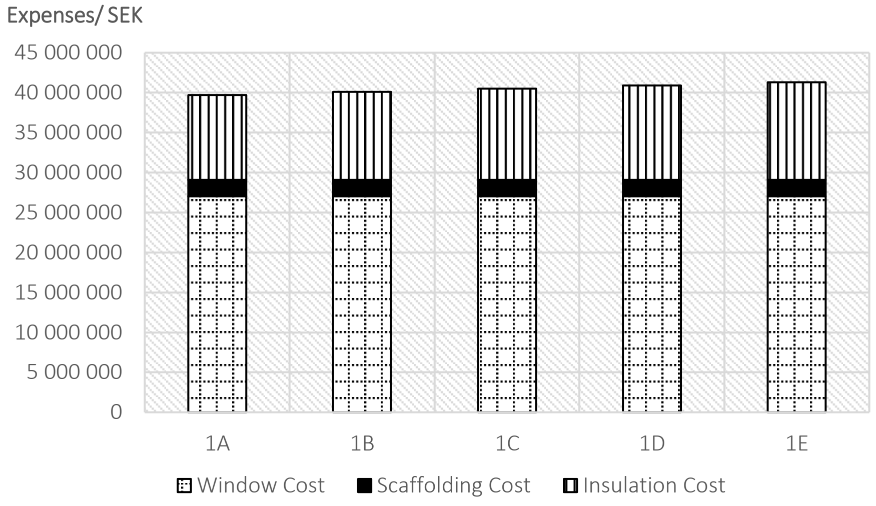


Figure 27 The initial renovation expenses of Case 1

Among those costs, the cost of the insulation is the only one that changes as the thickness of the insulation is increased. The costs that comprise the total insulation cost are shown in Figure 28 below.

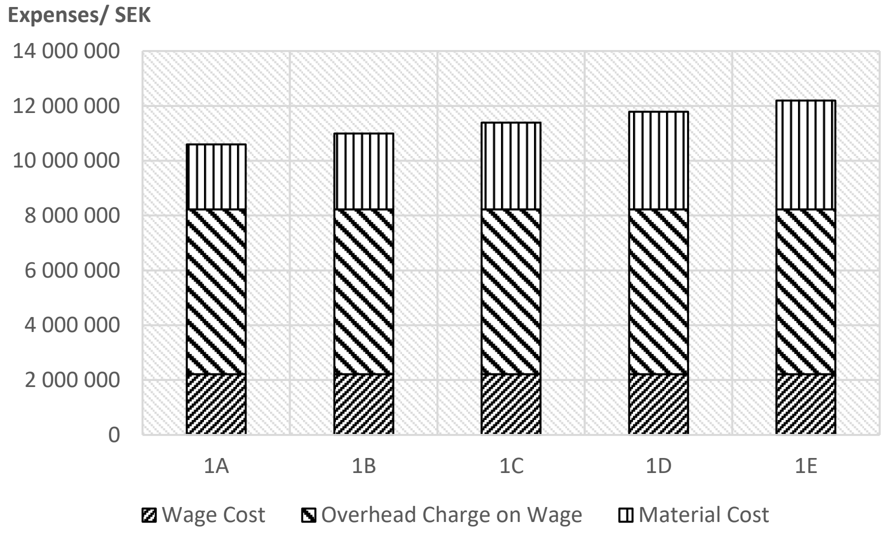


Figure 28 The wage, the material cost, and the overhead charge on the wage of the insulation cost.

3.2.2.3. Net Present Value and Payback Time

The NPV of every case in Case 1 is depicted in Figure 29. The difference among the cases is not noticeable since the curves are very close to each other. Besides, all of the curves seem to pass the breakeven point line, where the renovation cost and saved cost are equal, in the 21st year.

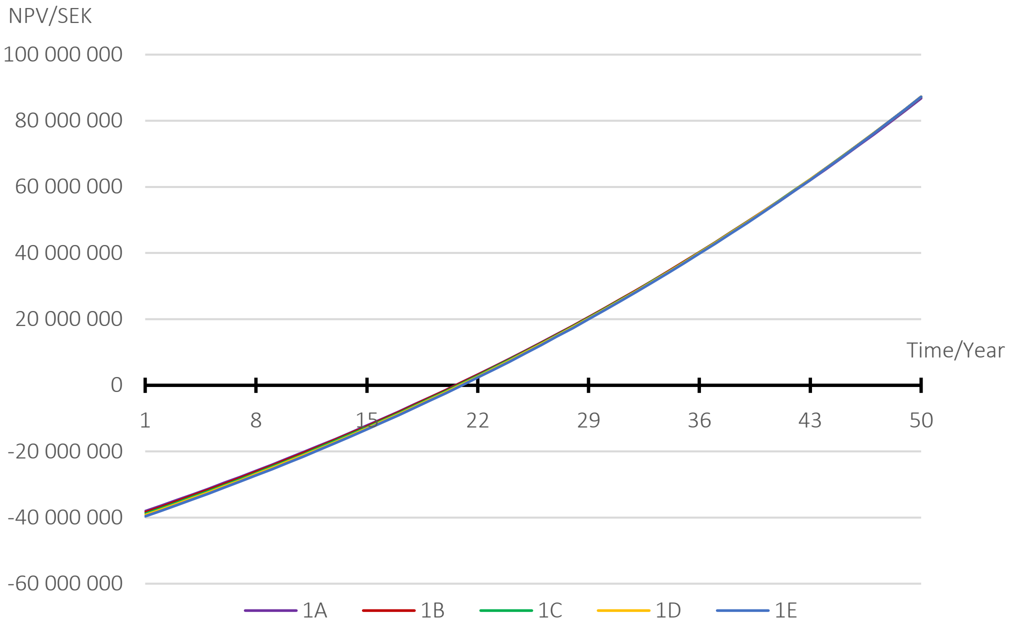


Figure 29 The NPV of Case 1 over a 50-year period of LCC analysis

However, taking a closer look as illustrated in Figure 30, it can be seen that the Case 1A got the payback earlier than the other cases after around 20 years and a half, followed by Case 1B, 1C, 1D, and 1E that got it exactly after 21 years.

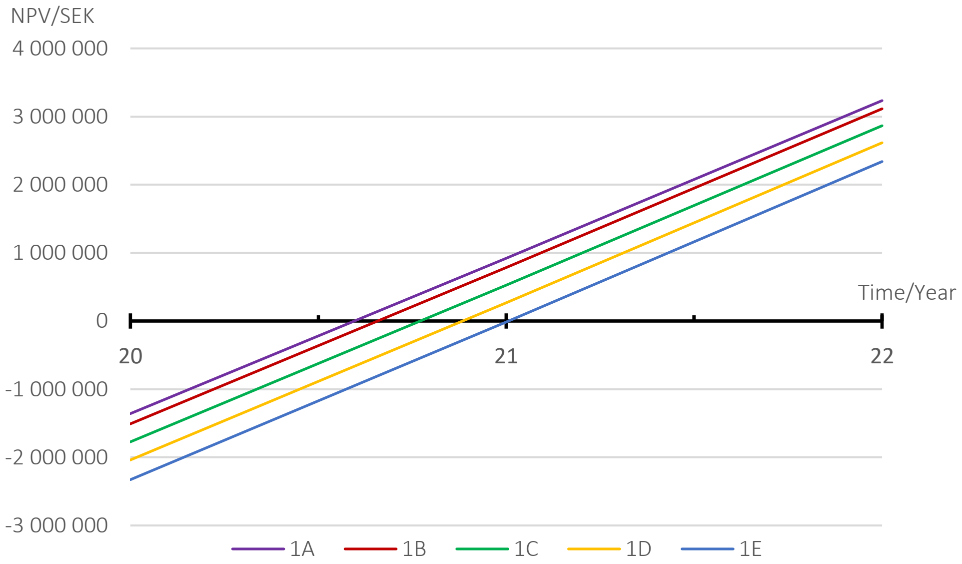


Figure 30 The NPV of Case 1 (between year 20- year 22)

Table 15 below shows the accumulative net saving after a period of 35 years and 50 years. The net saving was calculated by accumulating the saving on the heating energy expenses after the payback was reached.

Table 15 The accumulative net saving of Case 1

Case	Net Saving after 35 Years	Net Saving after 50 Years	Unit
1A	37 174 000	86 793 000	SEK
1B	37 274 000	87 215 000	SEK
1C	37 145 000	87 259 000	SEK
1D	37 013 000	87 300 000	SEK
1E	36 834 000	87 262 000	SEK

The accumulative expenses listed in Table 16 consists of the renovation cost, the maintenance cost, and the annual heating energy cost for a period of time.

Table 16 The accumulative expenses of Case 1

Case	Expenses after 35 Years	Expenses after 50 Years	Unit
1A	85 450 000	114 990 000	SEK
1B	85 350 000	114 568 000	SEK
1C	85 479 000	114 524 000	SEK
1D	85 611 000	114 483 000	SEK
1E	85 790 000	114 521 000	SEK

3.3. Case 2

3.3.1. Heating Energy Performance and Supply

As for the Case 2, when EAHP system was introduced to the existing building, the heating energy need the peak load remained the same since there was no improvement made on building envelopes like what was done to the Case 1 (see Table 14).

Nonetheless, the energy supplied to meet the heating need is now covered partially by the EAHP. As Figure 31 shows below, the EAHP covered approximately half of the total heating energy supplied to the cluster.

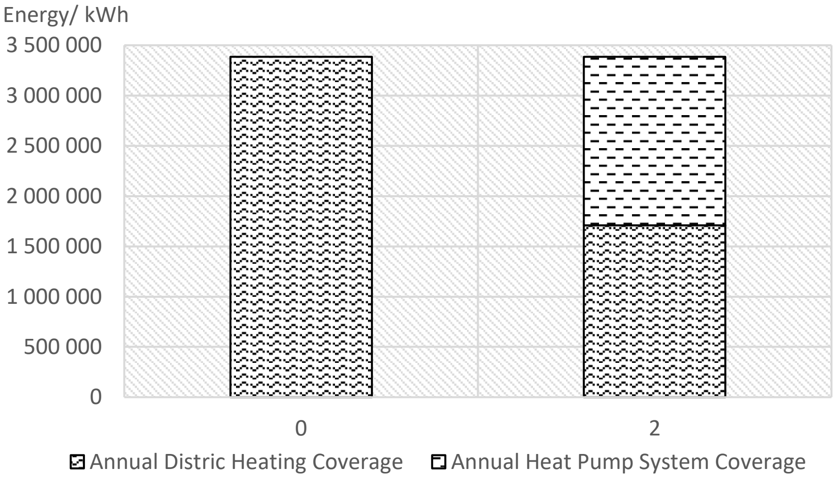


Figure 31 The annual heating energy coverage of the DH and the EAHP in Case 0 and Case 2

And since the EAHP system that was chosen has the COP of 3.6, the required electricity energy was not the same with the required heating energy supplied by the EAHP system (see Figure 31 and Figure 32). However, it should be pointed out that it does not mean that there was a saving of energy in this renovation since the amount of heating energy needed was still the same.

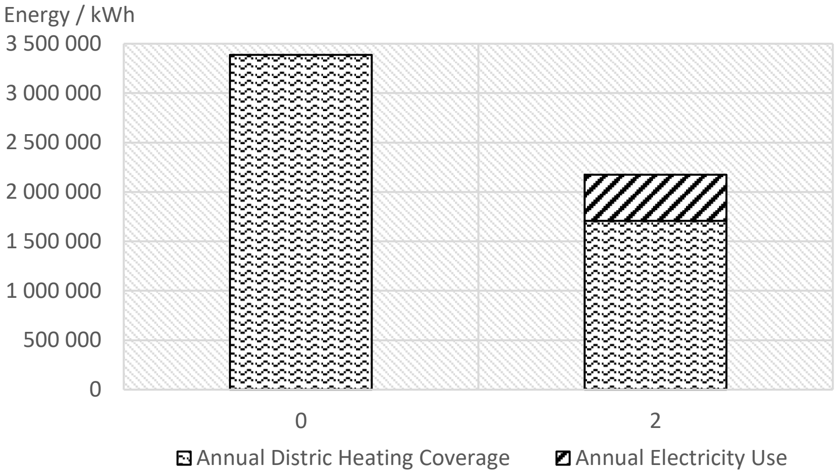


Figure 32 The annual DH and electricity energy use of Case 0 and Case 2

3.3.2. LCC Analysis

3.3.2.1. Annual Heating Energy Expenses

Figure 33 shows the annual expenses on electricity and district heating in order to satisfy the required heating energy in the cluster. Compared to the existing one, the annual expenses on energy decreased as much as 500.000 SEK.

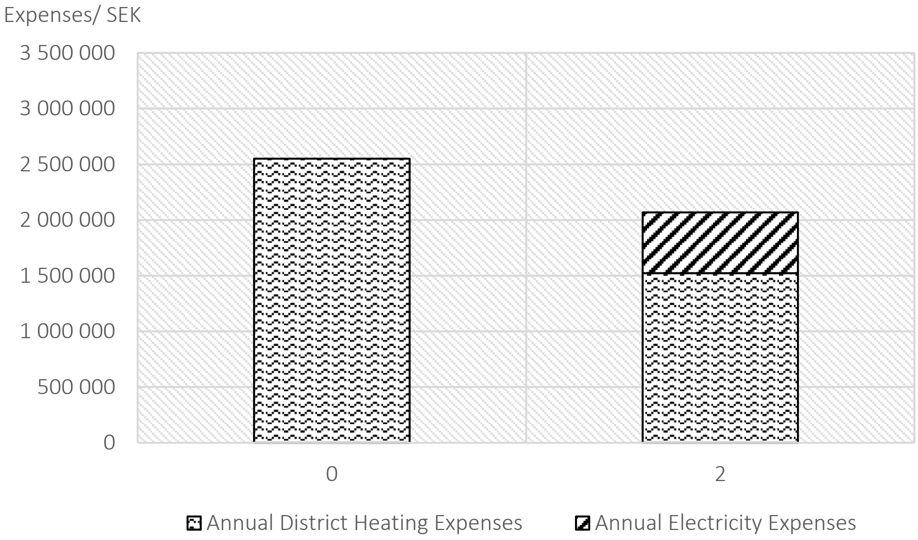


Figure 33 The annual expenses on the DH and electricity energy of Case 0 and Case 2

3.3.2.2. Renovation Expenses

Figure 34 illustrates the fixed cost of the renovation for Case 2. Both the EAHP installation cost and tank installation cost included the material cost, labor wage, and the overhead charge on the wage.

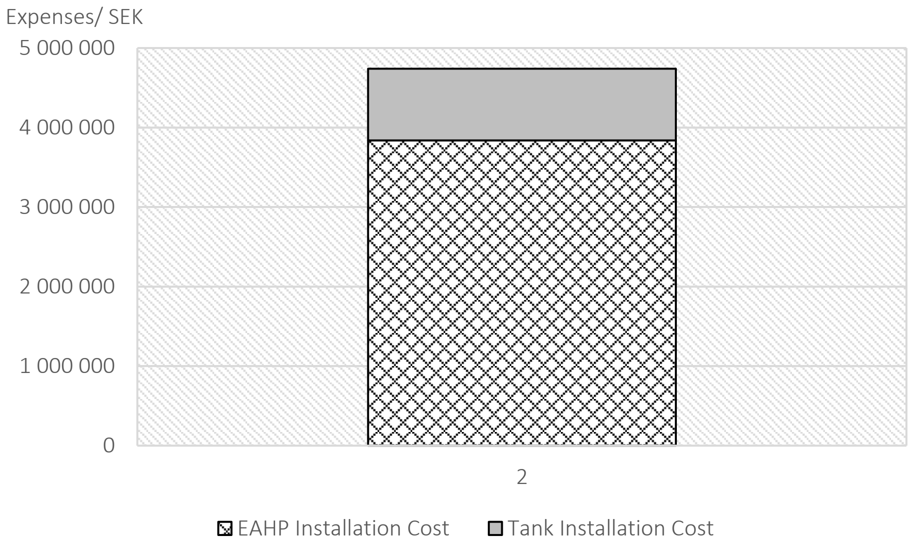


Figure 34 The initial renovation expenses of Case 2

As for the maintenance cost, the maintenances needed and the frequencies are listed in Table 17. The price sources are listed in Appendix D.

Table 17 The maintenance cost and frequency of Case 2

Maintenance Cost	Total Cost	Frequency
Heat Pump Maintenance	7 185 SEK	Once in a year
Compressor Repair	130 000 SEK	Once in ten years
Heat Pump Replacement	1 409 609 SEK	Once in twenty years

3.3.2.3. Net Present Value and Payback Time

The net present value of Case 2 in a 50-year period is shown in Figure 35.

As shown, the payback time of this case is around 8th year or 9th year after the renovation, where the cost of the renovation is equal to the cost of heating energy saved annually. As can be identified in the figure below, there are noticeable bumps every 20 years in the curve. This is due to the heat pump replacement that occurs once every 20 years.

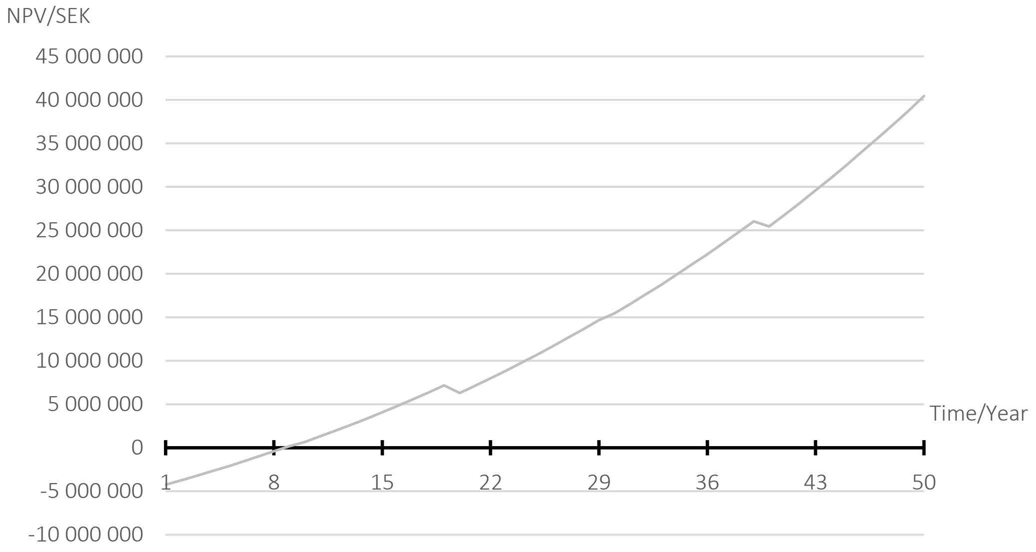


Figure 35 The NPV of Case 2 over a 50-year period of LCC analysis.

For the 35-Year period of LCC, the net saving of this renovation option is around 21 million SEK (see Figure 35 and Table 18). While after 50 years, the net saving almost doubles the number of that in the 35-Year period. Furthermore, the overall expenses are also shown in the table below.

Table 18 The accumulative net saving and expenses of Case 2

Case 2	After 35 Years	After 50 Years	Unit
Net Saving	21 077 000	40 446 000	SEK
Expenses	101 548 000	161 337 000	SEK

3.4. Case 3

3.4.1. Heating Energy Performance and Supply

The energy performance of Case 3 was carried out in the same way as Case 1. This is for the reason that both cases have the same renovation of the building envelopes and the windows. Figure 36 shows the annual heating energy need of each renovated building in the cluster compared to the existing one.

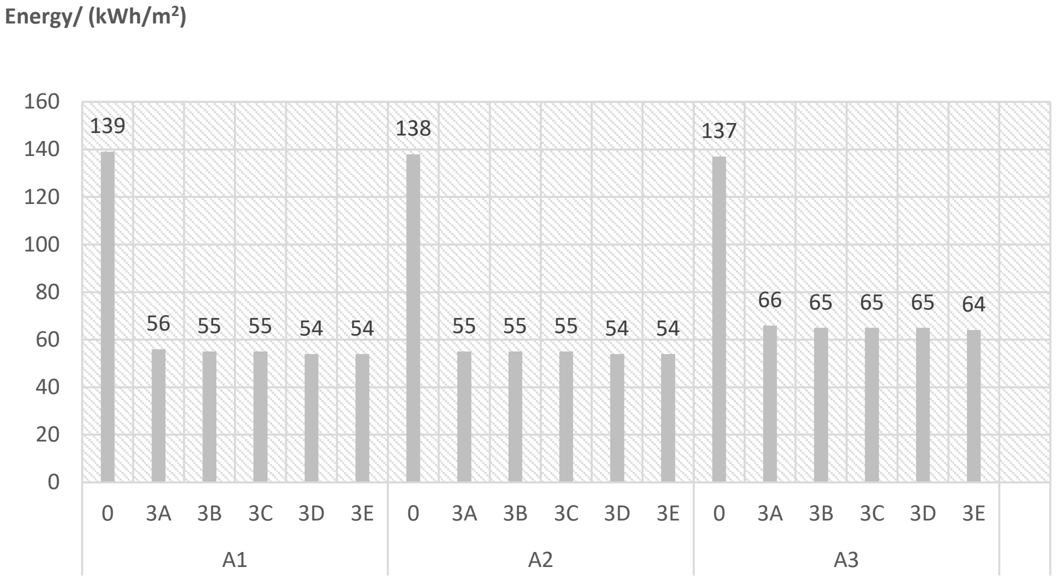


Figure 36 The annual heating energy demand of Case 0 and Case 3

Likewise, the peak load is also the same as the peak load in Case 1 for all of the buildings. For every building, the peak load halved when 120 mm of insulation was added to the existing wall. As the thickness of the added insulation was increased further, the change of the peak load was insignificant, shown in Figure 37.

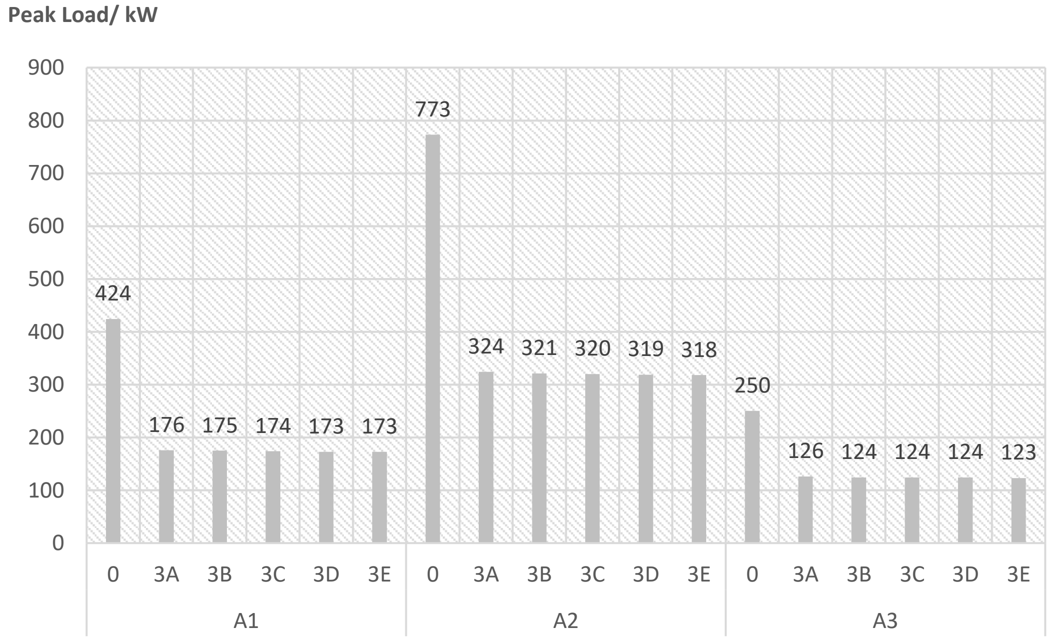


Figure 37 The peak load of Case 0 and Case 3

As for the annual heating energy usage, it is shown in Figure 38, and it is also the same as the annual heating energy usage of Case 1.

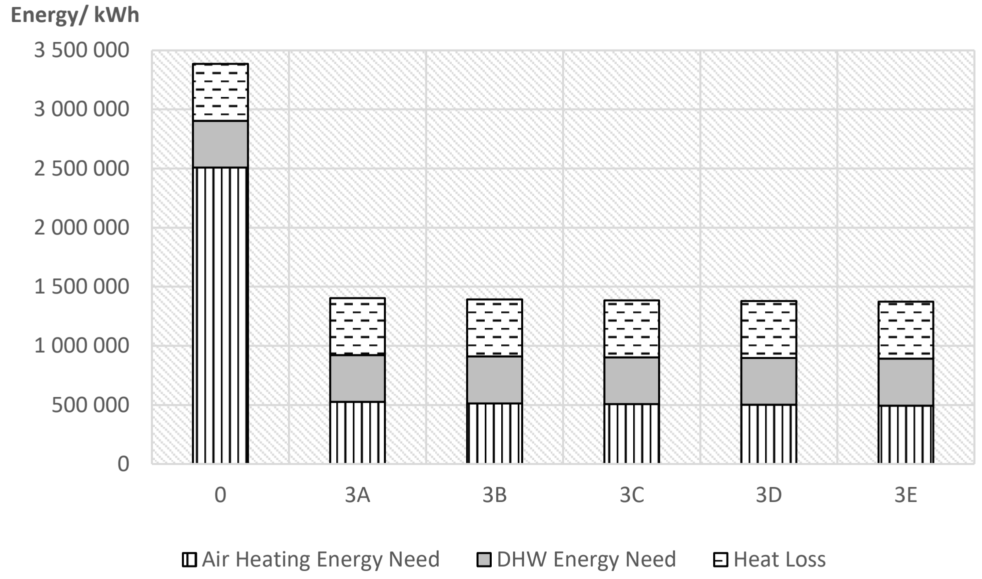


Figure 38 The annual air and DHW heating energy demand as well as the heat loss through the underground pipes of the Case 0 and Case 3

However, the heating energy is supplied both by the EAHP and district heating in this case. Figure 39 demonstrates that, in Case 3, the EAHP supplies more than 90 % of the annual heating energy need of the cluster, which is higher than the coverage of EAHP in Case 2 that only covers around 50 %. This is the result of the huge decrement of the annual heating energy need from around 3.4 million kWh to 1.4 million kWh.

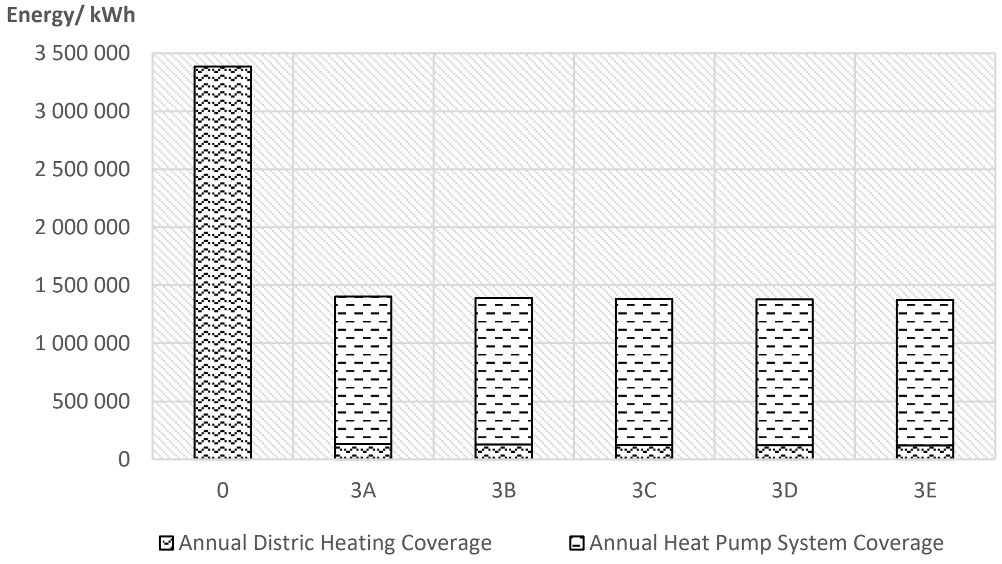


Figure 39 The annual heating energy coverage of the DH and the EAHP in Case 0 and Case 3

The EAHP system used in this case is completely the same as the one used in Case 2. With the COP of 3.6, the electricity and district heating annual energy use is depicted in Figure 40.

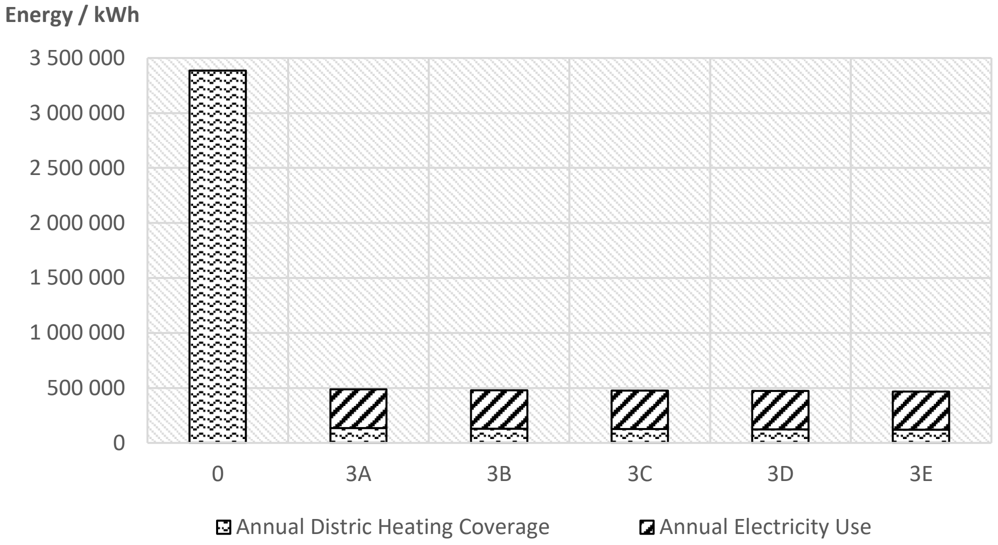


Figure 40 The annual DH and electricity energy use of Case 0 and Case 3

3.4.2. LCC Analysis

3.4.2.1. Annual Heating Energy Expenses

In this case, the annual expenses of heating energy use plummeted to only one-fifth of the existing one. Figure 41 shows that the figure decreased from 2.5 million SEK to around 500 SEK.

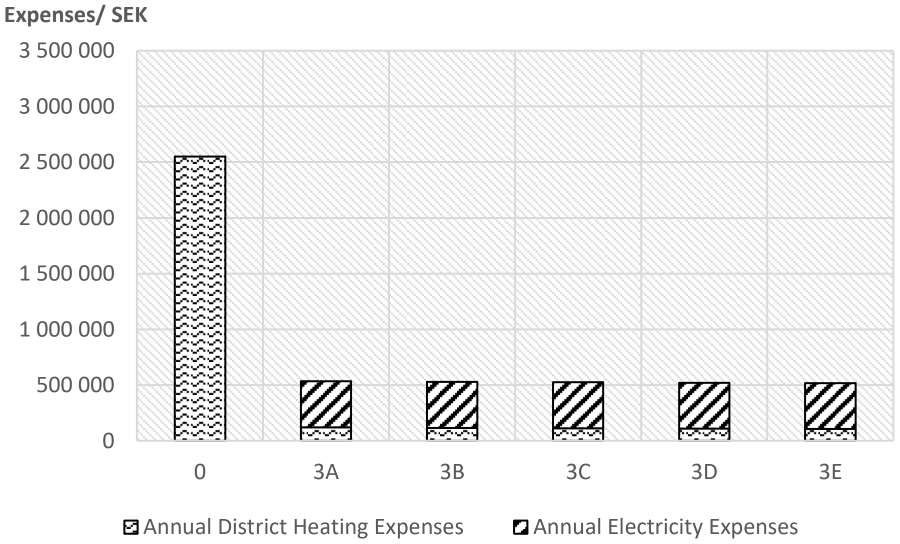


Figure 41 The annual expenses on the DH and electricity energy of Case 0 and Case 3

3.4.2.2. Renovation Expenses

The starting fixed cost of the case is shown in Figure 42. More than 50 % of the total cost is constituted of the cost of the window installation. As shown, the price of the insulation is the only cost that changed as the insulation thickness increased gradually from 120 mm in Case 3A to 280 mm in Case 3E. However, the increment is minor compared to the total fixed cost.

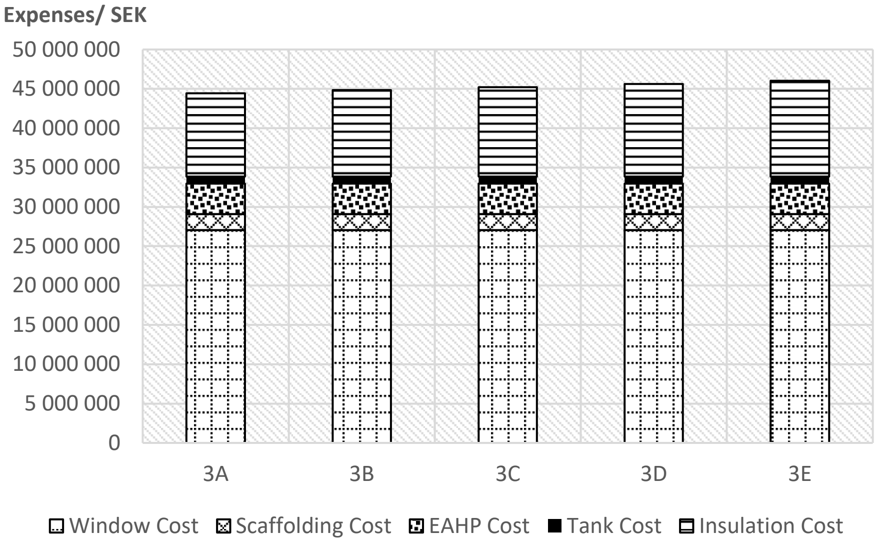


Figure 42 The initial renovation expenses of Case 3

As for the maintenance cost of Case 3, it is the same with the maintenance cost of Case 2. (See Table 17)

3.4.2.3. Net Present Value and Payback Time

Figure 43 shows the net present value of each case in Case 3 over 50 years. The curves, which are hardly distinguished from one another, show the fact that the increment of the insulation thickness did not give a considerable effect on both heating energy use and the cost. Besides, all of the curves seem to pass the breakeven point line in the same year.

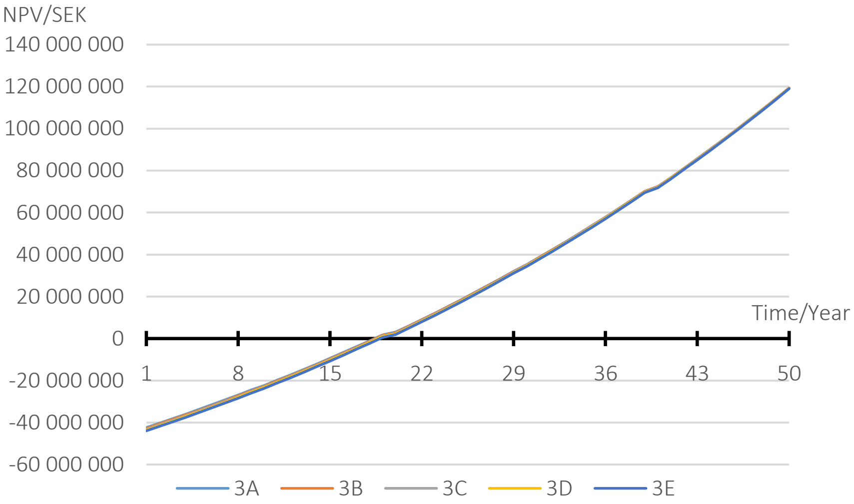


Figure 43 The NPV of Case 3 over a 50-year period of LCC analysis

Nonetheless, taking a closer look, Figure 44 depicts more clearly that Case 1A got the payback 18.5 years after the renovation, followed by the others.

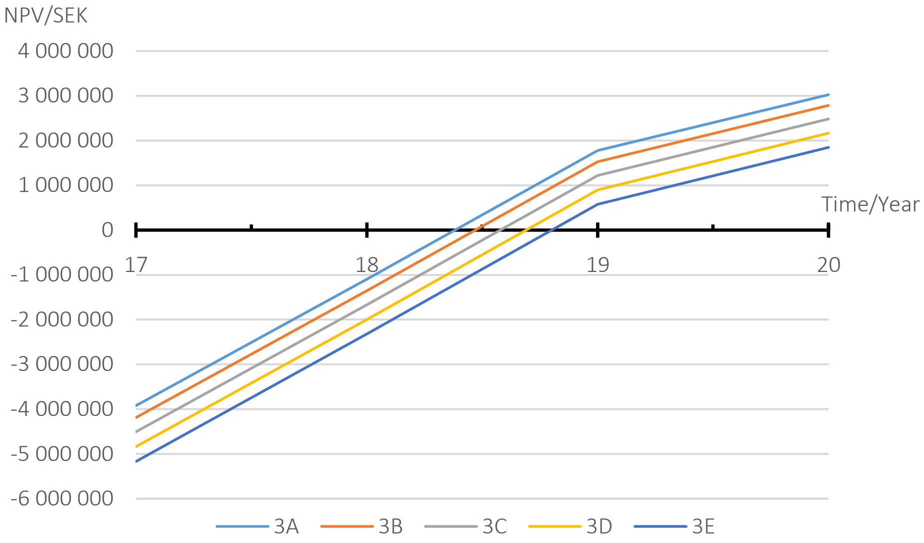


Figure 44 The NPV of Case 3 (between year 17- year 20)

Table 19 below shows the accumulative net saving after a period of 35 years and 50 years. As previously mentioned, the net saving was calculated by accumulating the saving on the heating energy expenses after the payback was met.

Table 19 The accumulative net saving of Case 3

Case	Net Saving after 35 Years	Net Saving after 50 Years	Unit
3A	53 907 000	119 294 000	SEK
3B	53 819 000	119 395 000	SEK
3C	53 610 000	119 301 000	SEK
3D	53 371 000	119 159 000	SEK
3E	53 130 000	119 014 000	SEK

The expenses listed in Table 20 consists of the renovation cost, the maintenance cost, and the annual heating energy cost for a period of time.

Table 20 The accumulative expenses of Case 3

Case	Expenses after 35 Years	Expenses after 50 Years	Unit
3A	68 717 000	82 489 000	SEK
3B	68 805 000	82 388 000	SEK
3C	69 014 000	82 482 000	SEK
3D	69 253 000	82 624 000	SEK
3E	69 494 000	82 769 000	SEK

3.5. Case 4

3.5.1. Heating Energy Performance and Supply

Since the renovation implemented in Case 4 was only an improvement regarding the energy supply, both the heating energy use and the peak load of each building in Case 4 remained the same with that of the existing one, Case 0. (See Table 14)

However, the difference lies on the supply of heating energy. The heating energy need was supplied entirely by only district heating in Case 0 while it is covered completely by the GSHP system in Case 4.

As was mentioned before, the GSHP systems have a COP of 3.3, 3.2, and 3.5 for the building A1, A2, and A3 respectively. Thus, the electricity energy needed is much less than the heating energy need of the cluster (see Figure 45).

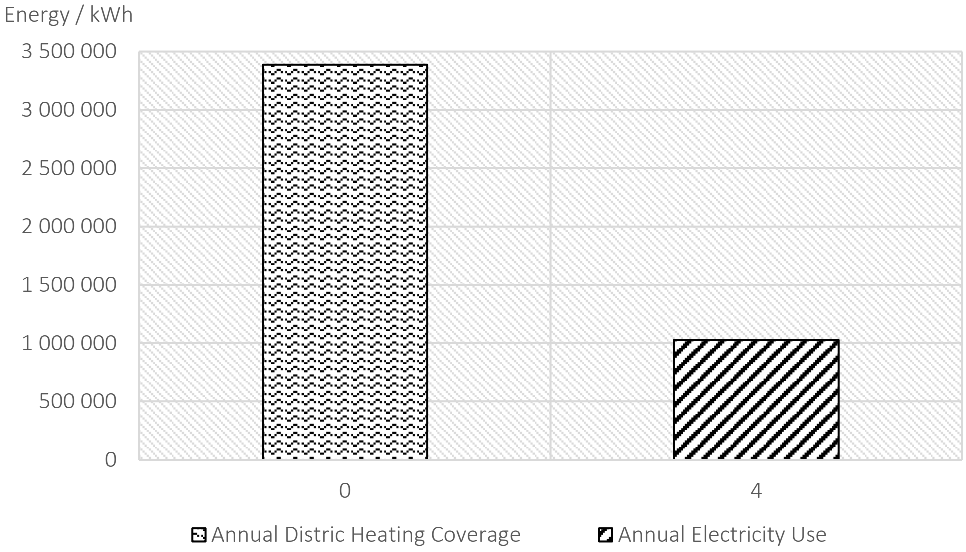


Figure 45 The annual DH and electricity energy use of Case 0 and Case 4

3.5.2. LCC Analysis

3.5.2.1. Annual Heating Energy Expenses

Figure 46 below demonstrates the annual expenses on the energy needed to supply the required heating energy in the buildings. The figure decreased by more than 50 % to 1 202 920 SEK from around 2.5 million SEK.

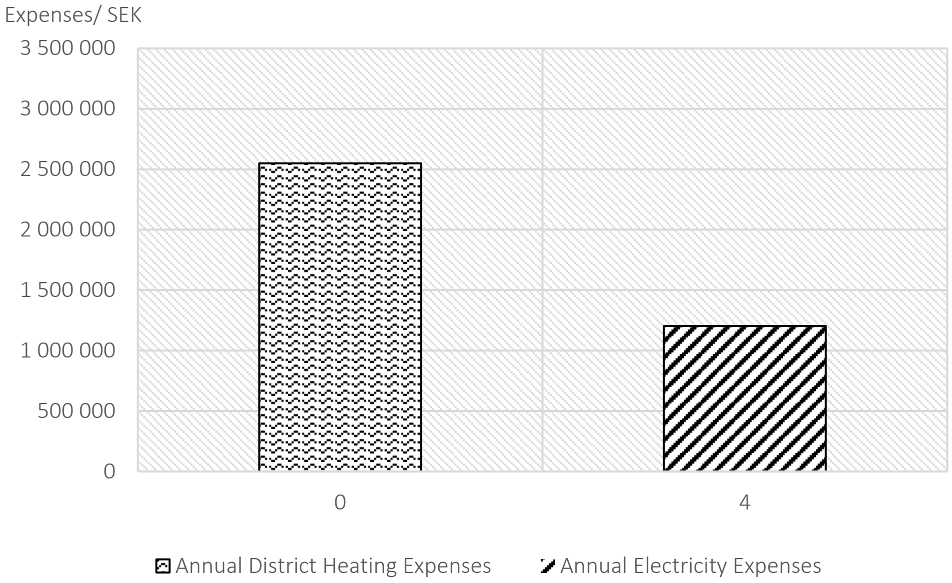


Figure 46 The annual expenses on the DH and electricity of Case 0 and Case 4

3.5.2.2. Renovation Expenses

The fixed starting cost of the renovation is 14.6 million SEK for Case 4. This cost comprises of the material cost, the wage, and the overhead charge on the wage.

Besides, Table 21 shows the maintenance costs needed. The costs shown below include both the labor cost and the material cost needed.

Table 21 The maintenance cost and frequency of Case 4

Maintenance Cost	Total Price	Frequency
Heat Pump Maintenance	20 000	Once in a year
Compressor Repair	100 000	Once in ten years
Heat Pump Replacement	1 737 340	Once in twenty years

3.5.2.3. Net Present Value and Payback Time

The NPV of Case 4 over 50 years is illustrated in Figure 47 below. As demonstrated, the curve crosses the 0 line at between the 9th and 10th year, indicating that it reaches the payback condition. From that point on, the saving started to develop as a profit. Besides, it can be seen from the illustration that there are bumps on the curve when it passes the x-axis of the 20th and 40th year. This is as a result of the heat pump replacement cost that happened once every 20 years.

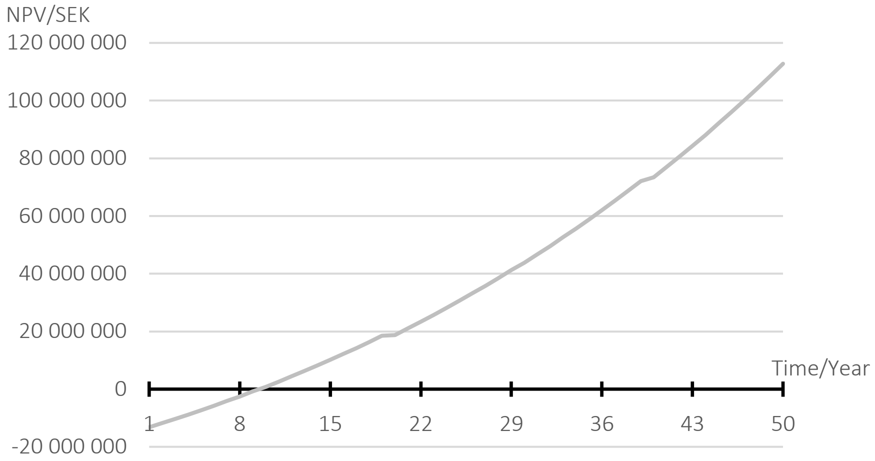


Figure 47 The NPV of Case 4 over a 50-year period of LCC analysis

As for the accumulative net saving and the expenses in 35 years and 50 years, they can be seen in Table 22. In 35 years, the accumulative net saving of the case after getting the payback was around 59 million SEK, while the total expenses of the renovation, the maintenances, and the annual heating energy expenses reached approximately 64 million SEK. As can be seen, the accumulative net saving increased for almost double the amount in 35 years only 15 years after that.

Table 22 The accumulative net saving and expenses of Case4

Case 4	After 35 Years	After 50 Years	Unit
Net Saving	58 812 000	112 778 000	SEK
Expenses	63 812 000	89 005 000	SEK

3.6. Case 5

3.6.1. The Heat Loss Calculation Result

The pipe diameters and the pipe length are shown in *Table 23*. The heat loss calculation result is shown in *Table 24*. As the floor plan with the pipes of the A3 building was missing, the pipe length was guessed based on the A1 and A2 pipe length.

Table 23 The underground pipes length of the building in the cluster

	Pipe diameter			
Building	15mm	18mm	20mm	Unit
A1	24.4	100	10.8	m
A2	122.2	163.4	\	
A3	56.9	35	\	

Table 24 The heat loss calculation result

	Heat loss	Unit
Internal	0.9	kWh/y/m²
External	9.8	kWh/y/m²

3.6.2. Heating Energy Performance and Supply

When the individual substations were implemented to each building in the cluster, it was considered in Case 5. The heat loss through the underground pipes was eliminated. As a result, Figure 48 demonstrates the improvement of the annual heating energy use of the building.

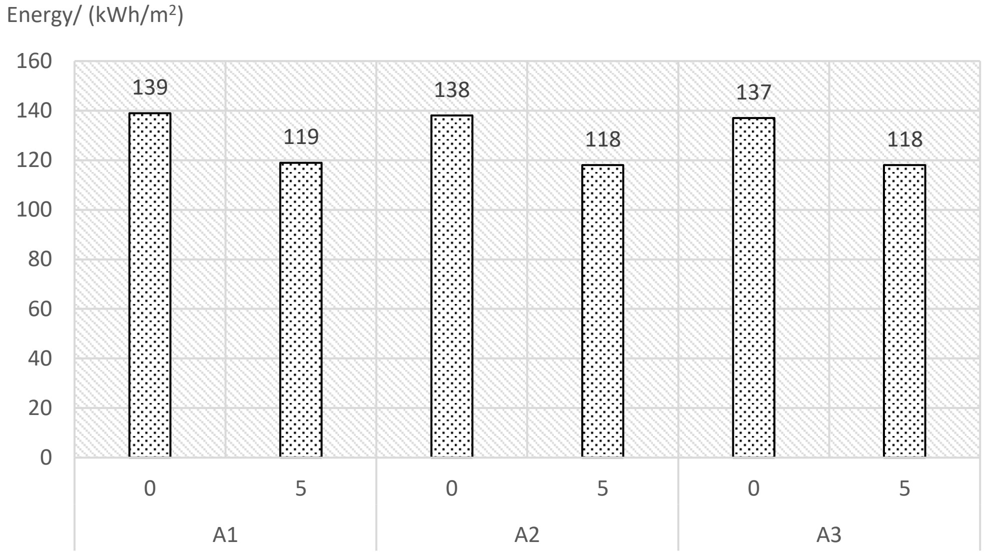


Figure 48 Annual heating energy demand of Case 0 and Case 5

Likewise, the peak load of the buildings in the cluster also decreased. Figure 49 depicts the minor decrement of the peak load in building A1, A2, and A3.

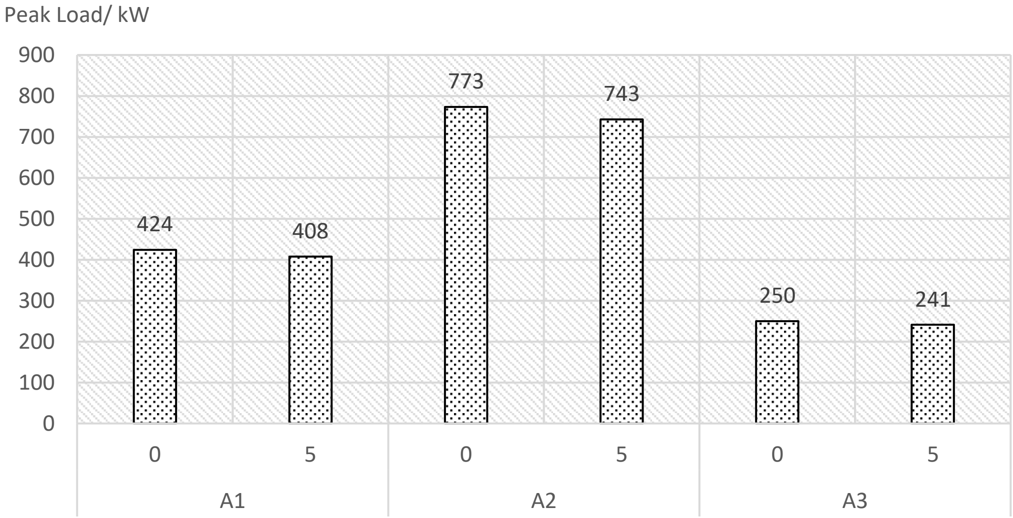


Figure 49 The peak load of Case 0 and Case 5

Similar to Case 1, the heating energy supply of this case is only by the district heating. Figure 50 below shows the annual heating energy need that comprises of the air heating energy, the DHW heating energy, and the heat loss through underground pipes. The annual heating energy need decreased for around 500.000 kWh when the individual substations were implemented in the existing building.

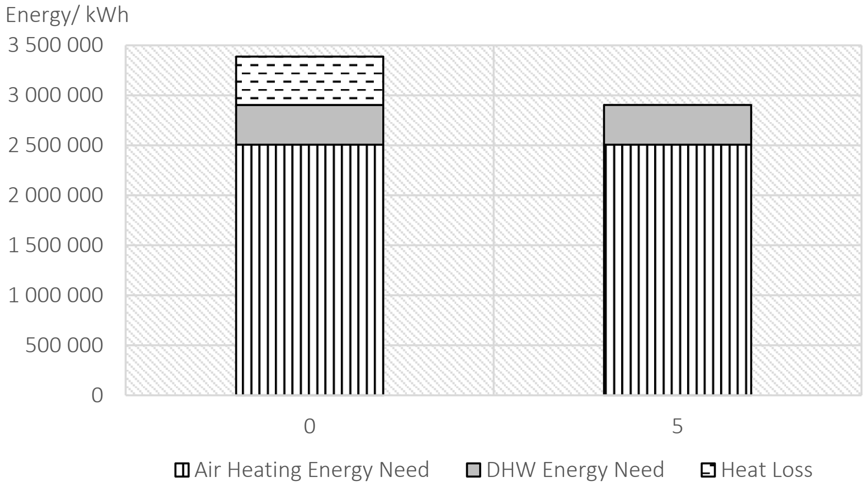


Figure 50 The annual air and DHW heating energy demand as well as the heat loss through the underground pipes of the Case 0 and Case 5

3.6.3. LCC Analysis

3.6.3.1. Annual Heating Energy Expenses

The annual expenses on heating energy need of Case 5 are shown in Figure 51. Just like in the existing case, the expenses on air heating energy need dominated the total of the cost. The refurbishment succeeded in slightly decreasing the annual expenses for 272.834 SEK by cutting out the expenses due to the heat loss through the underground pipes.

Figure 51 The annual expenses on air and DHW heating energy demand as well as the heat loss through the underground pipes of the Case 0 and Case 5

The initial fixed cost of the renovation of this case was 718 771 SEK. It comprises of the cost of the new individual substations including the new heat exchangers and also the cost of connecting the individual substation in building A1 and building A3 to the DH piping system (since the substation in building A2 was already connected to the DH piping system). The details of the initial cost can be seen in Appendix E. Regarding the maintenance cost, the maintenance of the heat exchangers took place once every six years for 5 100 SEK per maintenance.

3.6.3.2. Net Present Value and Payback Time

Figure 52 illustrates the NPV of Case 5 over 50 years period. The payback time was met around two and a half years after the renovation.

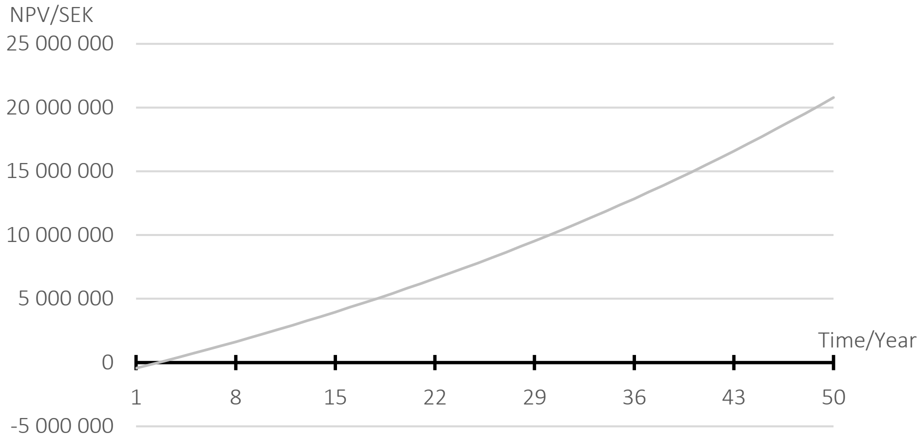


Figure 52 The NPV of Case 5 over a 50-year period of LCC analysis

The net saving and the expenses in 35 years and 50 years after the renovation are shown in Table 25.

Table 25 The accumulative net saving and expenses of Case 5

Case 5	After 35 Years	After 50 Years	Unit
Net Saving	12 363 000	20 790 000	SEK
Expenses	110 262 000	180 994 000	SEK

4. Discussion

4.1. Energy Performance and Supply

Concerning the heating energy use performance, it is obvious in Figure 53 that Case 2 and Case 4 have the same amount of heating energy need as that in Case 0, the existing building. When an EAHP and GSHP system were introduced to the building in Case 2 and Case 4 respectively, the heating energy use of the building remained the same since there was no improvement concerning heat loss of the building. However, as it is shown, the heating energy need in Case 2 is then supplied by the EAHP for about 50 %. As for Case 4, the GSHP system supplies the entire heating energy need of the cluster.

As for Case 5, the heating energy needs decreased due to the adding of individual district heating substation in the building A1 and A3 that completely cut off the huge heat loss through the underground pipes. These pipes were previously connecting the building A1 and A3 to the building A2 where the only district substation was located. When the district heating individual substations were installed, the hot water circulation among the buildings was no longer needed. However, it is worth mentioning that the cutting of heat loss is beneficial only for the side of the owner of the cluster, but the heat loss is still there on the district heating supplier side. That is to say, the corresponding heat loss is not eliminated but relocated instead.

As was mentioned before, building envelope plays a significant role in keeping heat inside the building by slowing down the heat transfer from inside the building. The addition of new insulation layers and the replacement of the windows in Case 1 and Case 3, which also helped to increase the airtightness of the building envelope, cut down the heating energy need of the cluster for around 60 % of the existing case. That is to say, in terms of the saving of heating energy use, both Case 1 and Case 3 performed the best among the other cases. And among the variations of Case 1 and Case 3, variation E achieved the most heat energy saving. However, as illustrated below, the difference among the variations seems negligible.

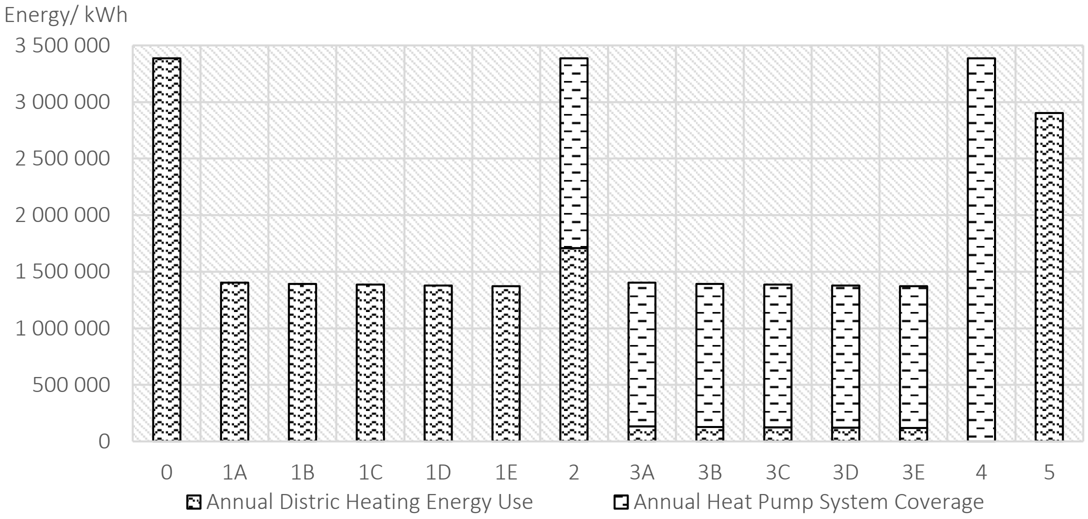


Figure 53 The annual heating energy demand of all of the cases

Even the fact that Case 2 and Case 4 had the same heating energy need as Case 0, Figure 54 illustrated that they required different amounts of energy to supply the heating energy since they have different energy supply systems. For Case 2, half of the heating energy need is supplied by the EAHP system, and since the EAHP used has the COP of 3.6, the needed electricity energy to run the EAHP is less than the heating energy that the EAHP produced. Likewise, the GSHP system in Case 4 consumed electricity energy as little as 30 % of the heating energy demand that it supplied. As a result, looking only at the needed energy to supply the heating energy to the building, Case 4 performed better than Case 2 and even Case 1 and Case 5 that, even had a better performance in terms of heating energy saving, was supplied entirely by the district heating.

Even though Case 1 and Case 3 had the same performance in saving the heat energy, all the variations in Case 3 required less energy to supply the heating energy need compared to the other cases since the EAHP with COP of 3.6 was also installed in Case 3.

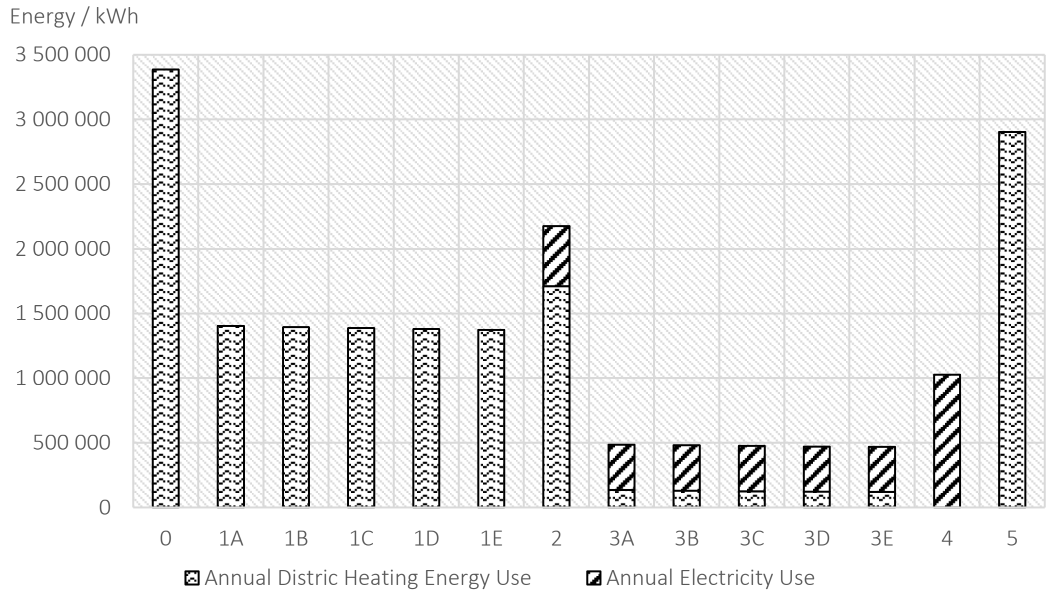


Figure 54 The annual DH and electricity energy use of all of the cases

4.2. Annual Heating Energy Expenses

As can be seen, Figure 55 below is similar to Figure 54. Concerning the annual heating energy expenses, Case 5 spent slightly less than the existing case. A bit lower than that, Case 2 spent a total of around 2.1 million SEK for both electricity and district heating energy annually. Case 4 that was entirely supplied by the GSHP spent even lesser on only electricity energy. And obviously, Case 3 had the lowest annual expenses among all the cases, even compared to Case 2 that had the same heat energy saving as Case 3. That is to say, the expenses on annual heating energy in a building depend not only on the heating energy saving but also on the energy supply system of the building.

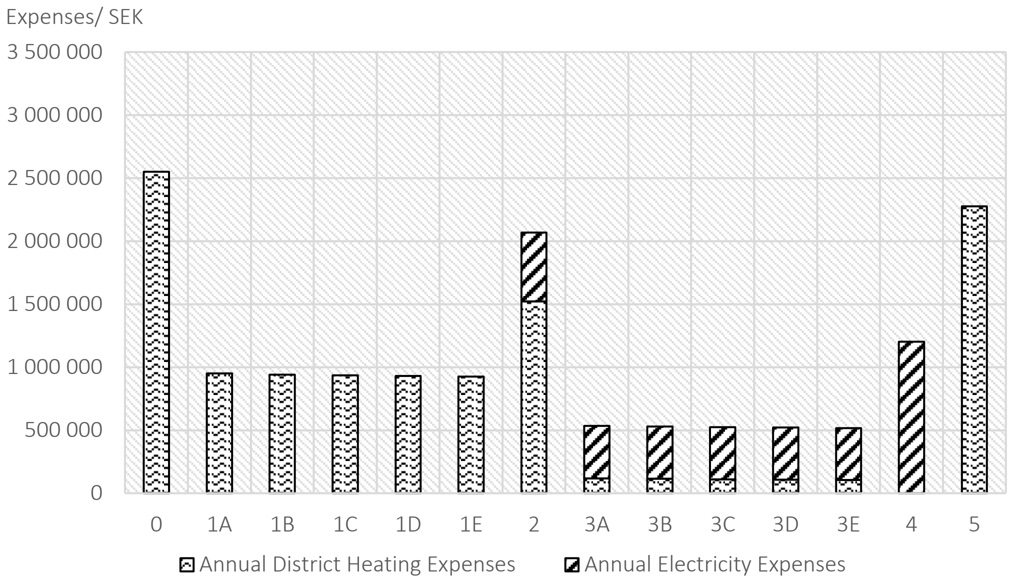


Figure 55 The annual expenses on DH and electricity energy use of all of the cases

4.3. Renovation Expenses

As illustrated before in Figure 28, even though there is an increment of the total fixed cost of the renovation for each case in Case 1, the difference among them is insignificant compared to the total amount itself. This is caused by the fact that the cost of the window replacement, that has the biggest proportion, and the cost of the scaffolding did not change since both of them remained the same for all variations in Case 1. The only change was only in insulation cost. However, the increment is also minor. Figure 28 demonstrates that even when the cost of the material of the insulation increased along with the thickness, the wage cost and the overhead charge on the wage remained the same and constructed more than 70 % of the total insulation installation cost. The same thing can be also observed for Case 3, where the increment of the renovation expenses did not increase significantly.

Comparing the renovation expenses of all cases, Figure 56 illustrates a coherent relation between the renovation expenses and the annual heating energy expenses (see Figure 55). Case 3A that spent the less on the annual heating energy expenses, spent the highest amount of money on the renovation expenses. As opposed to, Case 5 that spent the least on the renovation required to pay the highest amount of annual energy expenses compared to other renovation techniques. Certainly, the existing case needed to spend the most on the annual heating energy expenses since there was no renovation implemented. It can be said that the more expenses are spent on the renovation regarding the heating energy saving and the heating energy supply, the less amount of money is spent on the annual heating energy expenses. But in terms of only renovation expenses, Case 5 spent the least compared to the rest of the cases.

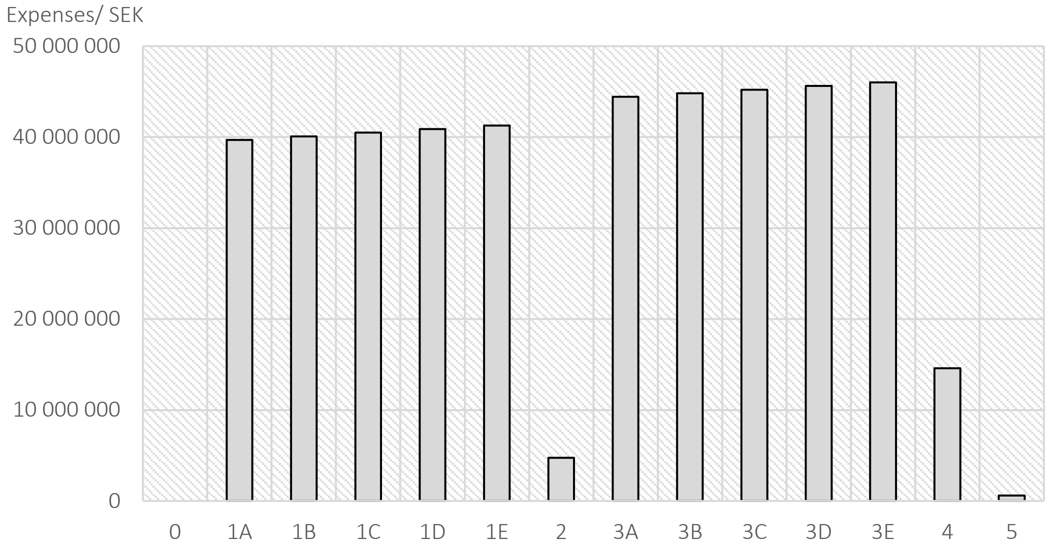


Figure 56 The initial renovation expenses of all of the cases

4.4. Net Present Value and Payback Time

Even though Case 1A reached the payback time earlier than the other variations in Case 1, Table 15 shows that, after 35 years, the accumulative net saving in Case 1B was the highest among the others. And in 50 years, Case 1D got the highest accumulative net saving. This trend happened for the reason that, when the period of the LCC analysis is longer, the case that was subjected with thicker insulation saved more energy (and thus more money) even though the difference of the annual saving is not that much. This is because the little difference piles up along with time. From another point of view (See Table 16), the LCC analysis with a shorter period (35 years) showed that Case 1B spent lower expenses compared to Case 1C, 1D, and 1E. It is based on evidence that Case 1B has a lower starting fixed cost than the other cases. As for Case 1A, even if it has a lower starting fixed cost than that of Case 1B, the annual expenses on the heating energy is higher than that of Case 1B. And after 35 years, the accumulation of the fixed cost and the annual heating energy cost of Case 1A becomes higher than the same figure of Case 1B. Likewise, the same manner was shown in the 50-Year period LCC analysis.

As Table 19 shows before, Case 3A had the highest NPV of saving 35 years after the renovation. Despite that fact and the fact that Case 3A had earlier payback than other cases, it turned out that Case 3B had the highest NPV of saving after 50 years. It is due to the same fact like that in Case 1D. Case 3B, even if it was not significant, collected the most saving on annual heating energy since it has thicker insulation. From another perspective, Table 20 illustrates the total expenses for 35-year and 50-year period. The expenses include the expenses of the renovation, the annual heating energy, and the needed maintenances. As has been pointed out, Case 3A had the lowest expenses in the 35-year period. It is simply because the fixed starting cost of renovation for this case is the lowest compared to the other cases. On the other hand, Case 3B that spent fewer expenses on annual heating energy saved a bit of the cost steadily every year, resulting in lower total expenses after 50 years compared to Case 3A that had higher annual expenses on heating energy and Case 3C, 3D, and 3E that had higher fixed starting cost of renovation.

As what has been mentioned before, the curves in Figure 57 below represent the difference between the present value of all expenses, including both the renovation expenses and the annual heating energy expenses, and the saving on the annual heating energy expenses over 50 years. The 0 line in the middle of the graph represents the condition where the aforementioned saving is equal to the corresponding expenses. While the crossing point between the curves means that their net present value is equal in that specific year after the renovation.

As illustrated below, the starting point of the Case 5 curve is higher than the other cases since it has the lowest renovation cost. As it was expected, the curve of the Case 5 is the least precipitous among the others since it has the lowest saving on the heating energy expenses, resulting in the lowest net present value over both 35 and 50 years period. Followed by the curve of Case 2 that behaves the same as Case 5. On the other hand, the curves of the variations in Case 3 that have the highest amount of money spent on the renovation are starting the lowest compared to the other cases but finishing the curves on the highest position over 50 years. This is due to the fact that Case 3 has the highest annual saving on heating energy expenses.

Comparing the curves of Case 1 and Case 3, it is clear that all of the curves start almost at the same starting point of around -40 million SEK. The curves of the Case 3 start a bit lower than that of Case 1 due to the installation cost of EAHP. However, because of the higher saving on the energy expenses, the slope of the curves of Case 3 is much steeper than the Case 3, resulting in higher net present value from 10 years after the renovation on.

Interestingly, the curve of Case 4 that spent lower in renovation cost is always on top of the curves of the Case 1 that spent much more on the renovation cost. It is caused by the fact that even though the saving on the annual heating energy expenses of all variations in Case 1 is bigger than that of Case 4, the difference of the saving is not that much compared to the difference of the renovation cost between them (see Figure 55 and Figure 56).

Moreover, it can be observed from the figure below that the curve of Case 5 is always on top of the other curves between 1 year until 11 years after the renovation. Likewise, the net present value of Case 4 continues to be the highest from around year 11 to around year 42. While for the period from year 42 to the end of the analysis period, the curves of the variations in Case 1 prevail as the highest in terms of net present value.

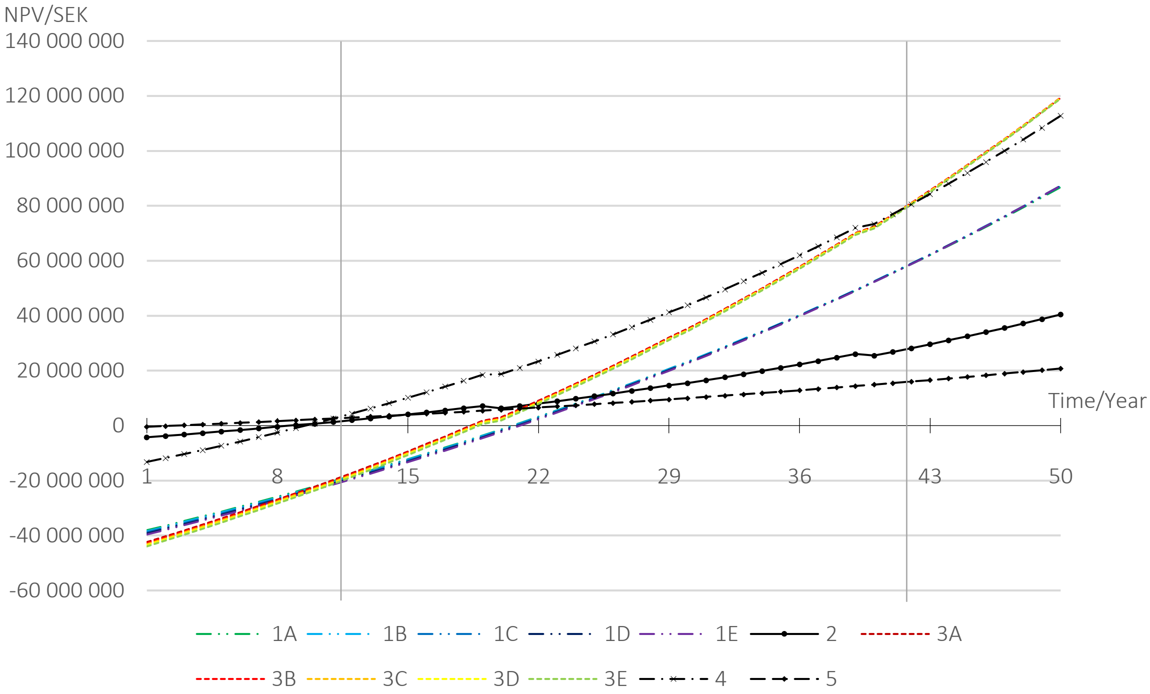


Figure 57 The NPV of all of the cases over a 50-year period of LCC analysis

From the perspective of the payback time, Figure 58 demonstrates the payback time of all of the cases. This figure has a coherent correlation with Figure 56. The less the renovation cost is, the faster the payback time will be. Nonetheless, even though Case 3 has higher renovation costs, all variations in Case 3 get the faster payback than the variations in Case 1. It strengthens the evidence that the adding of the EAHP system, as a heating energy supply in a building that is well insulated, has an excellent impact. The cost of installing a new EAHP system was less than the cost of the insulation and the windows (see Figure 56). The installed EAHP with 3.6 COP reduced the annual energy expenses. As a result, the annual saving on the energy expenses was higher (see Figure 55) and the payback was then reached faster.

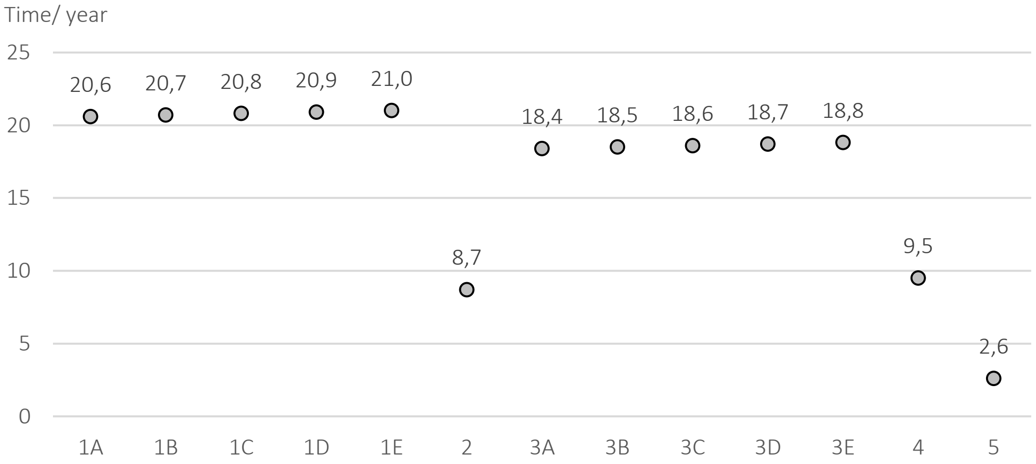


Figure 58 The payback time of all of the cases

4.5. Present Value of Accumulative Net Saving and Expenses in 35 Years

As aforementioned, the present value of the accumulative net saving is the present value of the saving on the energy expenses accumulated since the payback condition is reached. It can also be easily observed by looking at the curves after they pass the 0 line in Figure 57. To be easily grasped, Figure 59 shows that, for the 35-Year period of LCC analysis, Case 4 collected the highest amount of saving on the annual heating energy expenses of about 60 million SEK. As opposed to, Case 5 got the lowest saving after the same period of analysis.

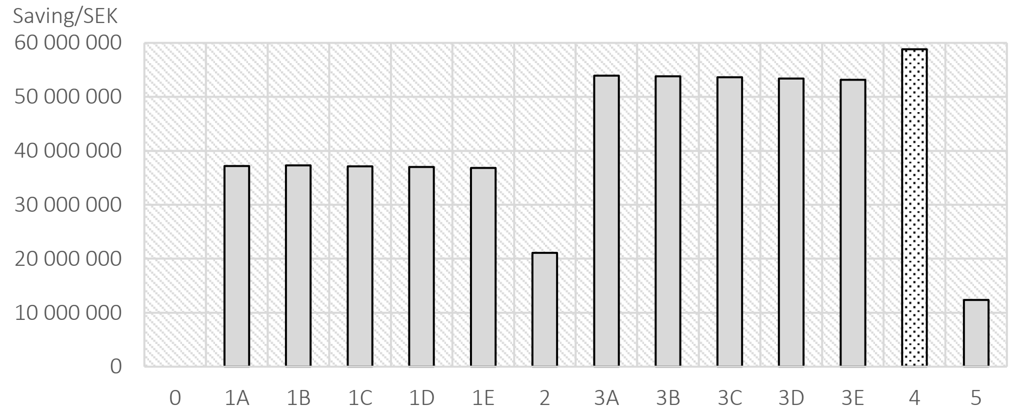


Figure 59 The accumulative net saving of all cases in 35 years

From the point of view of the expenses, which includes the expenses on the renovation, maintenance, and annual heating energy cost, Case 4 spent the least among the other cases (see Figure 60). It saved the highest amount of money that was supposed to be spent on supplying the required heating energy in the existing building.

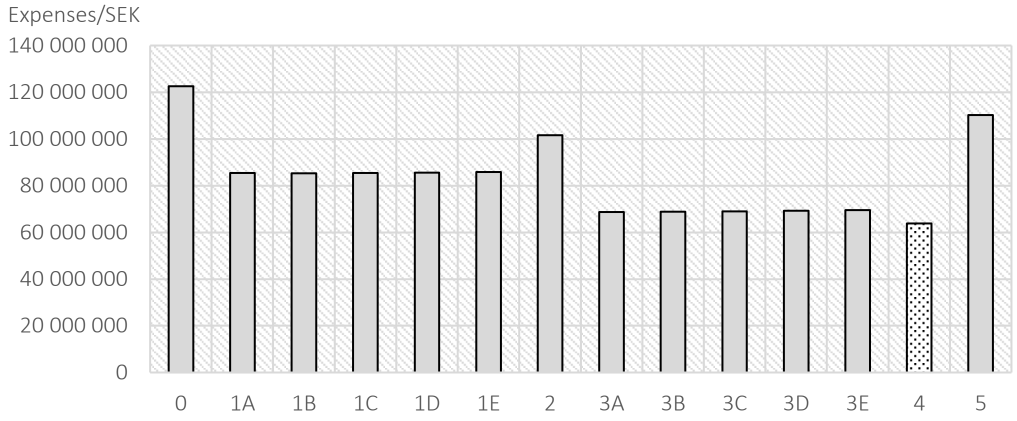


Figure 60 The accumulative expenses of all of the cases in 35 years

4.6. Present Value of Accumulative Net Saving and Expenses in 50 Years

With regard to the 50-Year period of LCC analysis, Case 3B got the highest saving of approximately 119.4 million SEK even though the difference among the variations in Case 3 is hardly noticeable. Similar to what is depicted in the 35-Year period of LCC analysis, Case 5 obtained the lowest amount of saving compared to other cases.

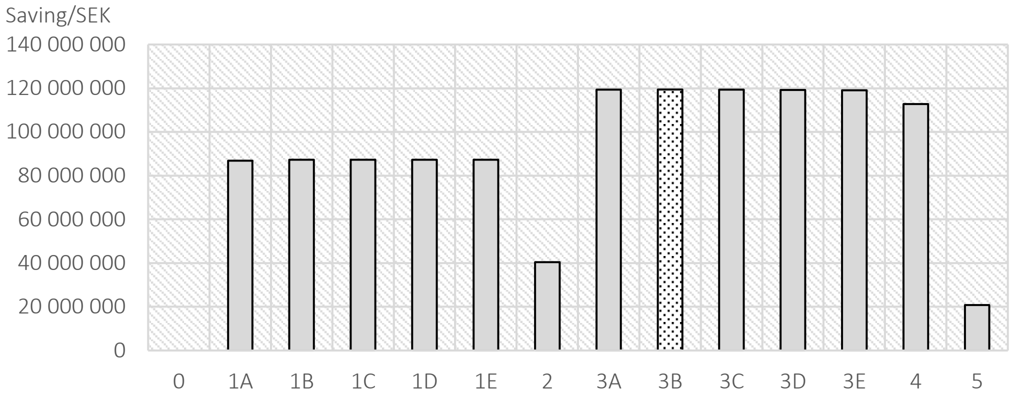


Figure 61 The accumulative net saving of all cases in 50 years

Regarding the overall expenses over the period of 50 years, Case 3B spent the least amount of money compared to the rest of the cases.

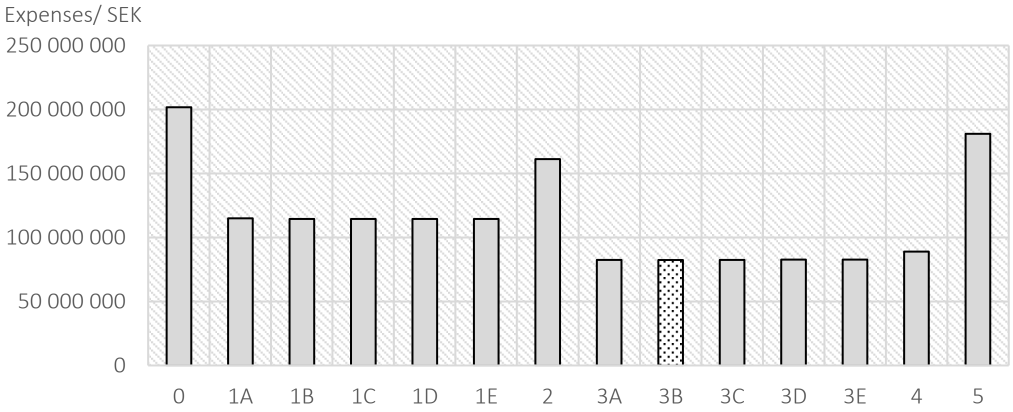


Figure 62 The accumulative expenses of all of the cases in 50 years

5. Conclusion

As it was expected, renovating the envelope of a building by adding insulation and replacing the old windows with new windows that have better thermal performance reduces the heating energy demand of a building. Besides, the assumed improvement of the airtightness of the building also helps to reduce the heating energy demand. However, when an EAHP is also implemented together with the renovation of the building envelope, it will perform better not only for the heating energy demand but also the energy used to supply the demanded heating energy. Thus, in terms of energy saving, Case 3 performed the best in this project.

The implementation of individual substations also reduces heating energy demand. That is to say, installing individual substations is beneficial in terms of saving the annual energy expenses for the building owner's side. However, it should be pointed out that the heating energy loss is not eliminated but rather relocated to the energy supplier company’s side. Moreover, the installation of individual substations might not be significant for a cluster that consists of low-rise buildings that are close to each other since the hot water circulation through the underground pipes might not be as much as that in the case where it consists of high-rise buildings.

Besides, the energy supply system also plays a significant role. The EAHP and GSHP harvest the energy from the surrounding, such as air, water, or ground, in order to help to provide heating energy into a building. The COP of a heat pump system determines how much less electricity needed to meet the heating demand. The combination of improving the building envelopes and introducing a heat pump system has been proved to be an excellent technique in terms of both energy saving and money saving.

The less the heat loss of a building is, the less the expenses on the heating energy use will be. However, saving the expenses on the energy used to heat a building does not always mean that there is a saving on the heating energy demand since the heating energy demand supplied remains the same. However, the use of a heat pump system, such as EAHP that has 3.6 COP in this project, is economically beneficial since with only 1 kWh of electricity energy, 3.6 kWh of the heating energy demand is covered. At the same time, the price of the electricity costs less than 3.6 times the district heating energy price. That is to say, if the price of the electricity is as high as the COP of the heat pump system, the annual expenses on the energy to provide the heating energy demand will be the same.

As commonly known, which renovation technique is the most economically beneficial depends on the price of the materials, wage, maintenance, and the economic parameters, such as the price change of materials, price change of energy, inflation rate, wage growth, and interest rate. Besides, the period chosen to do the LCC analysis is pivotal in choosing the best renovation technique. As if the LCC analysis period is short, it is commonly better to choose a renovation with lower starting fixed costs that will reach the payback condition faster. On the other hand, a renovation with a higher starting fixed cost might be economically feasible with a longer LCC analysis period since it saves much more on the expenses of the annual heating need. However, it is always crucial to compare between the renovation cost and the annual saving on heating energy use in a chosen LCC analysis period. Lastly, the payback time only indicates when the renovation cost is equal to the accumulative annual saving on heating energy use. Thus, giving clear evidence to decide which renovation is not economically feasible in a chosen period of LCC analysis. However, the net present value of each renovation provides more understanding of which renovation is the most beneficial. In this study, the implementation of the GSHP in Case 4 is the most economically feasible for the 35-year period of LCC analysis, while the combination between the adding of 160 mm of insulation, the replacement of the windows and the installation of EAHP in Case 3 is the most beneficial renovation for the 50-year period.

Moreover, the capital of the owner of a building certainly determines the plausible renovation proposals. And the chosen renovation technique that is based on the availability of the capital may not be the most economically feasible choice. Thus, the payback time and the initial or fixed cost of the renovation can be determining factors in choosing the possible renovation technique.

6. Further Research

The building envelope is one of the most pivotal factors to improve the energy performance of a building. As it has been pointed out, as the U-value of the wall layers is being decreased by adding more insulation, the decrement of heating energy demand was not decreasing at the same rate any longer. Thus, it is very crucial to try more variations of thickness for the added insulation for further research. In this project, 5 different thicknesses have been implemented and interpolated, starting from 120 mm to 280 mm. However, a thickness that is less or more than the ones that have been studied might be more optimal in other cases.

Secondly, more combinations between building envelope renovation and energy supply refurbishment might also be studied further. The combination of the adding of insulation, replacing the windows, and using EAHP as an energy supply system has been proved to show the best performance in terms of both the energy saving and the saving of annual energy expenses. However, it might perform even better if the individual substations are also included in the combination since it cuts off unnecessary heat loss and it has a small renovation cost compared to the cost of the insulation, window, and EAHP installation. Moreover, the use of GSHP to take the place of EAHP might also be more advantageous.

Compared to the existing condition, the heating energy demand remained the same when the GSHP system was implemented. Likewise, the heating energy demand of Case 1 and Case 3 was also the same. However, the energy used to meet the heating energy demand was not the same. The study about the life cycle analysis (LCA) can also be conducted in order to choose the better renovation technique in terms of LCA.

As for the individual substations' renovation, the length and the number of the pipes underground are not known so far. Also, the insulation of the pipes inside the buildings and walls are not visible, the calculation result is thus an indication. Further studies with more detailed information should be carried out in the future.

In this project, the size of the EAHP and the GSHP did not vary. Only one size of them was being studied. However, the smaller size of EAHP and GSHP might be better when the building envelope is also refurbished, as the heating energy demand will not be as high. That is to say, the capacity of the heat pump system can be lower and thus, the fixed starting cost and the maintenance cost needed will be also lower. The lower fixed starting cost of the renovation might have then a determining impact on the LCC analysis.

As was mentioned before, the economic parameters are determining factors for the LCC analysis result. Thus, the study based on different scenarios of the economic parameters is interesting to be conducted in the future to understand the effects of each economic parameter. The change of the economic parameters will change the inclination of the curves in the NPV graph and thus, will lead to different payback times and accumulative net saving for each of the renovations. Moreover, the study about the increment of property value due to the low operational cost caused by the renovation is also an interesting topic in terms of the LCC Analysis.

References

• *Sweden: Electricity prices 2018 | Statista* (no date). Available at: https://www.statista.com/statistics/418124/electricity-prices-for-households-in-sweden/ (Accessed: 10 May 2020).

Adalberth, K. (2016) 'Kv Eddans pilothus - energi Stadsdelsförnyelse av Kv Eddans pilothus - energi', 46.

Ahmadi, M. and Yousefi, T. (2009) 'Numerical analysis of heat transfer in a double glass window Mobile Sorption Cooling System Design View project Modeling the Free Convection Heat Transfer in a Horizontal Cavity with Flow Diverters Using Adaptive Neuro-Fuzzy Inference System View project ', (August). doi: 10.13140/2.1.2586.5920.

Akyüz, M. K., Altuntaş, Ö. and Söğüt, M. Z. (2017) 'Economic and environmental optimization of an airport terminal building's wall and roof insulation', *Sustainability (Switzerland)*, 9(10). doi: 10.3390/su9101849.

Aldawoud, A. (2017) 'Assessing the energy performance of modern glass facade systems', *MATEC Web of Conferences*, 120, pp. 1–7. doi: 10.1051/matecconf/201712008001.

Aspirebifolds (no date) *What are typical U-Values on windows and doors? | Aspire Bifolds Surrey*. Available at: https://www.aspirebifolds.co.uk/2018/03/what-are-typical-u-values-on-windows-and-doors/ (Accessed: 7 May 2020).

Bagge, H., Johansson, D. and Lindstrii, L. (2015) 'BRUKARRELATERAD ENERGIANVÄNDNING Mätning och analys av hushållsel och tappvarmvatten'.

BRE (2018) 'External Wall Insulation (EWI) Project guide'. Available at: https://gov.wales/sites/default/files/publications/2019-04/external-wall-insulation-project-guide.pdf.

Daouas, N. (2011) 'A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads', *Applied Energy*. Elsevier Ltd, 88(1), pp. 156–164. doi: 10.1016/j.apenergy.2010.07.030.

EC (2016) '2020 Climate & Energy Package', *Http://Ec.Europa.Eu/Clima/Policies/Strategies/2020/Index_En.Htm*, p. Browsed on 22nd Dec., 2015. Available at: https://ec.europa.eu/clima/policies/strategies/2020_pt (Accessed: 7 May 2020).

EN (2010) 'Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings', *Official Journal of the European Union*, pp. 13–35. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN (Accessed: 9 May 2020).

European Commission (2011) 'Energy Efficiency Plan 2011', *Energy*, p. 16. doi: SEC(2011) 277 final.

European Commission (2014) *2030 Climate & Energy Framework*, *Report*. doi: 10.1007/s13398-014-0173-7.2.

European Commission (2018) *2050 long-term strategy | Climate Action*, *2050 Long-Term Strategy*. Available at: https://ec.europa.eu/clima/policies/strategies/2050_en (Accessed: 7 May 2020).

Fehrm, M., Reiners, W. and Ungemach, M. (2002) ‘Exhaust air heat recovery in buildings’, in *International Journal of Refrigeration*. Elsevier, pp. 439–449. doi: 10.1016/S0140-7007(01)00035-4.

Fernando, P. *et al.* (2004) ‘Propane heat pump with low refrigerant charge: Design and laboratory tests’, *International Journal of Refrigeration*, 27(7 SPEC. ISS.), pp. 761–773. doi: 10.1016/j.ijrefrig.2004.06.012.

Ferrari, E. (2012) ‘Competing Ideas of Social Justice and Space: Locating Critiques of Housing Renewal in Theory and in Practice’, *International Journal of Housing Policy*, 12(3), pp. 263–280. doi: 10.1080/14616718.2012.709668.

Fischer, D. and Madani, H. (2017) ‘On heat pumps in smart grids: A review’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 70, pp. 342–357. doi: 10.1016/j.rser.2016.11.182.

GEARS (2013) *External Wall Insulation: Everything You Need To Know*. Available at: http://gogreena.co.uk/external-wall-insulation-everything-you-need-to-know/ (Accessed: 9 May 2020).

Gehlin, S. and Andersson, O. (2016) *Geothermal Energy Use, Country Update for Sweden*, *European Geothermal Congress*. Available at: www.igrene.se (Accessed: 9 May 2020).

Green Match (2020) *Air-water heat pump - Price and information | Varmepumppriser.se*. Available at: https://www.varmepumppriser.se/luft-vattenvaermepump (Accessed: 29 May 2020).

Hepbasli, A. and Kalinci, Y. (2009) ‘A review of heat pump water heating systems’, *Renewable and Sustainable Energy Reviews*. Pergamon, pp. 1211–1229. doi: 10.1016/j.rser.2008.08.002.

Historic inflation Sweden – historic CPI inflation Sweden (no date). Available at: https://www.inflation.eu/inflation-rates/sweden/historic-inflation/cpi-inflation-sweden.aspx (Accessed: 10 May 2020).

Högberg, L., Lind, H. and Grange, K. (2009) ‘Incentives for improving energy efficiency when renovating large-scale housing estates: A case study of the swedish million homes programme’, *Sustainability*, 1(4), pp. 1349–1365. doi: 10.3390/su1041349.

III, J. W. and Smith, M. R. (1998) *Life-Cycle Cost Analysis in Pavement Design- In Search of Better Investment Decisions*. Available at: https://books.google.se/books/about/Life_cycle_Cost_Analysis_in_Pavement_Des.html?id=f0FMwwy8Q-EC&redir_esc=y (Accessed: 10 May 2020).

Johansson, D. (2009) ‘The life cycle costs of indoor climate systems in dwellings and offices taking into account system choice, airflow rate, health and productivity’, *Building and Environment*. Pergamon, 44(2), pp. 368–376. doi: 10.1016/j.buildenv.2008.03.011.

Jonasson (2019) ‘Market Report : Sweden’, *Swedish Refrigeration & Heat Pump Association*, 37(1), pp. 21–26.

Joshi, S. (2010) *AIA Guide to Building Life Cycle Assessment in Practice Authorship and Acknowledgements A Guide to Life Cycle Assessment of Buildings 2*.

Lind, H. (2015) ‘The Effect of Rent Regulations and Contract Structure on Renovation: A Theoretical Analysis of the Swedish System’, *Housing, Theory and Society*. Routledge, 32(4), pp. 389–406. doi: 10.1080/14036096.2015.1053981.

Lindahl, J. *et al.* (2019) ‘National Survey Report of PV Power Applications in Sweden 2018 Task 1 Strategic PV Analysis and Outreach’. Available at: www.iea-pvps.org (Accessed: 10 May 2020).

Liu, L. *et al.* (2014) ‘Comprehensive investigation on energy retrofits in eleven multi-family buildings in Sweden’, *Energy and Buildings*. Elsevier B.V., 84, pp. 704–715. doi: 10.1016/j.enbuild.2014.08.044.

LTH AEBF10 (no date) *LTH Courses | AEBF10, Energianvändning och termisk komfort i byggnader*. Available at: https://kurser.lth.se/lot/?val=kurs&kurskod=AEBF10&lang=en (Accessed: 14 May 2020).

Lund, J. W. and Boyd, T. L. (2015) *Direct Utilization of Geothermal Energy 2015 Worldwide Review*, *Proceedings World Geothermal Congress*.

Mangan, S. D. and Oral, G. K. (2016) ‘Assessment of residential building performances for the different climate zones of Turkey in terms of life cycle energy and cost efficiency’, *Energy and Buildings*. Elsevier Ltd, 110, pp. 362–376. doi: 10.1016/j.enbuild.2015.11.002.

Morelli, M. *et al.* (2011) ‘Holistic energy retrofitting of multi-storey building to low energy level’, pp. 1323–1330.

National Board of Housing, B. and P. (2018) ‘Boverket´s mandatory provisions and general recommendations , BBR’, 1(154), pp. 1–154. Available at: https://www.boverket.se/en/start/publications/publications/2019/boverkets-building-regulations--mandatory-provisions-and-general-recommendations-bbr/.

NORDPOOL (2019) *Historical Market Data*, *Nordpool*. Available at: https://www.nordpoolgroup.com/historical-market-data/ (Accessed: 10 May 2020).

NREL (2017) *OpenStudio | OpenStudio*, *2017*. Available at: https://www.openstudio.net/ (Accessed: 11 May 2020).

Öresundskraft (2020) *ENERGIDEL FAST DEL*.

Pullen, T. (2018) ‘Internal Wall Insulation Guide’. Available at: https://www.homebuilding.co.uk/internal-wall-insulation/.

Rønneseth, Ø., Sandberg, N. H. and Sartori, I. (2019) ‘Is it possible to supply Norwegian apartment blocks with 4th generation district heating?’, *Energies*, 12(5). doi: 10.3390/en12050941.

Samir (2012) *Heat Loss From An Insulated Pipe | Excel Calculations*. Available at: http://excelcalculations.blogspot.com/2012/12/heat-loss-from-insulated-pipe.html (Accessed: 15 May 2020).

Statistics (no date). Available at: http://www.energimyndigheten.se/en/facts-and-figures/statistics/ (Accessed: 7 May 2020).

Sweden - Salary Growth (no date). Available at: https://sv.tradingeconomics.com/sweden/wage-growth (Accessed: 10 May 2020).

Swedish Energy Agency (2014) *Swedish Energy Agency*. Available at: http://www.energimyndigheten.se/en/ (Accessed: 9 May 2020).

‘Technical Data - Triple Glazing’ (no date), p. 673.

Troi, A. and Bastian, Z. (2015) *Energy efficiency solutions for historic buildings: A handbook*, *Energy Efficiency Solutions for Historic Buildings: A Handbook*. Birkhauser Verlag AG.

Turkington, R. *et al.* (2004) *High-rise housing in Europe High-rise housing in Europe Current trends and future prospects 28*, *Housing and Urban Policy Studies 28*. Delft University Press.

Valdbjorn Rasmussen, T. (2012) ‘Retrofitting Listed Buildings: Measures, Savings and Requirements’, *The Open Construction and Building Technology Journal*. Bentham Science Publishers Ltd., 5(1), pp. 174–181. doi: 10.2174/1874836801105010174.

Verbeeck, G. and Hens, H. (2005) ‘Energy savings in retrofitted dwellings: Economically viable?’, *Energy and Buildings*. Elsevier, 37(7), pp. 747–754. doi: 10.1016/j.enbuild.2004.10.003.

Wikells (2019a) *Sektionsfakta ROT*. Available at: https://sektionsfakta.se/Account/Login.aspx?ReturnUrl=%2F (Accessed: 10 May 2020).

Wikells (2019b) *Sektionsfakta VSS*. Available at: https://sektionsfakta.se/Account/Login.aspx?ReturnUrl=%2F (Accessed: 10 May 2020).

Zhang, J., Wang, R. Z. and Wu, J. Y. (2007) ‘System optimization and experimental research on air source heat pump water heater’, *Applied Thermal Engineering*, 27(5–6), pp. 1029–1035. doi: 10.1016/j.applthermaleng.2006.07.031.

Appendix

1. Appendix A

Report of Energy used for Heating of the existing building.

District Heating Energy Use [kWh/m^2]					
Month	2014	2015	2016	2017	2018
January	16.8	16.4	16.7	18.1	17.4
February	14.0	14.9	15.1	15.7	16.2
March	11.7	12.8	13.4	13.8	15.7
April	8.2	8.4	8.9	10.5	8.4
May	5.0	5.6	5.2	5.7	4.5
June	3.8	3.9	3.6	3.7	3.2
July	3.3	3.5	3.3	3.5	3.0
August	3.4	3.4	3.4	3.5	3.1
September	3.9	4.1	3.8	4.3	4.0
October	6.2	6.6	7.4	5.4	6.9
November	10.3	10.3	12.3	15.0	11.5
December	15.1	12.5	15.3	15.5	16.0
Annual Total	**101.6**	**102.3**	**108.3**	**114.5**	**109.9**
Electricity Energy Use for Heating [kWh/m^2]					
Month	2014	2015	2016	2017	2018
January	0.8	1.1	0.7	0.4	0.7
February	1.2	0.9	0.8	0.6	0.2
March	1.4	1.4	1.2	1.4	0.4
April	1.1	1.1	1.2	1.2	1.2
May	0.5	0.7	0.6	0.7	0.3
June	0.2	0.0	0.0	0.1	0.0

July	0.0	0.0	0.0	0.0	0.0
August	0.1	0.0	0.0	0.1	0.0
September	0.3	0.4	0.2	0.6	0.5
October	1.1	1.4	1.3	1.5	1.2
November	1.4	1.6	1.0	1.4	1.2
December	1.1	2.0	1.1	1.3	1.0
Annual Total	**9.2**	**10.7**	**8.1**	**9.0**	**6.8**

2. Appendix B

Inputs for Hand Calculation and Energy Simulation

List of Constant Parameters	Hand Calculation	Energy Simulation						Unit
	Case 0	Case 0	Variation A	Variation B	Variation C	Variation D	Variation E	
Heated Floor Area	24 532	24 532	24 532	24 532	24 532	24 532	24 532	m^2
Building Envelope Area	13 829	13 829	13 829	13 829	13 829	13 829	13 829	m^2
Glazing Area	3 580	3 580	3 580	3 580	3 580	3 580	3 580	m^2
Roof Area	3 149	3 149	3 149	3 149	3 149	3 149	3 149	m^2
Loads Schedule of Apartment	24	Honeybee Zone Program Schedule						h
Loads Schedule of Basement	24							h
Infiltration Schedule	24							h
Ventilation Schedule	24							h

Occupancy Schedule	-							h
Lighting Schedule	-							h
Equipment Schedule	-							h
Heating Setpoint of Apartment	21	21	21	21	21	21	21	°C
Heating Setpoint of Basement	21	18	18	18	18	18	18	°C
Infiltration Rate of Basement Floors	4	4	4	4	4	4	4	ACH
	0.003	0.003	0.003	0.003	0.003	0.003	0.003	$m^3/(m^2 \cdot s)$
Infiltration Rate of Apartment Floors	4.0	4.0	0.8	0.8	0.8	0.8	0.8	ACH
	0.003	0.003	0.0006	0.0006	0.0006	0.0006	0.0006	$m^3/(m^2 \cdot s)$
Ventilation (AFS 2009)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	$l/s \cdot m^2$
Occupancy of Apartment	-	0.03	0.03	0.03	0.03	0.03	0.03	ppl/m^2
Occupancy of Basement	-	0.02	0.02	0.02	0.02	0.02	0.02	ppl/m^2
Lighting Density of Apartment	-	11.84	11.84	11.84	11.84	11.84	11.84	W/m^2
Lighting Density of Basement	-	16.10	16.10	16.10	16.10	16.10	16.10	W/m^2
Equipment Load of Apartment	-	3.90	3.90	3.90	3.90	3.90	3.90	W/m^2

Equipment Load of Basement	-	2.90	2.90	2.90	2.90	2.90	2.90	W/m²
U-Value of 9th-Floor Wall	0.31	0.19	0.19	0.19	0.19	0.19	0.19	W/m²·K
U-Value of Roof	0.11	0.11	0.11	0.11	0.11	0.11	0.11	W/m²·K
U-Value of Intermediate Floor	0.31	0.31	0.31	0.31	0.31	0.31	0.31	W/m²·K
U-Value of Slab on Ground	0.13	0.13	0.13	0.13	0.13	0.13	0.13	W/m²·K
Thickness of Added Insulation	0.00	0.00	120.00	160.00	200.00	240.00	280.00	mm
U-Value of Basement Wall	0.31	1.25	0.22	0.27	0.14	0.12	0.10	W/m²·K
U-Value of Wall	0.31	0.31	0.15	0.13	0.11	0.10	0.09	W/m²·K
U-Value of Window	4.70	4.70	0.80	0.80	0.80	0.80	0.80	W/m²·K
G-Value of Window	-	0.87	0.70	0.70	0.70	0.70	0.70	-
VT of Window	-	0.89	0.74	0.74	0.74	0.74	0.74	-
Heat Recovery System	-	-	-	-	-	-	-	-

3. Appendix C

Building Envelope Assemblies

Condition	Material Layer (Interior to Exterior)	Thickness [mm]	Bulk Density [kg/ m^3]	Specific Heat Capacity [J/ kg.K]	Thermal Conductivity [W/ m.K]

Initial Wall of the Apartment Floor	Gypsum Board	13	1 150	1 100	0.350
	Mineral Wool	100	20	830	0.035
	Brick	120	2 000	1 000	0.960
Renovated Wall of The Apartment Floor	Gypsum Board	13	1 150	1 100	0.350
	Mineral Wool	100	20	830	0.035
	Brick	120	2 000	1 000	0.960
	Adhesive	4	1 500	1 000	1.000
	EPS (for variation A)	120	20	1 450	0.035
	EPS (for variation B)	160			
	EPS (for variation C)	200			
	EPS (for variation D)	240			
	EPS (for variation E)	280			
	Fibre Reinforced Mortar	5	1 300	1 000	0.450
	Finishing Mortar	3	1 330	1 000	0.450
Initial Reinforced Wall of The Apartment Floor	Gypsum Fibreboard	13	1 150	1 100	0.350
	Reinforced Concrete	140	2 400	880	2.500
	Mineral Wool	100	20	830	0.035
	Brick	120	2 000	1 000	0.960
Renovated Reinforced Wall of The Apartment Floor	Gypsum Board	13	1 150	1 100	0.350
	Reinforced Concrete	140	2 400	880	2.500
	Mineral Wool	100	20	830	0.035
	Brick	120	2 000	1 000	0.960
	Adhesive	4	1 500	1 000	1.000
	EPS (for variation A)	120	20	1 450	0.035
	EPS (for variation B)	160			

	EPS (for variation C)	200			
	EPS (for variation D)	240			
	EPS (for variation E)	280			
	Fibre Reinforced Mortar	5	1 300	1 000	0.450
	Finishing Mortar	3	1 330	1 000	0.450
Initial Basement Wall	Woodwool Panel	50	390	2 100	0.090
	Reinforced Concrete	200	2 400	880	2.500
Renovated Basement Wall	Plaster Board	13	680	960	0.250
	Vapour Retarder	1	130	1 700	0.220
	MW (for variation A)	120	20	830	0.032
	MW (for variation B)	160			
	MW (for variation C)	200			
	MW (for variation D)	240			
	MW (for variation E)	280			
	Levelling Mortar	10	1 200	1 000	0.440
	Woodwool Panel	50	390	2 100	0.090
	Reinforced Concrete	200	2 400	880	2.500
9th floor Wall	Gypsum Fibreboard	13	1 150	1 100	0.350
	PE Foil	0	930	1 800	0.400
	MW	170	20	830	0.035
	Gypsum Fibreboard	10	1 150	1 100	0.320
	Air Gap	50	0	1 000	-
	Style board MDF	16	600	1 800	0.100

Intermediate Floor	Reinforced Concrete	210	2 400	880	2.500
	Mineral Wool	100	20	830	0.035
	Gypsum Fibreboard	13	1 150	1 100	0.350
Roof	Gypsum Fibreboard	26	1 150	1 100	0.350
	Air Gap	28	0	1 000	-
	PE Foil	0	930	1 800	0.400
	MW	300	20	830	0.035
	Wood Fibres	3	40	1 900	0.050
	Air Gap	60	0	1 000	-
	Wood Wool Panel	25	460	2 100	0.090

4. Appendix D

The cost	Source
Heat pump maintenance	https://luftmiljobutiken.se/produkt/service-luft-vatten-varmepump/
Compressor repair	https://www.varmepumppriser.se/luft-vattenvaermepump
Heat pump replacement	From NIBE company

5. Appendix E

Input for the LCC analysis

Initial Cost

Apartment Wall Renovation (Oridinary & Reinforced Wall)						
Material	Quantity	Unit	Cost [SEK/unit]	Labour Time [h/unit]	Sub-Contractor Fee [SEK/unit]	Net Price [SEK/Unit]
Surface Cleaning	7 461.57	m^2	11.00	0.10	-	-
Surface Brushing	7 461.57	m^2	8.00	0.15	-	-

Adhesive, 4mm	7 461.57	m²	38.40	0.25	-	-
EPS 0.035 W/mK , 120 mm	7 461.57	m²	131.60	0.09	-	-
EPS 0.035 W/mK , 160 mm	7 461.57	m²	175.46	0.09	-	-
EPS 0.035 W/mK , 200 mm	7 461.57	m²	219.33	0.09	-	-
EPS 0.035 W/mK , 240 mm	7 461.57	m²	263.19	0.09	-	-
EPS 0.035 W/mK , 280 mm	7 461.57	m²	307.06	0.09	-	-
Fiber Cement	7 461.57	m²	24.00	0.10	-	-
Internal Plaster, 5 mm	7 461.57	m²	24.00	0.15	-	-
Final Coat, 3 mm	7 461.57	m²	16.00	0.38	-	-
Basement Wall Renovation						
Surface Cleaning	2 060.10	m²	11.00	0.10	-	-
Surface Brushing	2 060.10	m²	8.00	0.15	-	-
Levelling Mortar, 10 mm	2 060.10	m²	0.70	0.15	-	-
MW 0.032 W/mK , 120 mm	2 060.10	m²	104.00	0.09	-	-
MW 0.032 W/mK , 160 mm	2 060.10	m²	138.67	0.09	-	-
MW 0.032 W/mK , 200 mm	2 060.10	m²	173.33	0.09	-	-
MW 0.032 W/mK , 240 mm	2 060.10	m²	208.00	0.09	-	-
MW 0.032 W/mK , 280 mm	2 060.10	m²	242.67	0.09	-	-
Vapour Retarder sd= 10m, 5 mm	2 060.10	m²	81.90	0.10	-	-
Plaster Board, 12.5 mm	2 060.10	m²	28.50	0.20	-	-
Scaffolding						
Scaffolding Rent	11 769	m²	172.94	0.18	-	-
Horizontal Hung Window Replacement, 900 mm x 500 mm, 0.8 U-Value						
Old window removal	4	Unit	191.58	0.30	-	-
Glass, 900mm x 500 mm	4	Unit	4 222.00	1.55	-	-
Exterior Lining	4	Unit	48.64	0.32	-	-

Exterior Sill Board	4	Unit	14.44	0.19	-	-
Mineral Wool Insulating	4	Unit	19.04	0.22	-	-
Acrylic Sealant With Bottom Strip	4	Unit	35.56	0.25	-	-
White Painted MDF Int Sill Board	4	Unit	138.60	0.39	-	-
White Painted Int Lining	4	Unit	50.72	0.32	-	-
Varnished Drip Cap	4	Unit	-	-	246.00	-
Varnished Window Cap	4	Unit	-	-	319.00	-
Horizontal Hung Window Replacement, 600 mm x 1600 mm, 0.8 U-Value						
Old window removal	184	Unit	383.16	0.50	-	-
Glass, 600mm x 1600 mm	184	Unit	4 399.00	1.35	-	-
Exterior Lining	184	Unit	88.16	0.58	-	-
Exterior Sill Board	184	Unit	36.48	0.48	-	-
Mineral Wool Insulating	184	Unit	36.72	0.43	-	-
Acrylic Sealant With Bottom Strip	184	Unit	68.58	0.49	-	-
White Painted MDF Int Sill Board	184	Unit	267.30	0.76	-	-
White Painted Int Lining	184	Unit	91.93	0.58	-	-
Varnished Drip Cap	184	Unit	-	-	163.80	-
Varnished Window Cap	184	Unit	-	-	207.00	-
Horizontal Hung Window Replacement, 900 mm x 1300 mm, 0.8 U-Value						
Old window removal	935	Unit	383.16	0.50	-	-
Glass, 900mm x 1300 mm	935	Unit	6 769.00	1.70	-	-
Exterior Lining	935	Unit	72.96	0.48	-	-
Exterior Sill Board	935	Unit	26.60	0.35	-	-
Mineral Wool Insulating	935	Unit	29.92	0.35	-	-
Acrylic Sealant With Bottom Strip	935	Unit	68.58	0.49	-	-

White Painted MDF Int Sill Board	935	Unit	217.80	0.62	-	-
White Painted Int Lining	935	Unit	76.08	0.48	-	-
Varnished Drip Cap	935	Unit	-	-	245.70	-
Varnished Window Cap	935	Unit	-	-	310.50	-
Horizontal Hung Window Replacement, 1400 mm x 1300 mm, 0.8 U-Value						
Old window removal	554	Unit	459.79	0.60	-	-
Glass, 900mm x 1300 mm	554	Unit	11 580.00	1.85	-	-
Exterior Lining	554	Unit	88.16	0.58	-	-
Exterior Sill Board	554	Unit	30.40	0.40	-	-
Mineral Wool Insulating	554	Unit	36.72	0.43	-	-
Acrylic Sealant With Bottom Strip	554	Unit	68.58	0.49	-	-
White Painted MDF Int Sill Board	554	Unit	267.30	0.76	-	-
White Painted Int Lining	554	Unit	91.93	0.58	-	-
White MDF, Ventilated	554	Unit	355.00	0.45	-	-
Varnished Drip Cap	554	Unit	-	-	245.70	-
Varnished Window Cap	554	Unit	-	-	310.50	-
Glass Door Replacement, 900 mm x 2100 mm, 0.8 U-Value						
Old door removal	263	Unit	613.06	0.80	-	-
Door Glass, 900 mm x 2100 mm	263	Unit	10 144.00	2.00	-	-
Exterior Lining	263	Unit	80.56	0.53	-	-
Exterior Sill Board	263	Unit	38.76	0.51	-	-
Mineral Wool Insulating	263	Unit	40.80	0.48	-	-
Acrylic Sealant With Bottom Strip	263	Unit	76.20	0.54	-	-
White Painted MDF Int Sill Board	263	Unit	252.45	0.71	-	-
White Painted Int Lining	263	Unit	84.01	0.53	-	-

Handle Including Lock	263	Unit	985.00	0.28	-	-
Varnished Drip Cap	263	Unit	-	-	245.70	-
Varnished All Side Bracket	263	Unit	-	-	245.70	-
Exhaust Air Heat Pump Installation						
EAHP of Building A1	76	kW	-	-	-	15 000
EAHP of Building A2	134	kW	-	-	-	15 000
EAHP of Building A3	46	kW	-	-	-	15 000
Water Tank, 300 l	3	Unit	8 332.40	1.90	-	-
Water Tank, 500 l	2	Unit	20 755.22	6.25	-	-
Water Tank, 750 l	12	Unit	61 780.00	8.08	132.83	-
Ground Source Heat Pump Installation						
GSHP of building A1, 255 kW	1	Unit	-	-	-	4 300 000
GSHP of building A2, 425 kW	1	Unit	-	-	-	6 500 000
GSHP of building A3, 170 kW	1	Unit	-	-	-	3 800 000
Individual Substation Installation						
Connection Pipes to A1	1	Unit	-	-	-	125 750.0
Connection Pipes to A2	1	Unit	-	-	-	103 875.0
Heat Exchanger, 400 kW	1	Unit	-	-	-	153 518.9
Heat Exchanger, 750 kW	1	Unit	-	-	-	221 149.5
Heat Exchanger, 250 kW	1	Unit	-	-	-	114 477.7

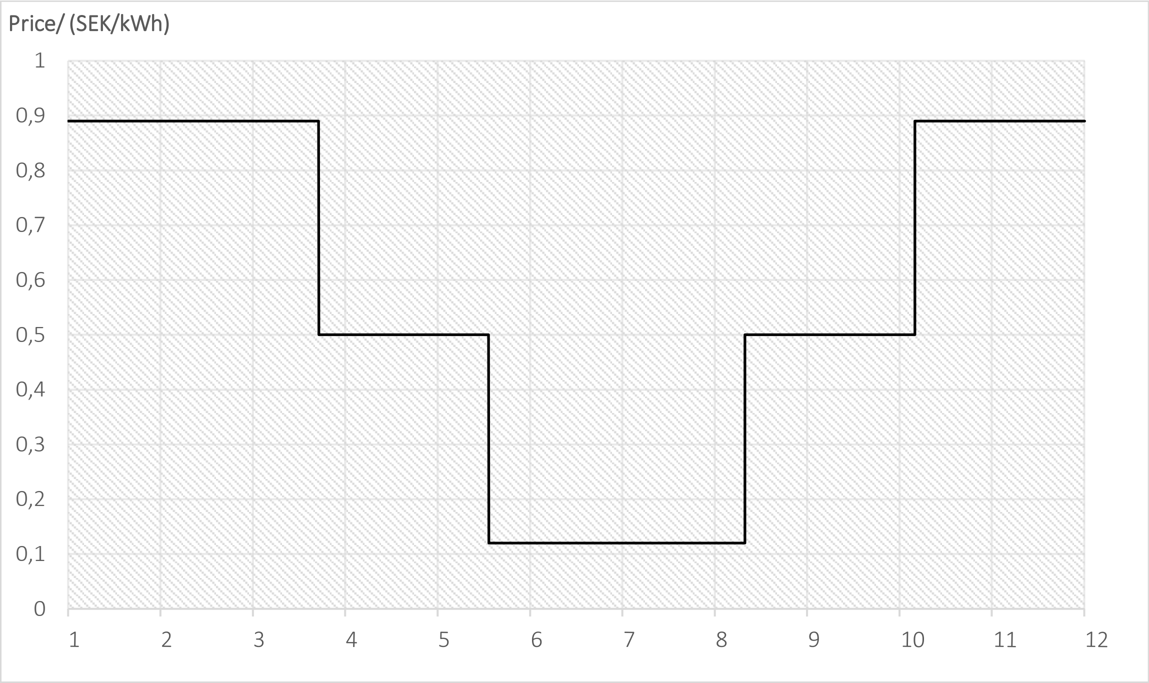
Maintenance and Replacement Cost

Maintenance	Quantity	Unit	Material Cost [SEK/unit]	Net Labour Cost [SEK/unit]	Net Price [SEK/Unit]	Frequency [Times/y]
EAHP Maintenances						

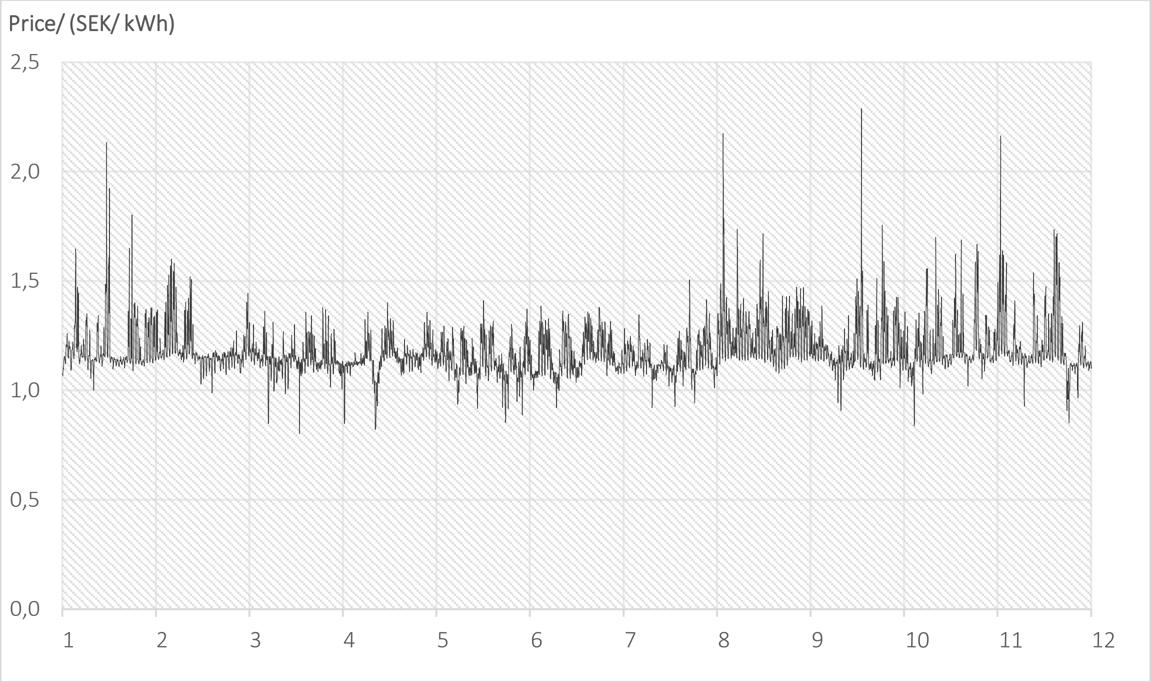
EAHP F1155-16 Replacement	10	Unit	98500	7000	-	Once/ 20
EAHP F1355-28 Replacement	3	Unit	102310.92	7000	-	Once/ 20
Compressor Maintenance	13	Unit	-	-	10000	Once/ 10
EAHP Maintenance	3	Bldg	-	-	7185	Once/ 1
GSHP Maintenances						
GSHP Mega XL Thermia Replacement	10	Unit	166734	7000	-	Once/ 20
Compressor Maintenance	10	Unit	-	-	10000	Once/ 10
GSHP Maintenance	11	Unit	-	-	2000	Once/ 2
Individual Substation Maintenances						
Substation Maintenance	3	Unit	-	-	1700	Once/ 6

6. Appendix F

Hourly Price of District Heating



Hourly Price of Electricity


Price/ (SEK/ kWh)
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
4
5
6
7
8
9
10
11
12

LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design

Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services