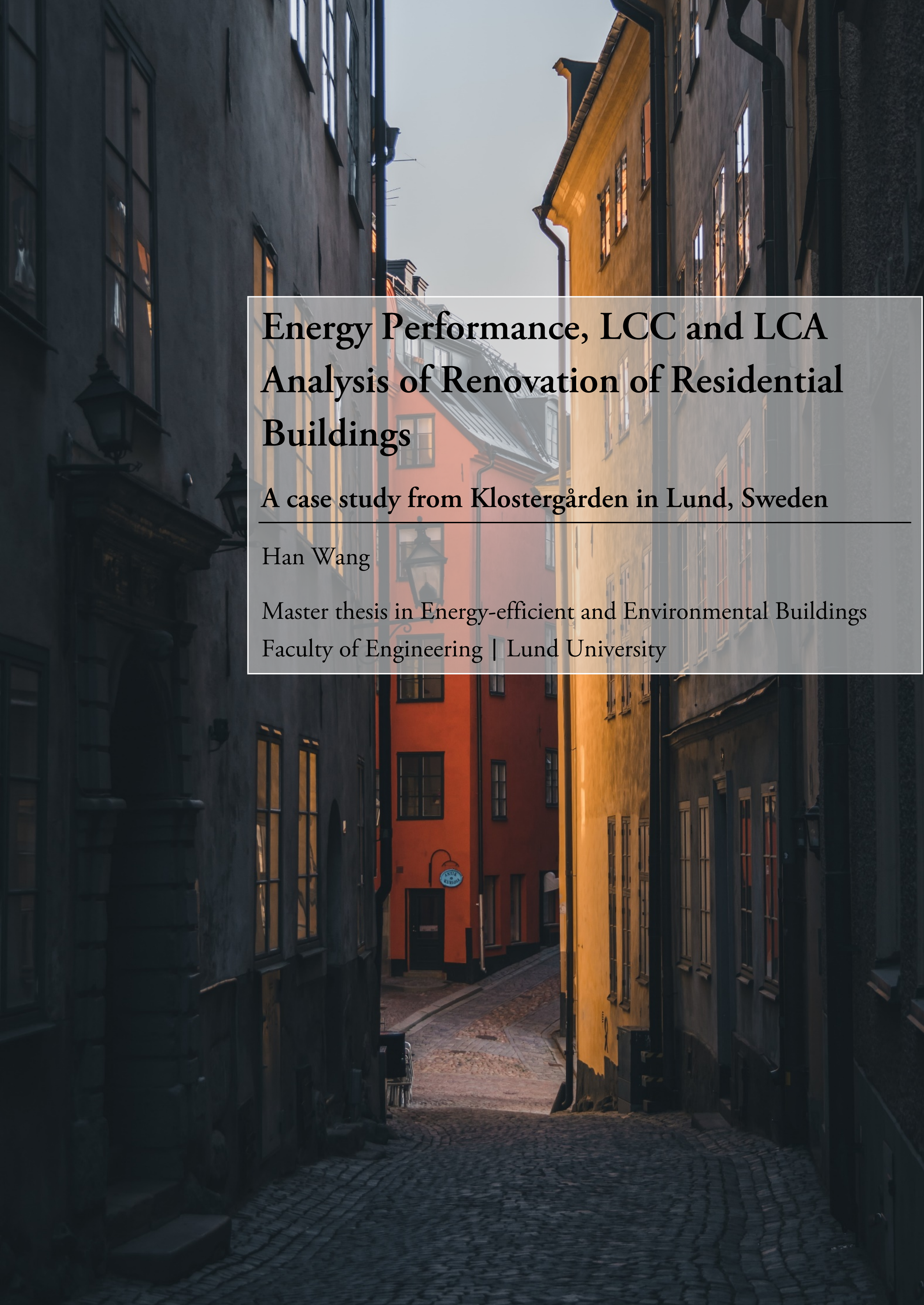

Energy Performance, LCC and LCA Analysis of Renovation of Residential Buildings

A case study from Klostergården in Lund, Sweden

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

Lund University

Lund University, with eight faculties and a number of research centres and specialised 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. A number 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 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme 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' behaviour and needs, their health and comfort as well as the overall economy.

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

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Supervisor: Henrik Davidsson (Energy and Building Design), Rafael Campamà Pizarro (Energy and Building Design)

Keywords: Building energy demand, building renovation, insulation, windows, ventilation, heat pump, photovoltaic, cost, global warming potential

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Abstract

This study conducted an evaluation of the energy performance of a building complex located in Lund. Since the complex has a great need for renovation, five renovation measures were proposed. In order to improve thermal insulation and airtightness of the external walls, replacing the old double-glazed windows with more insulated triple-glazed windows, mounting Smart1 to replace part of the ventilation airflow provided by the exhaust ventilation system, replace district heating by ground source heat pumps to supply heating demand of the complex, and install photovoltaic panels on the roofs.

The energy demands of the buildings with the renovation measures were calculated by computer simulations. The costs of these renovation measures over 35 years were calculated using a database from Wikells. By using environmental product declarations from manufacturers on products involved in renovations, the global warming potential of each renovation measure was estimated over a period of 35-years. Finally, the most efficient scenarios in terms of energy and cost, global warming potential and cost were found through Pareto efficiency analysis.

In terms of primary energy saving, ground source heat pump, Smart1, and photovoltaic panels are Pareto efficient measures. In the external wall renovation, 120 mm additional insulation had the lowest life cycle cost. Replacing windows reduced primary energy use but increased life cycle cost. These two measures are optional measures that can be considered according to the renovation budget.

When it comes to global warming potential (GWP), Smart1 and photovoltaics are the most Pareto efficient measures. However, external wall renovation led to an increase in global warming potential over the 35-year period studied. Ground source heat pumps led to a decrease of GWP when windows are also replaced.

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Abbreviations

ASHP	Air source heat pump
CO_2	Carbon dioxide
DH	District heating
EAHP	Exhaust air heat pump
EPD	Environmental Product Declarations
GSHP	Ground source heat pump
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle cost
LKF	Lunds Kommuns Fastighets AB
NPV	Net present value
PV	Photovoltaic
SAM	System Advisor Model

Notations

U-value	Thermal transmittance (W/m²/K)
R	Thermal resistance of the material (m²·K/W)
λ	Heat conductivity (W/m/K)
d	Thickness (m)
Q_{trans}	Heat transmission loss (W/K),
A	Area (m²)
Q_{vent}	Ventilation heat loss (W/K)
ρ	Density of the air (kg/m³)
C_P	Specific heat of the air (J/kg/K)
q_{vent}	Intentional ventilation (l/s/m²)
$q_{leakage}$	Leakage infiltration (l/s/m²)
Q_{annual}	Annual total heating energy need (kWh/year)
T_{indoor}	Indoor temperature (°C)
$T_{outdoor\ average}$	Average outdoor temperature (°C)
A_1	Annual cost at the end of calculation year 1 (SEK)
g	Price increase rate
i	Interest rate
N	Calculation period

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1 Introduction

To tackle global climate change and environmental degradation, European Commission launched The European Green Deal as a new growth strategy. Buildings account for 40 % of the energy used. Today the annual renovation rate of the building stock was still below 1.2 % in the EU countries. This rate will need at least to double to reach the EU's energy efficiency and climate objectives (European Commission, 2019).

In Sweden, there has been significant improvement in energy use within new buildings due to the continually increased environmental requirements in the Swedish building regulations. However, these new buildings represent only a small amount of the building stock (Hjortling et al., 2017). For Sweden to meet its climate goals, it will be necessary to improve the existing building stock through renovation.

All buildings need to be refurbished throughout their lifetime as individual systems and components wear out or no longer work efficiently. During the renovation, there is great potential to improve the energy performance and reduce the local carbon dioxide (CO_2) emissions (Ramírez-Villegas et al., 2016).

When it comes to renovation on a building scale, by having well-insulated and airtight building envelopes, low-energy buildings can be achieved (Uffelen, 2012). These approaches include increasing insulation on external walls, replacing old windows with advanced windows etc. On the other hand, renovations, for instance, introducing renewable energy and energy supply systems at a neighbourhood scale, are also necessary but easily overlooked.

1.1 Background

The case buildings for this project locates in Klostergården in Lund, Sweden. The buildings are owned by municipal housing company Lunds Kommuns Fastighets AB (LKF) and are in great need of renovation. This study includes reviewing and putting forward renovation measures and finally carrying out a comprehensive financial assessment and environmental impact analysis for the investigated cases.

1.1.1 Review of previous study

In the diploma work carried out by Stevson Sonny Widjaja and Yinxin Liu in 2020, five renovation strategies were researched. Improving the building envelope with insulation and windows, adding an exhaust air heat pump (EAHP), changing the heating source to a ground source heat pump (GSHP), and improving district heating (DH) substation design is considered in the study. Their results show that all five techniques reduced the heating demand of this neighbourhood. In terms of profitability, improved building envelope, GSHP and EAHP have significant advantages (Stevson and Yinxin, 2020).

1.1.2 Renovation strategies

However, in addition to the combination of EAHP and improved building envelope, no other combination of renovation strategies was studied by Widyaya and Liu (2020). In order to find out the best performing renovation scenarios, more strategies and their combinations were studied in this research.

New ventilation with heat recovery and photovoltaic (PV) system were investigated in this study. In addition to the two new strategies, adding insulation materials, replacing windows and installing GSHP, these three strategies studied in the previous study are also included. Then the five strategies were arranged and combined. Finally, the economic feasibility analysis of these hundreds of combinations was conducted.

1.1.2.1 Insulation

Wall insulation is one of the most recommended energy efficiency retrofits. A study in France shows external wall insulation reduces space heating energy use by an average of about 29 % in buildings of different classes (Belaïd et al., 2021).

To meet current building standards, the building envelope requires a mean U-value under 0.6 W/(m²K). The U-values for the roof under 0.13 W/(m²K), walls under 0.18 W/(m²K), ground floor under 0.15 W/(m²K), and windows and doors under 1.2 W/(m²K) (BBR., 2018:4).

By adding supplementary insulation or a vapour barrier from the interior, temperature in the outer layers of the construction could be reduced, and its breathability hampered, resulting in accumulation of moisture and finally to potential structural impairment (Johansson, n.d.). Therefore, additional insulation material preferably is installed from the exterior side of the walls.

Poor airtightness might be responsible for about 40 % of heat loss from building fabric, depending on the temperature difference between indoor and outdoor (Cuce, 2017). While installing insulation materials to exterior walls, airtightness can also be improved by adding a vapour barrier or adopting insulation with an integrated wind-stop layer.

1.1.2.2 Windows

On average, 47 % of total heat loss through residential buildings can be attributed to the windows due to their considerably higher U-values compared to other building elements. And 33 % of reduction in heat losses can be achieved via airtight windows (Cuce, 2017).

To meet the current building standards, the U-value of windows also needs to be reduced under 1.2 W/(m²K). Compared to double-pane windows, more advanced windows, for instance, triple-pane windows with low-emissivity coating and filled with heavier gases, have lower U-value.

1.1.2.3 Ventilation

A study in Sweden shows that ventilation systems with heat recovery can give significant final energy reduction. The primary energy saving of applying ventilation heat recovery for space heating and ventilation can be up to 55%. However, the primary energy benefit depends strongly on the type of heat supply system, and also on the airtightness of buildings (Dodoo et al., 2011).

In the previous study, an exhaust air heat pump was studied to saving energy from the ventilation system. However, considering the complaints from residents about bad indoor air quality, a new ventilation system with heat recovery was studied.

1.1.2.4 GSHP

The ground source heat pump (GSHP) has been recognised to provide viable, environment-friendly alternatives to conventional unitary systems and make substantial contributions to reducing energy usage and CO_2 emissions (Liu et al., 2014). Electricity has a more significant environmental impact than equivalent district heating, and it has a primary energy factor of 1.6 while calculating the primary energy (BBR, 2018:4.). Despite this, a ground source heat pump with a COP of 3.5 can save nearly 70 % of energy, making it still an environmentally and economically feasible renovation option.

1.1.2.5 PV

The growing concern for climate change is driving demand for renewable energy solutions ("Solar PV – Analysis," n.d.). Utilising solar energy to provide electricity through photovoltaic panels could prove a promising alternative to current mixed electricity, including non-renewable energy source.

The usable roof area for solar PV installation per capita is 49 m² for Sweden on average. There is still huge potential for solar PV in Sweden to grow (Yang et al., 2020). The application of solar power, serving as a renewable energy source, could lessen the current climate crisis.

1.2 Objective

The first objective is to put forward renovation measures based on the current conditions of the building complex. The second objective of this study is to conduct building energy simulations of these renovation proposals. The third objective is to perform the life cycle costs (LCC) of these measures and their combinations to obtain the optimal scenarios in terms of energy-saving and economic feasibility. The final objective is to perform a life cycle assessment (LCA) of all scenarios.

1.3 Scope

This research aims to study the energy performance of the building complex before and after renovation, financial analysis and environmental impact assessment of renovation measures. The renovations include installing additional insulation on the external walls and replacing old windows with more advanced windows - both ways to decrease the mean U-value of the building envelopes and reduce energy consumption. Besides, a new ventilation system with heat recovery was also introduced, aiming to improve indoor air quality. Finally, new energy source and renewable energy are also included, with GSHP replacing district heating and solar panels installed on roofs. All of the above measures were designed and simulated individually, then combined into different scenarios. A further study corresponding to economic feasibility is conducted by analysing life cycle costs, which considers energy, materials and equipment costs, and construction costs. Finally, an LCA assessment of all scenarios was performed by evaluating their global warming potential (GWP).

2 Methodologies

In order to conduct this study, quantitative methods were applied. In the first place, a literature review was done to obtain information for the simulations. Next, an initial statistical analysis based on the original data and previous work was carried out. The original data collected on the existing building needs to be analysed to find the areas most in need of renovation. Then, computer simulations were used to verify the feasibility of renovation strategies. By entering known parameters, building energy consumption can be calculated by simulation based on a 3D model. To conclude, the LCCs of different scenarios were calculated to determine the renovation strategies with the best economic profitability. As well, an LCA assessment of renovation strategies was carried out to study their environmental impact.

Due to the mutual influence on economic feasibility among different renovation measures, their combinations may produce results that are not simply additive. For instance, the installation of external wall insulation materials and the replacement of windows can be carried out at the same time to reduce expenses. The introduction of GSHP may make it less profitable to install additional insulation materials on building envelope. The energy simulation and life cycle cost analysis of the 168 combinations of all renovation strategies was launched in this diploma work.

2.1 Existing buildings

The building complex in this study locates on Klostergården in Lund, southern Sweden. This complex contains three buildings, of which two taller buildings A1 and A2, each have nine floors above ground, and an L-shaped building A3 with two floors above ground. The site plan of the complex is shown in Figure 1.

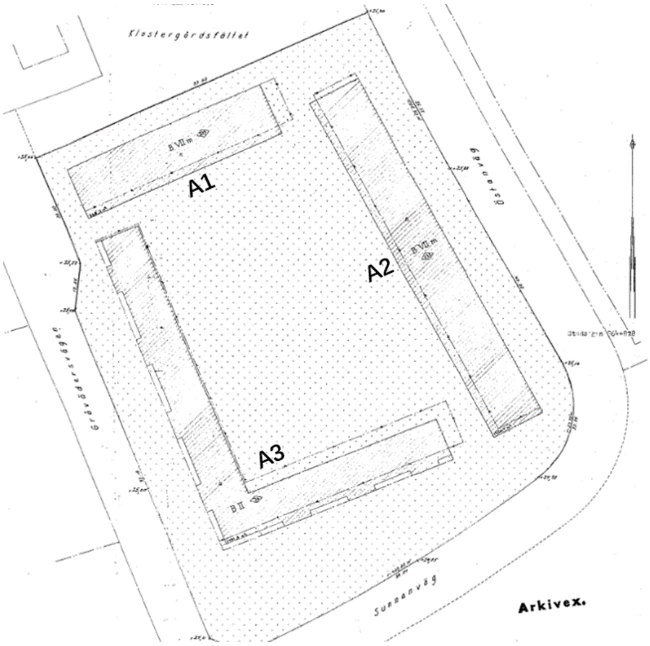


Figure 1 Site plan of the complex from LKF

The height of each floor is 2.5 meters. Each building has a basement floor, but there are no renovation measures for basements carried out in this case study, so that the basements will be ignored in the following paper. The general information of this complex is shown in Table 1.

Table 1 General information of studied building complex

Number of buildings	**3**	**Unit**
Heated floor area	21 070	m²
Basement area	3 462	m²
Envelop area	13 830	m²
Glazing area	3 580	m²
Roof area	3 150	m²
HAVC system	Exhaust Air System	-
Heat recovery	-	%
Heating source	District heating	-

The apartments in this complex have one to four rooms. These apartments with one to four rooms have 1.42, 1.63, 2.18 and 2.79 occupants according to the standard statistics (BEN 2 BFS, 2017:6). There are a total of 265 apartments and 522 occupants in the complex. The number of these apartments and occupants are listed in Table 2.

Table 2 Number of apartments and occupants

	One-room	Two-room	Three-room	Four-room	Number of apartments	Number of occupants
A1	21	7	25	22	75	157
A2	52	39	68	3	162	294
A3	0	2	8	18	28	71

The construction of the exterior concrete wall is shown in Figure 2 below, which is composed of bricks, mineral wool, concrete and plaster board from the outer layer to the inner layer. The U-value of the exterior concrete wall is 0.336 W/m²K. Figure 3 illustrates the construction of the building's external wall, which has no concrete layer compared to the exterior concrete wall and has a U-value of 0.343 W/m²K. Since the U-values of the two external wall structures are close, a U-value of 0.34 W/m²K was adopted for all the external walls in the building energy simulation. This means the difference of the external wall constructions was not considered when analysing building energy performance.

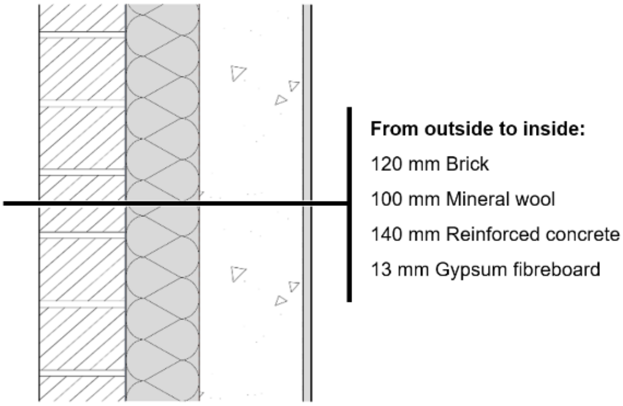


Figure 2 Construction of existing exterior concrete wall

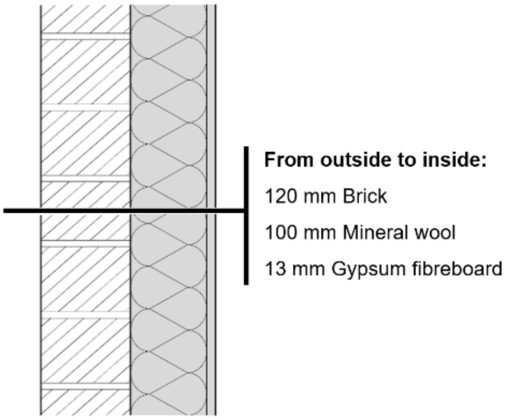


Figure 3 Construction of existing external wall

The construction of the roofs of this complex is shown in Figure 4 below, which is assemblies of gypsum fibreboard, air gap, PE foil, mineral wool, wood fibres, air gap and wood wool panel from outside in. The U-value of this construction is 0.12 W/m²K.

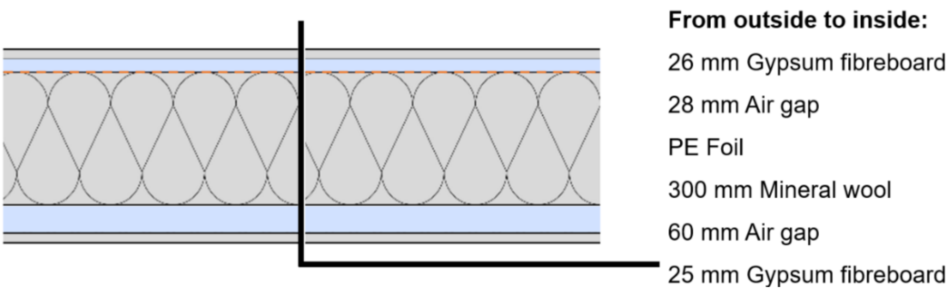


Figure 4 Construction of roof

The existing windows on the buildings are wooden framed double-glazed windows, and the U-value is assumed to be 3 W/m²K. Due to the poor condition, some windows have significant air gaps between the panes and are not tightly sealed, which may cause air convection to take heat directly from the inner panes. However, it is difficult to quantify the U-value of windows in this situation. The number of windows in similar conditions is unknown, so the U-value of a typical double-glazed window is adopted in the building energy simulation. Therefore, the heating energy demand results in the simulation may be lower than the actual situation.

The existing ventilation system is an exhaust ventilation system, but the current fresh airflow is lower than required due to insufficient maintenance and cleaning. Thus, the building owner received complaints from residents. In the building energy simulations, the ventilation rate was set to the minimum value of 0.35 $l/s/m^2$ required by the BBR standard.

The main heating energy source for space heating and domestic hot water in this complex is district heating. At the same time, there is also an air source heat pump (ASHP) used to provide a small part of heat energy. Considering the poor condition of the ASHP, its COP is assumed to be 2.8. Table 3 below shows the average heating energy use of the buildings during five years from 2014 to 2018. Due to the poor condition of the ASHP, it is considered no longer operating in the future in this study. Therefore, all heat energy will be provided by district heating.

Table 3 Heating energy use of the complex during 5 years

	Average over five years	**Unit**
Electricity consumed by ASHP	8.8	$kWh/y/m^2$
COP	3.5	-
Heating supplied by ASHP	30.8	$kWh/y/m^2$
District heating	107.3	$kWh/y/m^2$
Heating energy use in total	138	$kWh/y/m^2$

2.2 Design and simulation tools

Firstly, the buildings were modelled from the original construction drawings. The 3D model was made in SketchUp and Rhino 6 for assessment of design and energy.

Energy simulations were performed in Sefaira (Sefaira, n.d.), a web-based interface for the EnergyPlus (EnergyPlus, n.d.) engine. The energy demand simulations were based on Lund weather data. In order to verify the simulation results from Sefaira, they were compared with the results from hand calculation carried out in Excel, which used a degree-hours method. Besides, PV system design was carried out in System Advisor Model (SAM). The simulation of electricity production was based on Lund weather data. Finally, the primary energy of each scenario was calculated. By adding up district heating demand with a factor of 1, and electricity demand with a factor of 1.6 (BBR, 2018:4).

2.2.1 Modelling

The model built in Rhino 6 is shown in Figure 5. On the body of the buildings, the light blue rectangles are windows, and the balconies and shadings were marked in green.

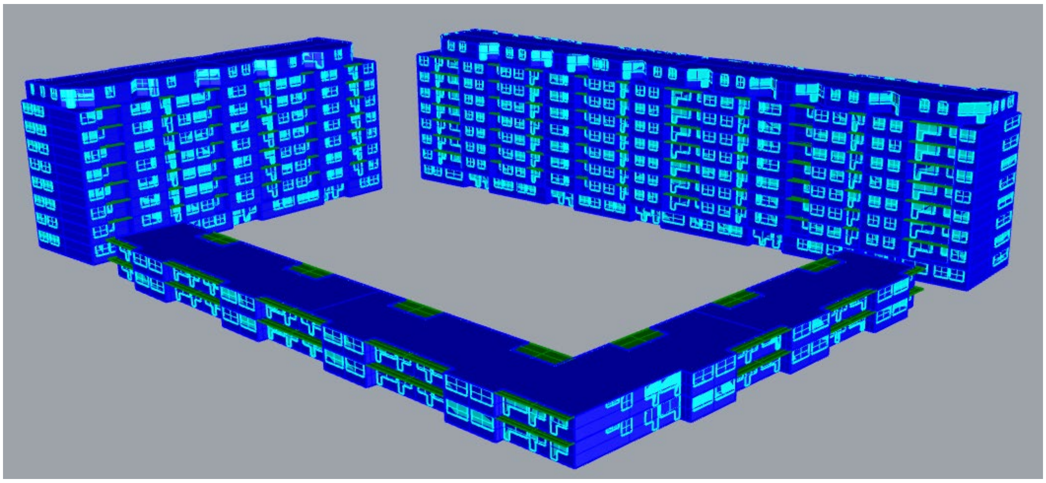


Figure 5 3D model of building complex

In this model, the thickness of building components was ignored. Only their U-values were involved in the energy simulation. Also, all doors on the facade are considered windows because of their similar U-values. Surrounding buildings in the south are far away, and vegetations are lower than the buildings studied. The impact on energy demand is minimal, so they are ignored in this model. In order to simplify the process and shorten the time needed for modelling and simulation, the apartments inside floors are not modelled, and each floor is set as one zone, so the building complex has a total of 20 zones.

Therefore, there could be some discrepancy between the as-built construction and the model. For the purpose of this study, where the effects of hypothetical renovations were compared, this was deemed acceptable.

A building model was created in Sketchup and uploaded to the Sefaira for later building energy simulations.

2.3 Renovation Strategies

Five different renovation proposals were studied, and the details of each proposal are explained below.

2.3.1 Improving wall

Additional insulation materials were assumed to be installed outside of the buildings' external walls; both ordinary walls and concrete wall are included. Considering the poor airtightness of brick structures, a vapour barrier should be constructed simultaneously as the insulation materials are installed. Finally, the façade of the building was redecorated with mortar and a finishing layer. The proposed new constructions are shown in Figure 6 and Figure 7 below.

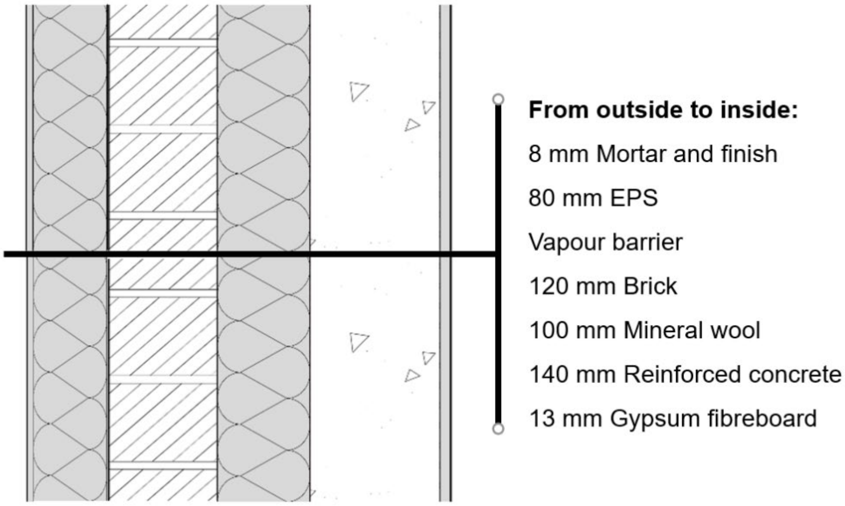


Figure 6 New construction of exterior concrete wall

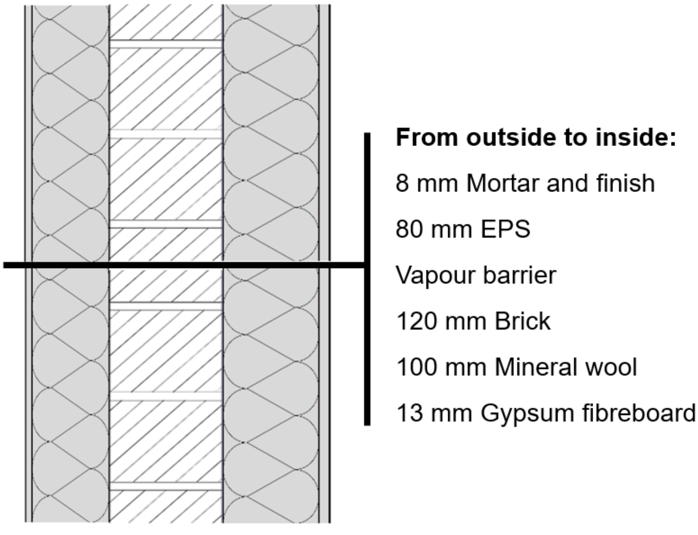


Figure 7 New construction of external wall

Since EPS is rigid and light, it can be installed easily and rapidly. EPS has low embodied energy and can be recycled after disposal. The newly added insulation material is therefore EPS, with a thermal conductivity of 0.038 W/m/K. Seven different thicknesses of insulation materials were considered to be installed on external walls. The U-values and total thicknesses are shown in Table 4.

Table 4 Properties of external wall after adding different thickness of insulation

Added EPS thickness	**0**	**40**	**80**	**120**	**160**	**200**	**240**	**mm**
U-value	0.34	0.25	0.2	0.16	0.14	0.12	0.11	$W/m^2/K$
Wall thickness	233	273	313	353	393	433	473	mm

The infiltration rate of the existing buildings is assumed to be 9.0 $m^3/m^2/h$ at 50 Pa. After adding a vapour barrier layer to the external walls while putting on insulation, the infiltration rate can be reduced by approximately 40 % (Younes et al., 2012) to 5.4 $m^3/m^2/h$.

2.3.2 Improved windows

Windows, like other opaque building envelope elements, transfer heat via conduction and convection, but also through radiation.

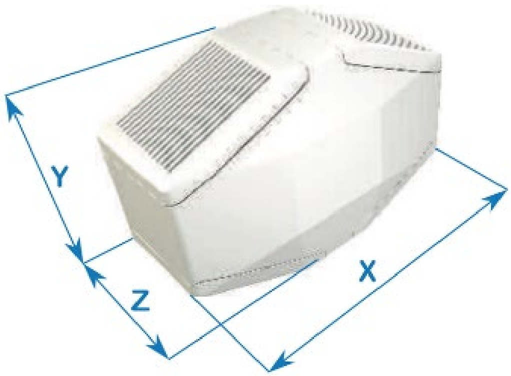
The advanced windows contain triple glazing with Low-E coating are adopted, and the gaps between glazing are filled with argon. The window frame is made of aluminium and wood, with a low thermal bridge structure that is well insulated. The U-value of the whole window is 0.8 W/m^2K. Also, the airtightness of the window needs to be guaranteed by using seals while mounting new windows.

After applying new windows, the infiltration rate can be reduced by approximately 40 % (Ridley et al., 2003), to 1.8 $m^3/m^2 \cdot h$ in the cases where external walls were also renovated, or to 5.4 $m^3/m^2 \cdot h$ in other cases.

2.3.3 Improve ventilation with heat recovery

In order to address the issue of no heat recovery in the ventilation system in these buildings, Smart1 (Smartvent, n.d.) was considered to be mounted on external walls to replace part of ventilation airflow.

Each unit can provide 6 l/s to 15 l/s of airflow, and the flow rate of each unit can be set according to the occupancy of each apartment. At the same time, Smart1 has a heat recovery efficiency of approximately 85 %, which can significantly save energy while increasing the outdoor air supply. The power of this device is about 2 W typically, and no more than 4 W at full capacity. The appearance and dimensions of a Smart1 unit are shown in Figure 8.



X	420 mm
Y	310 mm
Z	139 - 156 mm

Figure 8 Smart1

The existing exhaust ventilation system in the buildings will be retained, but the airflow will be reduced in consideration of their disrepair. The extract terminals in the kitchen and bathroom are determined to keep an airflow rate of 10 l/s each. The outside air intakes in the living room will be reserved for exhaust ventilation. And Smart1 will be installed in bedrooms and providing ventilation around 8 l/s each. It is possible to increase the airflow by adjusting the Smart1 unit setting for different sizes and occupancies. The noise level of Smart1 is determined by airflow volume and is not expected to exceed 30 dB. So, it can be considered quiet. As an example, the illustration of the new ventilation in a three-room apartment is shown in Figure 9.

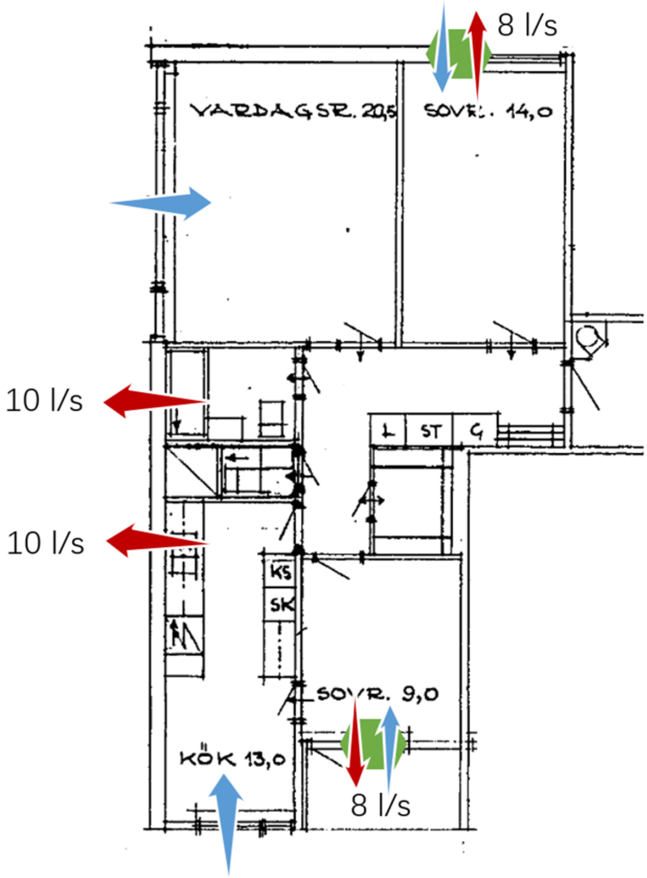


Figure 9 New ventilation of a three-room apartment

The apartments in this complex have one to four rooms. The number of Smart1 adopted in other apartments and the airflow provided is shown in Table 5 below.

Table 5 Smart1 number and airflow

	One-room	Two-room	Three-room	Four-room	Unit
Exhaust airflow	20	20	20	20	l/s
Smart1 number	0	1	2	3	-
Smart1 airflow	0	9	16	23	l/s

The total airflow supplied by Smart1 is 3049 l/s, and the airflow of the current exhaust ventilation system was reduced to 5061 l/s, which means the total ventilation rate after renovation will remain the same.

After renovation, the airflow of 3049 l/s supplied by Smart1 has a heat recovery of 85%, while 5061 l/s airflow from exhaust ventilation has no heat recovery. Therefore, an overall heat recovery efficiency of 32 % was achieved. Meanwhile, the overall specific fan power of new ventilation dropped from 0.6 W/l/s to 0.45 W/l/s due to the higher efficiency fans in Smart1.

2.3.4 Replacing district heating with ground source heat pumps

In addition to reducing the energy consumption of buildings, the use of sustainable energy is also crucial. Therefore, it is considered to introduce ground source heat pumps in this complex to reduce the primary energy needed for heating. In this renovation strategy, space heating and domestic hot water will be provided by the GSHP system. The application of GSHP is a change in the energy source; the heating energy demands were divided by the COP of GSHP to the corresponding electrical energy demands.

The solution of the GSHP system is provided by EnergyMachines.

The sizing of GSHP is based on the heating peak load of the building complex. GSHP usually has a peak load coverage of 50 % to achieve economic feasibility, while the other 50 % will be provided by hot water stored in the tank and a peak boiler. Three system solutions were adopted to meet the different heating demands resulting from adding insulation, replacing Windows and introducing new ventilation units in this study. The three sizes of GSHP systems will cover all cases from 610 kW to 973 kW. The critical information of the three systems is listed in Table 6.

Table 6 Properties of three GSHP systems

	EM4	**EM5**	**EM6**	**Unit**
Heating capacity	387.7	469.7	611.7	kW
Electricity power	114.7	142.3	180.2	kW
COP	3.38	3.30	3.39	-
Heating peak range of applied scenarios	610 to 767	820 to 935	973	kW

2.3.5 Adding PV panels on the roof

Considering that the two buildings A1 and A2 are taller than the surrounding context, and their roofs are flat, it makes them ideal candidates for installing roof PV systems. The retrofitting is simple and does not ruin the architectural aesthetics. A1 and A2 have a total roof area of about 1600 m². With a ground coverage ratio of 0.3, 504 m² of photovoltaic panels can be settled.

As an extended option, the installation of PV panels on the roof of A3 is also feasible if renewable energy is highly urged, adding another 504 m² to its 1380 m² roof. However, as the height of the A3 building is only two stories, there is a high chance that the PV modules can be seen from the surrounding area, which will affect the aesthetics of the building. Figure 10 illustrates the layout of rooftop PV in this building complex.

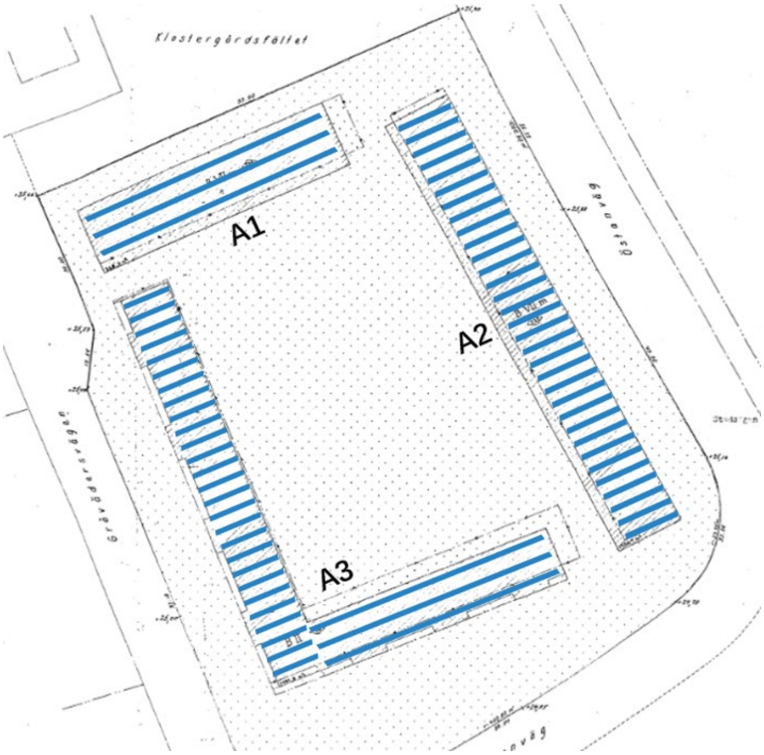


Figure 10 Schematic layout of rooftop PV

In this study, no batteries are considered in the system; instead, this PV system will be connected to the grid. The photovoltaic panels are oriented 25 ° south by east to be placed parallel to the buildings. The tilt of the PV panels is 30 °, where the production maximised in the parametric simulation. Other properties of the two PV systems are listed in Table 7.

Table 7 Properties of PV systems

	Small	Large	Unit
Panel efficiency	20 %		-
Power of panel	335		W
Inverter capacity	8		kW
Inverter numbers	10	20	-
Number of panels	300	600	-
System capacity	100.5	201	kW
Tilt	30		deg
Azimuth	155		deg
GCR	0.3		-

2.4 Energy simulation

In the following simulations, the Lund weather data is used as outdoor climate conditions. The outdoor mean temperature is 7.7 °C, and the average wind speed is 6.4 m/s. Global horizontal irradiation is 2.7 kWh/m²/d.

2.4.1 Building energy simulation

Building energy simulation is carried out in Sefaira, which is an online simulation tool based on EnergyPlus. In the uploaded 3D model, buildings were zoned by floors, and there are a total of 20 zones in this complex. The simulation of the current buildings was preliminarily carried out. The input parameters used in the base case are listed in Table 8.

Table 8 Energy simulation input parameters of base case

Inputs		Unit	Reference
U-value of window	3	W/m²K	-
SHGC of window	0.6	-	-
U-value of wall	0.34	W/m²K	-
U-value of floor	0.13	W/m²K	-
U-value of roof	0.12	W/m²K	-
Infiltration rate	9	m³/m²·h	(Rønneseth et al., 2019)
Window to wall ratio	0.31	-	-
Occupant density	37.5	m²/person	(BEN 2 BFS, 2017:6)
Equipment power density	5	Wh/m²	(BEN 2 BFS, 2017:6)
Lighting power density	5	Wh/m²	(BEN 2 BFS, 2017:6)
Heating setpoint temperature	21.5	°C	-
Heating setback temperature	18	°C	-
Mechanical ventilation	0.35	L/ m²·s	(BBR, 2018:4)
Diversity schedule	Figure 11	-	-
Specific fan power	0.6	W/L·s	(BBR, 2018:4)
Heat recovery	0	-	-

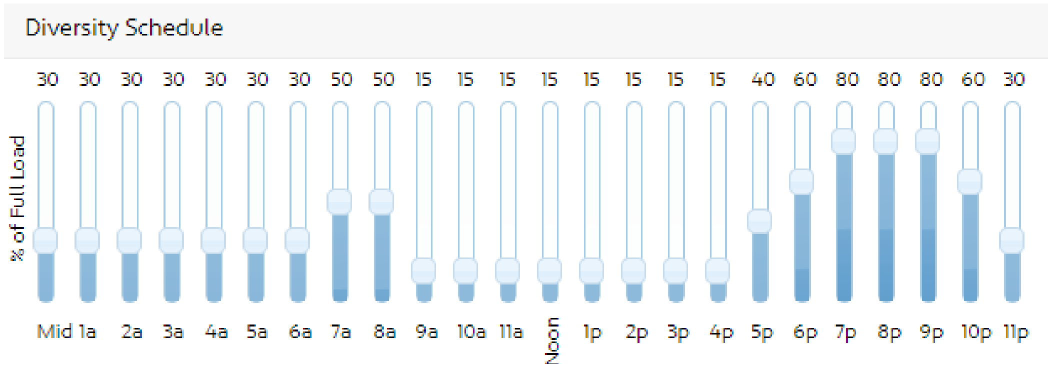


Figure 11 Occupancy schedule in Sefaira simulation

Figure 11 shows how the assumed occupancy density varied with the diversity schedule. More loads occur in the early morning and evening.

Some of the input parameters were changed after the addition of insulation and replacement of windows. The U-value of the external walls was decreased according to the increased thickness of insulation material, and the U-value of windows was decreased after replacing windows. At the same time, both renovations would reduce the infiltration rate of the buildings. The altered input parameters can be found in Table 9 and Table 10.

Table 9 The altered input parameters of adding insulation

Inputs								**Unit**
U-value of window	3							W/m²K
Added EPS thickness	0	40	80	120	160	200	240	mm
U-value of wall	0.34	0.25	0.2	0.16	0.14	0.12	0.11	W/m²K
Infiltration rate	9	5.4	5.4	5.4	5.4	5.4	5.4	m³/m²·h

Table 10 The altered input parameters of replacing windows

Inputs								**Unit**
U-value of window	0.8							W/m²K
Added EPS thickness	0	40	80	120	160	200	240	mm
U-value of wall	0.34	0.25	0.2	0.16	0.14	0.12	0.11	W/m²K
Infiltration rate	5.4	1.8	1.8	1.8	1.8	1.8	1.8	m³/m²·h

After mounting Smart1 as additional ventilation devices, the outdoor airflow of the buildings was increased. The altered input parameters can be seen in Table 11.

Table 11 The altered input parameters of mounting Smart1

Inputs		Unit
Specific fan power	0.45	W/l/s
Heat recovery	0.32	-

The recorded outputs, by which each simulation was quantified, were: annual heating demand (kWh/m²/y), Heating Peak Load (W/m²), annual electricity demand (kWh/m²/y).

2.4.2 Verification

The simulation results of the base case are compared and verified with hand calculation and report provided by the building owner. The mean of a five-year energy report was shown above in Table 3.

The hand calculation used a degree-hours method was carried out in Excel. The annual heating demand is calculated by estimating heat transmission through the building envelope and heat loss of ventilation.

The inputs of building envelopes include the dimensions of the buildings, U-values of the window, wall, roof, and floor. The heat transmission through building envelopes was calculated based on Equation 1 to Equation 4.

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

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

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

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

Where, U is U-value, the thermal transmittance (W/m²/K),
R is the thermal resistance of the material (m²·K/W),
λ is the conductivity (W/m/K),
d is the thickness (m),
Q_{trans} is the heat transmission loss. (W/K),
A is the area (m²).

The inputs of ventilation include ventilation airflow rate, heat recovery and infiltration rate. The air leakage at 50 Pa was divided by the number 30, according to standard 13829 (Swedish Standards Insutitute, 2000) for exhaust ventilation, to get the leakage at normal air pressure. Heat loss through ventilation was calculated according to Equation 5.

$$Q_{vent} = \rho \cdot C_P \cdot q_{vent} + \rho \cdot C_P \cdot q_{leakage} \qquad \text{Equation 5}$$

Where, Q_{vent} is the ventilation heat loss (W/K)
ρ is the density of the air (kg/m³)
C_P is the specific heat of the air (J/kg/K)
q_{vent} is the intentional ventilation (l/s/m²)
$q_{leakage}$ is the leakage infiltration (l/s/m²)

Finally, the average outdoor temperature of Lund was included to conduct degree-hours. Annual heating demand was calculated according to Equation 6.

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

Where, Q_{annual} is annual total heating energy need (kWh/year)
T_{indoor} is the indoor temperature (°C)
$T_{outdoor\ average}$ is the average outdoor temperature (°C)

2.4.3 Renewable energy simulation

The heat energy originally provided by district heating will be replaced by a new system that includes GSHPs. In order to simplify the calculation, the original heating energy is divided by the COP to obtain the electrical energy consumed by the GSHP system.

The simulation of photovoltaic power generation was carried out in SAM, and the weather data of Lund was adopted. The energy loss caused by self-shading is considered, while the shading of other buildings and vegetation is not included in this simulation.

2.5 LCC analysis

First of all, the LCC of each renovation strategy was calculated separately. When combining techniques, the shared costs, for instance, scaffolding for external renovation and windows replacement, were not double-calculated. The LCC calculation includes material cost, labour cost, tool rental cost, post-maintenance cost and replacement cost of wearing parts; finally, the cost of district heating and electricity were added on.

In the study carried out by Widyaya and Liu (2020), a 35-year period and a 50-year period was investigated. Considering the uncertainty of estimating a longer period, only a 35-year period is included in this study. This period was calculated with an expected interest rate of 1 % and a growth rate of 0.5 %. All the considered future costs are converted to the net present value (NPV) and added to the initial investment to get the total cost of each renovation strategy.

NPV was calculated according to Equation 7.

$$NPV = A_1 \frac{1-(1+g)^N(1+i)^{-N}}{i-g} \text{ SEK} \qquad \text{Equation 7}$$

where A_1 is the annual cost at the end of calculation year 1,
g is the price increase rate,
i is the interest rate, and N is the calculation period of 35 years.
Costs are represented as positive values.

All the calculations are done in Excel. The prices used in the calculation are shown in Table 12. As well as the construction speeds of the main components can be found in Table 13.

Table 12 Prices of renovation components

Product	Price	Unit	Reference
EPS insulation	1 097	SEK/m³	(“CELLPLAST 8,64 M² , n.d.)
Scaffolding	197	SEK/m²	(Wikells AFG.51)
Vapour barrier	7	SEK/m²	(Wikells JFS.54)
Mortar	45	SEK/m²	(Wikells KBC.3111)
1.5x1 Window	6 203	SEK	(Wikells NSC.1103)
1.5x1.5 Window	10 517	SEK	
1.5x2 Window	12 406	SEK	
2x1 Window	8 127	SEK	
1.5x3 Window	18 609	SEK	
0.5x2 Window	5 704	SEK	
Anchor	20	SEK	(Wikells ZSE)
Seal rubber	9	SEK/m	-
Smart1	5 990	SEK	(“Smart ventilation solutions,” n.d.)
Fan replacement	500	SEK	
Smart1 maintenance	200	SEK/2yrs	
EM4 GSHP system	10 855 600	SEK	(EnergyMachines™ , n.d.)
EM5 GSHP system	12 681 900	SEK	
EM6 GSHP system	15 904 200	SEK	
GSHP maintenance	5 000	SEK/y	
PV system	13 000	SEK/kW	(“Solceller i 2021,” n.d.)
Inverter	22 000	SEK	-
Labour	61 500	SEK/month	(Wikells AF)
District heating	0.83	SEK/kWh	(“Energiföretagen Sverige,” n.d.)
Electricity	1.54	SEK/kWh	(“Priser på el för hushållskunder” n.d.)
Interest	1.00 %	-	-
Growth rate	0.50 %	-	-
Period	35	-	-

Smart1 fan replacement happens in year 20, and its maintenance includes cleaning every two years. The inverter replacement of PV system occurs in year 9, 18 and 27.

Table 13 Construction speed of renovation components

Product	Speed	Unit	Reference
40 mm EPS installation	0.08	h/m²	(Wikells IBE24)
80 mm EPS installation	0.09	h/m²	
120 mm EPS installation	0.09	h/m²	
160 mm EPS installation	0.1	h/m²	
200 mm EPS installation	0.1	h/m²	
240 mm EPS installation	0.1	h/m²	
Vapour barrier laying	0.09	h/m²	(Wikells JFS.54)
Mortar finishing	0.14	h/m²	(Wikells KBC.3111)
Window replacing	1.5	h/each	(Wikells NSC.1103)
Cladding speed	0.3	h/each	-
Smart1 Installation	0.67	h/unit	("Smart ventilation solutions," n.d.)

2.6 LCA

The global warming potential (GWP) of all cases was assessed using Environmental Product Declarations (EPD) in Table 14. The calculation period was 35 years. The investigation focused on the selected category in GWP/kg CO_2-equivalents. It is a measure of how many emissions of 1 kilogram of greenhouse gas were released over a studied period, relative to the emissions of 1 kilogram of carbon dioxide (CO_2).

The objects of this investigation include EPS and mortar used for constructing more insulated external walls, new windows mounted, GSHP system, PV system, district heating demand and electricity demand. Due to the limited data of the adopted ventilation unit, it was decided to calculate the plastic components of the Smart1 unit without considering ceramics and fans. The Energy consumption used in the LCA was derived from building energy simulations.

The GWP of all scenarios were calculated in Excel. System boundaries of products, for which processes in the products life cycle included in the LCA, are different due to limited data and research. The input parameters of renovation measures are shown in Table 14.

Table 14 GWP of renovation components

Product	System boundary	Functional unit	GWP (kg CO_2eq)	Reference
EPS	A1-A5, C1-C4 and D	1 m² of EPS insulation with an R-value of 1 m²K/W (38mm thickness)	2.67	(EPS 80 insulation board, n.d.)
Mortar	A1-A3	1 kg of dry mortar	0.25	(Mortars, n.d.)
Wood/aluminium fixed window	A1–A3	1 m² window	66.7	(windows and patio doors, n.d.)
Wood/aluminium inward window			84.6	
Wood/aluminium inward Kipp-dreh window			89.3	
Smart1	A1	2.24 kg of ABS plastic and 2.54 kg of ceramics used in one Smart1 unit	9.96	(GreenDelta, 2020)
GSHP system with heat storage	A1-A3	1 kW system	344.53	(Aquino et al., n.d.)
PV system	A-D	1 kWh of electricity generated and distributed by PV modules	0.0105	(Photovoltaic Modules, n.d.)
District heating	-	1 kWh of district heating	0.0114	(Kraftringeng, n.d.)
Electricity	-	1 kWh of electricity	0.047	-

2.7 Pareto front

There are 168 combinations of the above five renovation strategies. In order to find out the scenarios with plus in terms of energy and cost, an evaluation method proposed by Pareto was adopted.

The Pareto front is the set of all Pareto efficient allocations. In this case study, the Pareto front is a set of renovation scenarios that are all Pareto efficient. Pareto efficiency is a circumstance where no energy-saving can be better off without making costs grow off. By yielding all 168 combinations, a trade-off between primary energy and LCC can be made using Pareto's method.

The assessment of primary energy and LCC, as well as GWP and LCC of all cases and their Pareto fronts, are carried in Microsoft Power BI. The final results and Pareto front were shown in scatter plots.

3 Results

The results include energy demand simulations and calculation results of the five renovation measures, as well as the LCC and LCA of each measure. Finally, the primary energy, LCC and LCA of 168 combinations of all refurbishment measures were analysed and evaluated to find one or more Pareto efficient scenarios.

3.1 Energy demand simulation

3.1.1 Base case

The energy demand simulation of this building complex obtained from Sefaira is shown in Table 15, compared with the heating energy report provided by the building owner and the result from the degree-hour method carried out in Excel to verify the results.

Table 15 Simulation results comparison

	Sefaira	**Degree-hour**	**Report**	**Unit**
Space heating	2 202 670	2 374 080	-	kWh/y
Domestic hot water	396 440		-	kWh/y
Heat loss through pipes	482 410		-	kWh/y
Total heating demand	143	154	138	kWh/y/m²

Sefaira and Excel showed that the annual heating demand of the existing buildings is 143 kWh/m² and 154 kWh/m², respectively. The difference in the simulation results is within the acceptable range. The subsequent analyses were based on Sefaira simulation results.

At the same time, the electricity demands were calculated in Sefaira according to the schedule and internal loads, which are listed in Table 16.

Table 16 Electricity demand of base case

	Energy demand	**Unit**
Lighting & equipment	676.3	MWh/y
Fan	42.6	MWh/y
Pump	5.5	MWh/y
Electricity in total	724.5	MWh/y
	33.6	kWh/m²/y

3.1.2 Wall insulation and improved windows

The retrofitting of additional insulation materials, the improvement of envelope airtightness and the replacement of windows can significantly reduce the space heating demand of the building. While the pump electricity demand can also be slightly reduced due to the reduction of circulated hot water.

These two renovation strategies have no effect on other outputs. Space heating demand and pumping electricity demand are listed in the following tables. The results of Table 17 are external wall renovation based on existing windows, and Table 18 simulated with advanced windows.

Table 17 Energy results of external wall renovation

Insulation	**0**	**40**	**80**	**120**	**160**	**200**	**240**	**mm**
Space Heating	2 203	2 095	2 063	2 037	2 023	2 010	2 003	MWh
Heating total	143.0	138.0	136.5	135.3	134.70	134.1	133.7	kWh/m²
Pump	5.5	5.0	4.9	4.8	4.7	4.7	4.6	MWh
Electricity total	33.62	33.60	33.60	33.59	33.59	33.58	33.58	kWh/m²

Table 18 Energy results of external wall renovation and window replacement

Insulation	**0**	**40**	**80**	**120**	**160**	**200**	**240**	**mm**
Space Heating	1 566	1 474	1 446	1 424	1 413	1 401	1 396	MWh
Heating total	113.5	109.2	107.9	106.9	106.4	105.8	105.6	kWh/m²
Pump	2.8	2.5	2.4	2.3	2.2	2.2	2.2	MWh
Electricity total	33.50	33.48	33.48	33.47	33.47	33.47	33.47	kWh/m²

It can be seen that after external wall renovation, the space heating reduced from 143 kWh/m² to 138 kWh/m² when 40 mm insulation materials were installed. The minimum is 133.7 kWh/m² when 240 mm insulation was installed. This corresponds to reductions from 4 % up to 9%. Merely replacing the windows can achieve better energy-saving than adding 240 mm insulation material, reduced space heating demand by 30 kWh/m², corresponding to a reduction of 29 %.

3.1.3 Improved ventilation with heat recovery

After mounting Smart1, the space heating demand and electricity demand decreased slightly due to the heat recovery, also lowered pump and fan energy use. The results are shown in Table 19 below.

Table 19 Energy results of ventilation renovation

Old window								
Insulation	0	40	80	120	160	200	240	mm
Space Heating	1 852	1 742	1 709	1 682	1 668	1 654	1 647	MWh
Heating total	126.7	121.6	120.1	118.8	118.20	117.6	117.2	kWh/m²
Pump	4.4	3.9	3.8	3.7	3.6	3.6	3.6	MWh
Electricity total	33.08	33.05	33.05	33.04	33.04	33.04	33.04	kWh/m²
Advanced window								
Insulation	0	40	80	120	160	200	240	mm
Space Heating	1 188	1 088	1 058	1 034	1 021	1 009	1 003	MWh
Heating total	95.9	91.3	89.9	88.8	88.2	87.6	87.3	kWh/m²
Pump	2.0	1.6	1.5	1.5	1.4	1.4	1.4	MWh
Electricity total	32.96	32.95	32.94	32.94	32.94	32.94	32.94	kWh/m²

Comparing with the results in Table 17, The mounting of Smart1 units decreased the space heating demand from 143 kWh/m² to 126.7 kWh/m², which corresponds to a reduction of 12 % in the base case. This measure had s similar reduction in the scenarios with insulation added. Comparing with the results in Table 18, if windows are replaced with triple-pane windows, the heating energy use can be reduced from 113.5 kWh/m² to 95.9 kWh/m², which corresponds to a reduction of 26 %.

3.1.4 Introduction of GSHP and PV

The introduction of GSHP does not change the space heating demand of the buildings but reduces the energy loss of district heating through underground pipes. The total heating and total electricity demand of different scenarios are compared and shown in Table 20.

Table 20 Heating demands of DH and electricity demands of GSHP cases

Insulation (mm)	Window	Ventilation	District heating (kWh/m²)	GSHP Electricity (kWh/m²)
0	Old window	Exhaust	143.0	42.2
0	Old window	Smart1+Exhaust	126.7	38.4
0	Advanced window	Exhaust	113.5	33.6
0	Advanced window	Smart1+Exhaust	95.9	28.4
40	Old window	Exhaust	138.0	41.8
40	Old window	Smart1+Exhaust	121.6	36.9
40	Advanced window	Exhaust	109.2	32.3
40	Advanced window	Smart1+Exhaust	91.3	27.0
80	Old window	Exhaust	136.5	41.4
80	Old window	Smart1+Exhaust	120.1	36.4
80	Advanced window	Exhaust	107.9	31.9
80	Advanced window	Smart1+Exhaust	89.9	26.6
120	Old window	Exhaust	135.3	41.0
120	Old window	Smart1+Exhaust	118.8	36.0
120	Advanced window	Exhaust	106.9	31.6
120	Advanced window	Smart1+Exhaust	88.8	26.3
160	Old window	Exhaust	134.7	40.8
160	Old window	Smart1+Exhaust	118.2	35.8
160	Advanced window	Exhaust	106.4	31.5
160	Advanced window	Smart1+Exhaust	88.2	26.1
200	Old window	Exhaust	134.1	40.6
200	Old window	Smart1+Exhaust	117.6	35.6
200	Advanced window	Exhaust	105.8	31.3
200	Advanced window	Smart1+Exhaust	87.6	25.9
240	Old window	Exhaust	133.7	40.5
240	Old window	Smart1+Exhaust	117.2	35.5
240	Advanced window	Exhaust	105.6	31.2
240	Advanced window	Smart1+Exhaust	87.3	25.8

The annual productions of two sizes of PV systems are shown in

Table 21.

Table 21 PV production

	Small	Large
Panel area / m²	504	1 008
Annual electricity generated / (MWh)	95	190

When PVs were only installed on the roofs of A1 and A2 (see Figure 10), the annual electricity output is 95 MWh. When PVs were also installed on the roof of the A3, the capacity doubles to almost 190 MWh. When GSHP is not considered, the two sizes of solar photovoltaic can replace about 95 MWh or 190 MWh out of 724 MWh of the electricity use from the grid annually.

3.2 Costs of renovation proposals

The renovation costs of all renovation measures were calculated in Excel and listed in Table 22 below. All values have been converted to net present value (NPV). The first two measures, adding insulation materials to external walls and replacing to advanced windows, are divided into three sub-costs in the calculation process: scaffolding cost, material cost and labour cost. Besides, neither of these measures took into account maintenance or replacement costs. The total cost of the Smart1 ventilation unit, GSHP and PV consists of initial investment, maintenance and replacement.

Table 22 Renovation costs of all renovation measures

	Scaffolding cost (MSEK)	**Material cost (MSEK)**	**Labour cost (MSEK)**	**Total costs (MSEK)**
40 mm EPS	2.28	0.79	0.98	4.05
80 mm EPS	2.28	1.15	1.01	4.44
120 mm EPS	2.28	1.51	1.01	4.80
160 mm EPS	2.28	1.87	1.04	5.19
200 mm EPS	2.28	2.22	1.04	5.54
240 mm EPS	2.28	2.58	1.04	5.90
Advanced window	1.61	14.6	0.92	17.13
	Initial cost (MSEK)	**Maintenance (MSEK)**	**Replacement (MSEK)**	**Total costs (MSEK)**
Smart1	2.37	1.33	0.17	3.87
GSHP - EM4	10.86	0.16		11.02
GSHP - EM5	12.68	0.16		12.84
GSHP - EM6	15.9	0.16		16.06
504 m² PV	1.31	0.63		1.93
1008 m² PV	2.62	1.25		3.87

The renovation costs above do not include district heating cost and electricity cost. These were included in the LCC calculation. The LCCs of all 168 scenarios are shown in Figure 12 As mentioned in method section 2.5, the above costs do not add up directly when calculating the cost of the combination of renovation measures. For instance, when renovating external walls and windows simultaneously, the scaffolding can be shared at the cost of 2.28 MSEK. Likewise, due to more insulated external walls or windows, lower heating peak load resulted in a smaller size of GSHP, EM4 or EM5, to reduce costs.

3.3 LCA of retrofitting proposals

The GWP of the renovation measures, adding insulation materials, replacing windows, Smart1, GSHP and PV systems, were calculated and listed in Table 23 below. However, the following results do not include the GWP of district heating and electricity over a 35-year period. The total GWP of each scenario excluding energy consumption during this period is shown in Figure 18.

Table 23 GWP of renovation measures

	GWP excluding energy (ton CO_2 eq.)
40 mm EPS*	56
80 mm EPS	79
120 mm EPS	102
160 mm EPS	125
200 mm EPS	148
240 mm EPS	171
Advanced window	255
Smart1	3.8
GSHP - EM4	40
GSHP - EM5	49
GSHP - EM6	62
504 m² PV	32
1008 m² PV	64

*40 mm EPS external wall renovation includes GWP of mortar used, same for the following five.

3.4 Primary energy and LCC

3.4.1 Pareto efficient scenarios of primary energy and LCC

The primary energy and LCCs of the 168 scenarios are shown in Figure 12. The Pareto efficient scenarios are marked in red.

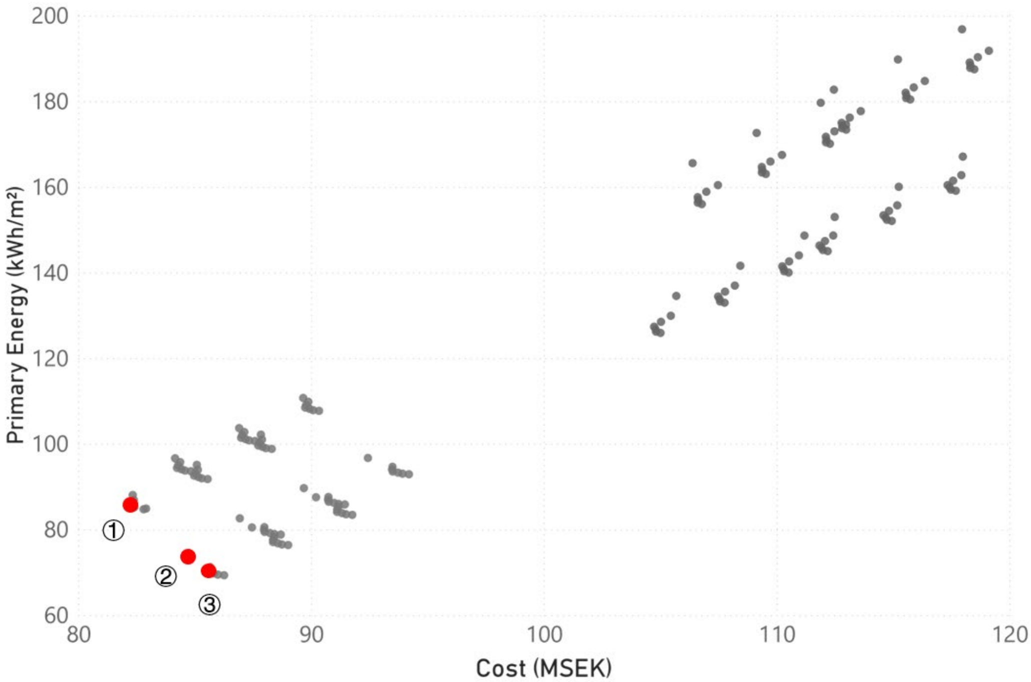


Figure 12 Analysis of primary energy and LCCs of 168 scenarios

Pareto efficient scenarios from left to right are:

① Adding 120 mm insulation + Smart1 + GSHP + Large PV

② Advanced windows + Smart1 + GSHP + Large PV

③ Adding 120 mm insulation + Advanced windows + Smart1 + GSHP + Large PV

To the right of the third Pareto efficient scenario, there are another three Pareto efficient scenarios were not marked. The only difference comparing with ③ is the thickness of their additional insulation materials, which are 160 mm, 200 mm, and 240 mm separately.

3.4.2 Analysis of primary energy and LCC

In addition to the Pareto optimal cases concerning primary energy and LCC, more results of renovation measures are presented and compared in this section.

Figure 13 illustrates the results of scenarios with different thicknesses of additional insulation materials.

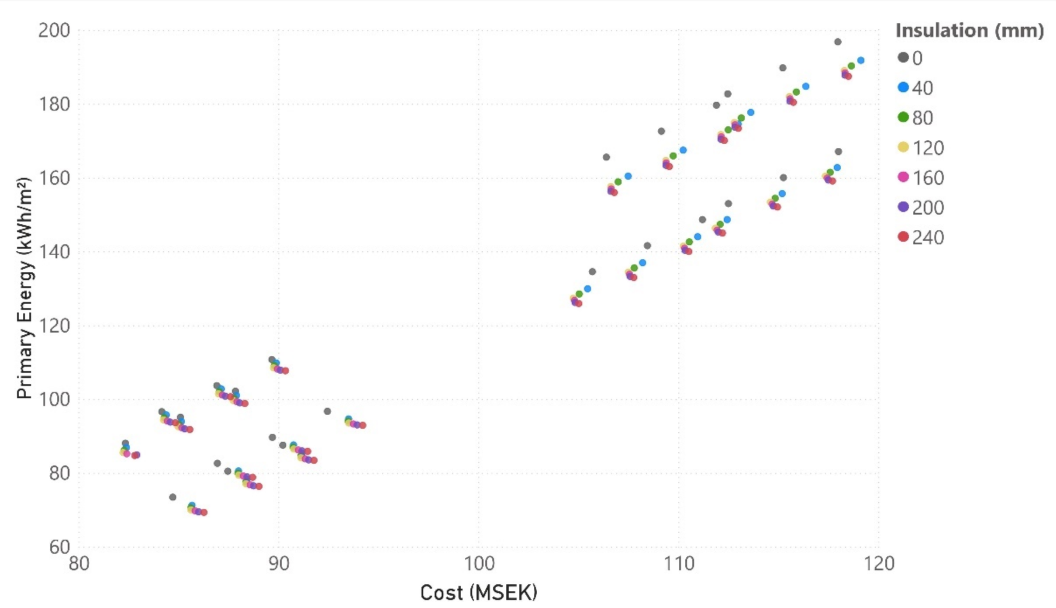


Figure 13 LCC and primary energy for different additional insulation thicknesses

The results of scenarios with old and advanced windows are compared in Figure 14. It can be concluded that the replacement of windows can reduce the primary energy demand considerably.

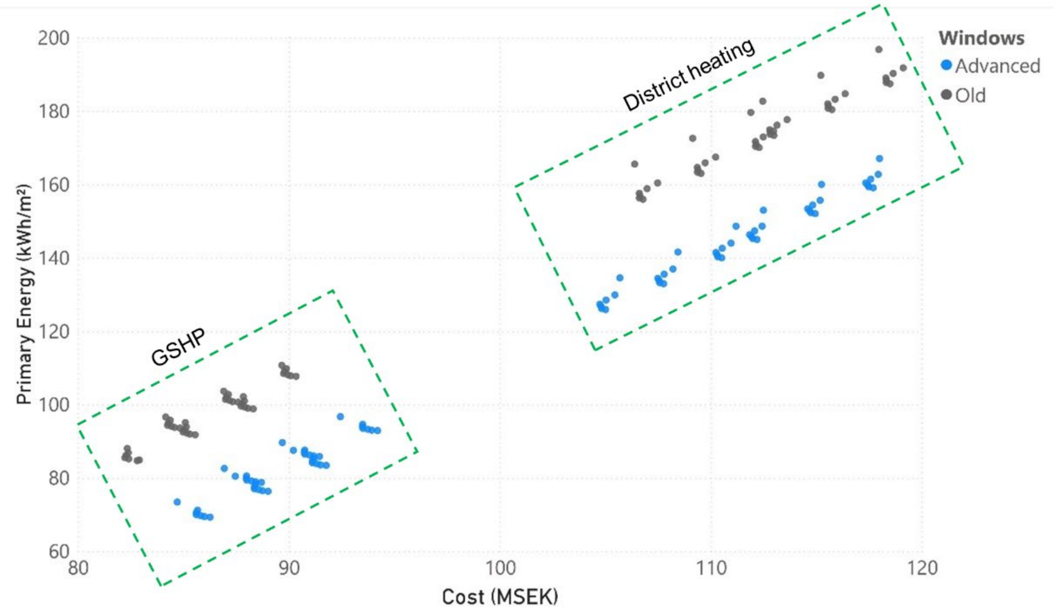


Figure 14 LCC and primary energy for different windows and heating sources

It can be seen from Figure 14 that GSHP has reduced the primary energy demand by nearly half and decreased the LCC by around 20 MSEK over a 35-year period, which is the most effective renovation measure. Comparing within the two green boxes, it shows that the window replacement reduced primary energy demand and LCC when district heating supplying heat. However, with GSHP installed, the LCC was increased by replacing windows.

Figure 15 below illustrates the results of scenarios with different ventilation strategies. The use of Smart1 reduced primary energy demand and LCC in all scenarios. Comparing with Figure 14, it can be seen that the reduction was weakened in the scenarios with GSHP installed.

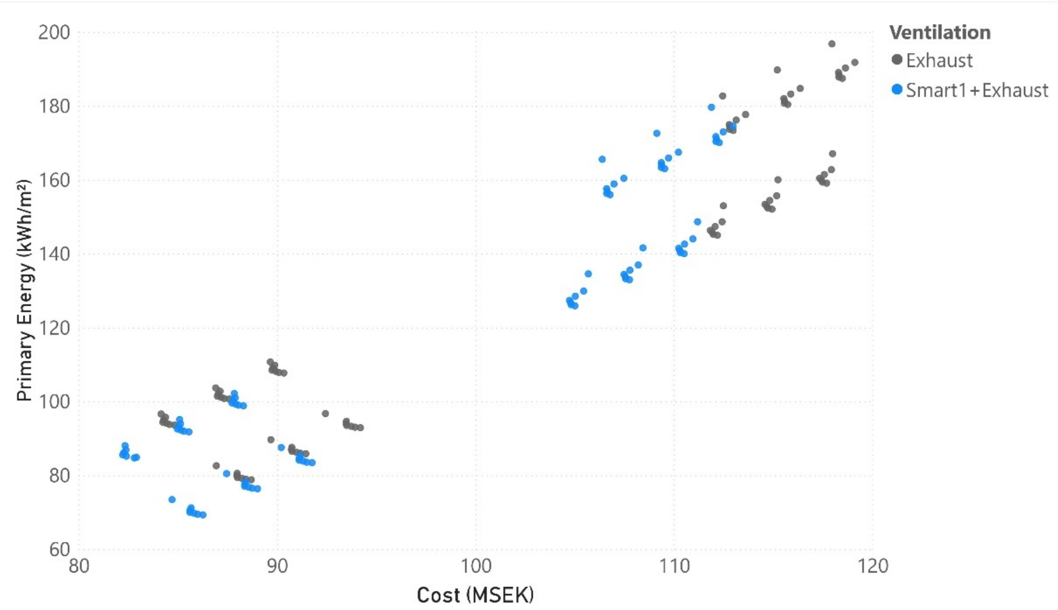


Figure 15 LCC and primary energy for different ventilation systems

Figure 16 demonstrates the LCC and Primary energy results of different sizes of PV systems.

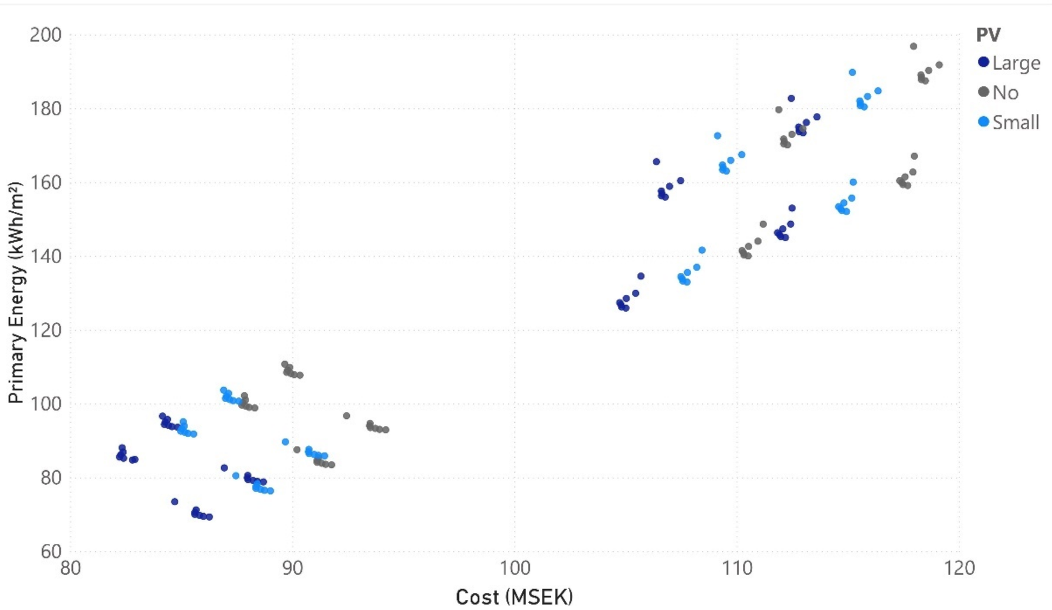


Figure 16 LCC and primary energy for different amount of PV panels

3.5 LCA and LCC

3.5.1 Pareto efficient scenarios of LCA and LCC

The LCA (GWP was investigated) and LCCs of the 168 scenarios are shown in Figure 17. The Pareto efficient scenarios are marked in red.

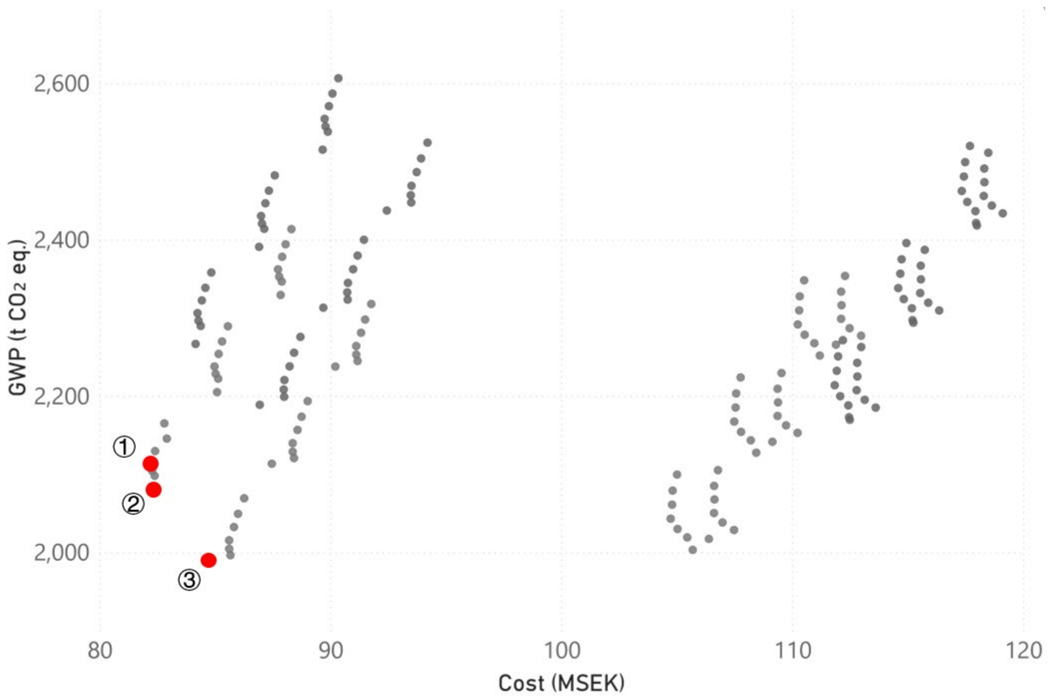


Figure 17 Analysis of GWP and LCC of 168 scenarios

Pareto efficient scenarios from left to right are:

① Adding 120 mm insulation + Smart1 + GSHP + Large PV

② Smart1 + GSHP + Large PV

③ Adding Advanced windows + Smart1 + GSHP + Large PV

3.5.2 Analysis of LCA and LCC

In addition to the Pareto optimal scenarios concerning LCC and LCA (GWP was investigated), more results of renovation measures are presented and compared in this section.

As Figure 18 shows, during the 35 years, installing additional insulation materials on external walls increased GWP. The thicker the insulation, the more greenhouse gas emissions throughout its life cycle. In contrast, the LCC reaches its lowest at 120 mm insulation in some of the scenarios.

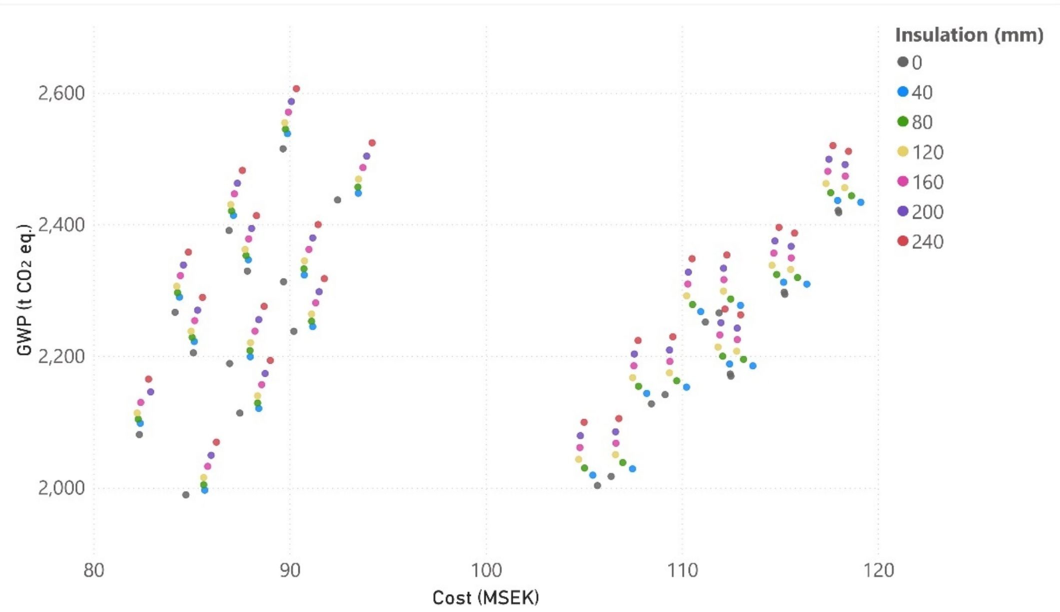


Figure 18 LCC and LCA for different additional insulation thicknesses

Figure 19 demonstrates, over the 35-year period, the results of scenarios with different types of windows and different heating energy sources.

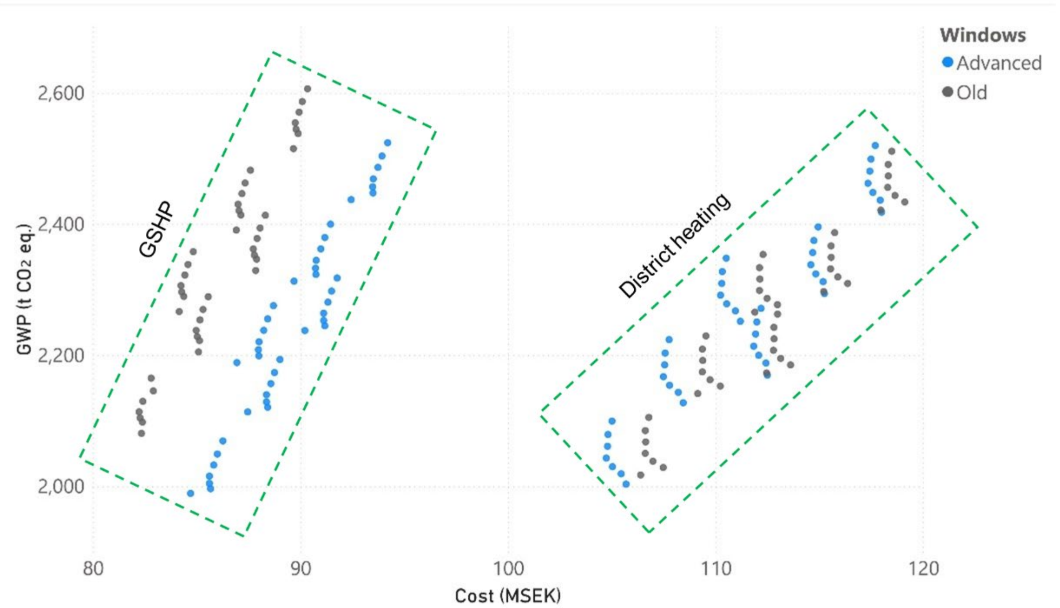


Figure 19 LCC and LCA for different windows and heat sources

Comparing the two green boxes shows that when a GSHP system was installed, replacing windows increased LCC and decreased GWP. However, in the scenarios without GSHP, window renovation decreased the LCC whereas the GWP was unchanged.

Figure 20 illustrates that Smart1 effectually reduces GWP and LCC in all scenarios.

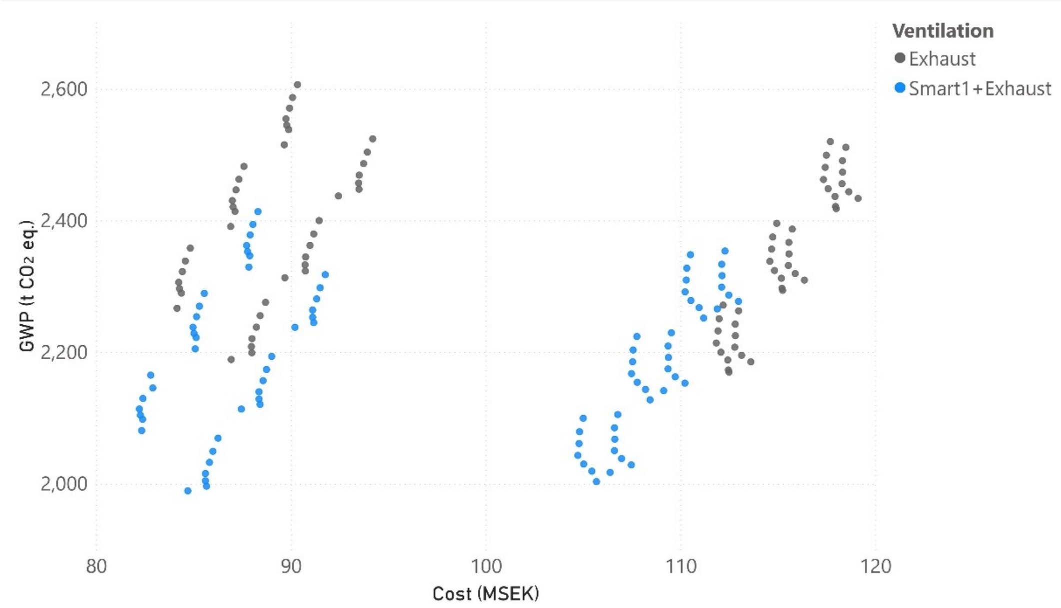


Figure 20 LCC and LCA for different ventilation systems

Figure 21 illustrates that the installation of roof PV is beneficial to reduce both the GWP and LCC of the current building complex.

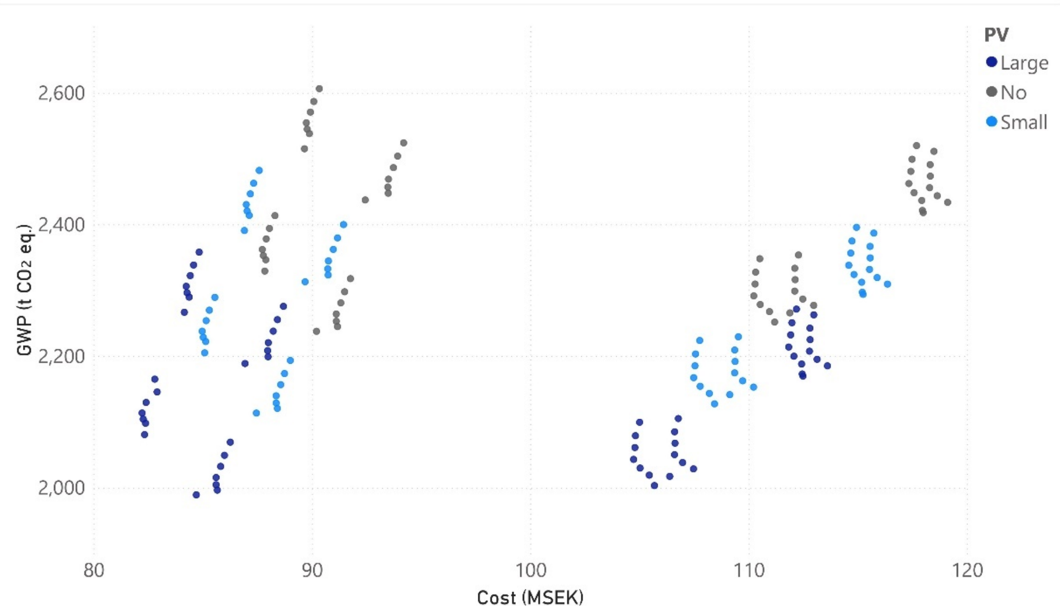


Figure 21 LCC and LCA for different amount of PV panels

4 Discussion

4.1 Building energy simulation

As compared in Table 15, in the base case, the simulation results obtained from Sefaira and Excel are slightly larger than the energy report from the owner of the building complex. Due to the lack of maintenance of the current exhaust ventilation system, the actual ventilation is less than the 0.35 $l/s/m^2$ required by the standard. The missing ventilation airflow led to less heat loss through ventilation, which is believed to be the reason for the difference. Moreover, the U-value of external wall might be underestimated, because the current insulation materials has come loose. There is probably also an air gap beside insulation, resulting more heat loss.

The infiltration reduction of applying external wall renovation was considered to be 40 %, as did the replacement of windows. These values come from two independent pieces of research (Ridley et al., 2003; Younes et al., 2012). It is uncertain whether these two conclusions can be simply added when both renovation measures were applied. The infiltration rate was decreased by 80 % in the simulation input when both measures were applied, from 9 $m^3/m^2/h$ to 1.8 $m^3/m^2/h$ (2.5 $l/m^2/s$ to 0.5 $l/m^2/s$), which is slightly higher than passive house standard 0.3 $l/m^2/s$. By installing a vapour barrier and replacing windows, the airtightness of building envelopes is expected to be close to passive house's. Therefore, 1.8 $m^3/m^2/h$ is considered a reasonable input for scenarios that include both renovation measures.

As mentioned in section 2.1, current external walls contain 100 mm insulation, and the U-value is 0.34 W/m^2K. From Table 17 and Figure 13, it can be seen the heating demand is only saved on the margin by additional insulation materials. Which makes external wall renovation less profitable.

Replacing windows saves more space heating energy than external wall renovation. According to the simulation, the heat loss through windows accounts for nearly 40 % of the total heat losses in the base case, while the external walls only account for approximately 10 %. Therefore, replacing the exterior windows with a lower U-value and better airtightness significantly improves energy saving.

All the information of Smart1 obtained from the manufacturer were rated in a balanced room. However, in this project, the unit is expected to work with an exhaust ventilation system. This may result in a change of fan power when supplying the same airflow of ventilation or a different heat recovery efficiency. Due to the lack of research in this situation, the matter was ignored. There is also a potential to install Smart1 in toilets that have exterior windows. 10 l/s airflow in each toilet will have an 85 % heat recovery, this means more heating energy can be saved.

4.2 LCC and primary energy

When looking at the trade-off between LCC and primary energy, in all Pareto efficient scenarios, Smart1, GSHP and Large PV are included. External wall renovation and window replacement are able to save more primary energy, but at the same time increase the LCC. Therefore, these two measures are optional depend on the expected LCC.

It can be seen in Table 17 in the result section, when the thicker insulation material was added, the reduction rate of heat demand began to decrease, where the marginal benefit begins to appear. This resulted in the lowest LCC at 120 mm insulation in the scenarios without GSHP. When insulation material added to more than 120 mm, the LCC starts to increase due to the higher initial cost.

It can be seen in Figure 14, whether it is economically feasible to replace windows depends on if the GSHP system was installed.

As Figure 14 shows that installing GSHP reduced the primary energy demand by nearly half, making it the most efficient alternative. However, GSHP weakened the effects of energy-saving measures. For instance, compared in the green boxes, when GSHP was installed, the window replacement increased the LCC, although its primary energy was reduced. Which means that when GSHP installed, the priority of measures aimed at energy saving is lowered.

As Figure 15 shows, Smart1 is a good alternative in all scenarios. As discussed, the energy-saving advantage of Smart1 was also weakened by the installation of GSHP.

Due to the small area of rooftop PV, the impact of PV on cost and energy saving is relatively small. However, from Figure 16, it can be found that the installation of the PV system decreased primary energy demand and LCC in all scenarios.

When calculating the cost of renovation proposals, only a 35-year period was considered. Therefore, the results for longer life cycle costs may differ from the results presented. The following facts can explain the difference: insulation typically lasts longer than 50 years, and high-quality windows have a lifespan of nearly 45 years. Moreover, these two renovation measures have almost no follow-up costs beyond the initial investment. A GSHP system also has a lifespan of more than 50 years, though the pump needs to be replaced approximately every 20 years. It can be speculated that adding insulation on walls, replacing windows and install GSHP will be more profitable when a longer period is calculated. On the other hand, Smart1 and PV system are expected to have a large proportion of replacement after 35 years.

4.3 LCC and LCA

When looking at the trade-off between LCC and LCA, GSHP and Large PV are included in all Pareto efficient scenarios. When external wall renovation with 120 mm insulation was also carried out (scenario 1 in section 3.5.2), the LCC decreased while GWP increased. The results of window replacement (scenario 3 in section 3.5.2) are just the opposite.

As Figure 18 illustrates, during the 35 years, external wall renovation is a less eco-friendly measure. However, the life of insulation materials is commonly longer than 50 years, so perhaps for a longer period, external wall renovation would be an environmentally friendly measure. However, when it comes to LCC, 120 mm additional insulation had the largest cost reduction during the 35-year period.

In section 3.1.2 Insulation and Window, it was concluded that replacing windows can significantly reduce the heat demand, resulting in a smaller GSHP system that can supply heating for the building complex. Comparing in Figure 19 shows that installing GSHP (EM5 or EM6) without replacing windows increased GWP. However, in the scenarios of replacing windows, the introduction of GSHP (EM4) resulted in an almost unchanged GWP. This shows that the size of the GSHP system has a great impact on its LCA. A smaller GSHP system not only means money saving, but also makes it easier to achieve the goal of reducing GWP.

Smart1 and PV effectually reduced greenhouse gas emissions and costs in the life cycle of the buildings, making them a good alternative in all scenarios.

As mentioned on section 4.2, longer calculated periods could bring about different cost results. Due to the limitations of the EPD files obtained, the system boundaries (see Table 14) of these products are different; hence some of the results may vary in reality.

The system boundaries of EPS and PV include all periods in their life cycle. However, the LCA of the windows only includes stages A1 to A3 and does not include the construction process stage, end of life stage, and resource recovery stage that significantly impact the GWP of window replacement. Therefore, this led to a higher GWP of replacing windows than expected. Considering that GSHP needs maintenance and replacement, there are additional greenhouse gas emissions in the use stage but not included in the LCA. Thus, the actual result may be considerably higher than the calculated. Due to the limited research on Smart1 or similar products, only plastic and ceramics used in the Smart1 unit were included in the LCA. However, fans and electric control components were not contained. Therefore, the LCA result of Smart1 may considerably differ from reality.

4.4 Correction in Sefaira

Although the simulation results obtained from Sefaira and Excel are relatively similar in the base case, when the infiltration rate was reduced by 40 %, Excel calculated a 2.4 % reduction in space heating demand. In comparison, the decrease in Sefaira was 12.8 %. After reviewing the result reports exported from Sefaira, the following points were found:

First, in the base case, the leakage airflow in Sefaira was 1.93 m^3/s, while the airflow calculated by Excel according to standard 13829 was 1.53 m^3/s. However, the different airflows obtained by different methods were not enough to cause such a significant difference in the total heat demand.

While in the table of heating peak load from Sefaira, after reducing the infiltration rate by 40 %, the heat losses of ventilation and infiltration were reduced together by about 40 %.

Finally, after discussions with supervisors and researchers proficient in HVAC, this is considered an error in the data processing of Sefaira simulation. As the airflow of ventilation and leakage was calculated together, the heat loss of the ventilation is also reduced mistakenly when only the infiltration rate was changed.

In order to solve this issue, it was decided to combine the Excel calculation to adjust the input of infiltration in Sefaira. The adjusted input parameters are shown in Table 24. By calculating the ratio of ventilation airflow and leakage airflow, infiltration input was reduced according to this ratio to force a reasonable heat loss value (i.e., the reduction in the sum of the heat losses of the ventilation and the leakage in Sefaira is equal to the reduction should have in 40 % lower infiltration).

Table 24 Adjust input in Sefaira

				Unit
Actual infiltration	9	5.4	1.8	$m^3/m^2 \cdot h$
Input in Sefaira	9	8.4	7.8	$m^3/m^2 \cdot h$

By adjusting the infiltration rate in Sefaira, the result is basically consistent with the hand calculation in Excel.

4.5 Limitations

This study focused on the above-ground apartment floors of the building complex and did not propose suggestion or conduct research on basement renovation.

The changes in the appearance of the building caused by the renovation of the external walls have not been studied. The thickening of the walls caused by the addition of insulation materials will decline daylighting in the rooms, but this effect has not been studied in this study. The moisture risk of the new external wall structure has been analysed. Since the insulation material is intended to be installed outside the wall, the building components have fewer chances of exposure to moisture risks.

Since many factors influence the cost of construction of the GSHP system, the cost adopted was based on the experience of the consultant from EnergyMachines.

Only two PV areas were studied, the GCR was set at 0.3, and different PV panels' densities were not studied.

The material and construction prices of renovation measures are highly depending on details of the building, especially when it comes to neighbourhood level. The prices given in this report are average prices on the market, they can vary in an actual project.

The costs were calculated over a 35-year period. There is not a longer term studied, and it is likely to have changes in current results.

Due to limited data and researches, the LCA of some products did not include all system boundaries. The GWP of district heating from the energy supply company is not conclusive. Also, the GWP of electricity used in this study from Swedish mix electricity, not local data from Lund.

5 Conclusions

According to the building energy demand simulation, the five renovation measures all reduced the primary energy demand of the building complex as expected. Replacing old windows with more insulated windows has a great advantage for space heating energy saving. Replacing part of the airflow initially supplied by the exhaust ventilation with Smart1 also considerably reduced the heat demand. GSHP and PV also significantly reduce the primary energy demand of the building complex in terms of energy source.

When weighing the primary energy demand and LCC of the renovation measures, the following conclusions can be drawn. Firstly, Smart1, GSHP and Large PV are beneficial in all situation. Especially GSHP saved the most primary energy and LCC. Secondly, the optimal additional insulation thickness is 120 mm (the U-value reduced to 0.16 W/m²K), where the lowest LCC can be found. Thirdly, window replacement increased the LCC when GSHP was also installed.

When weighing between the GWP and the LCC of renovation measures, the following conclusions can be drawn. Firstly, as mention above, Smart1 and Large PV are still winners in all scenarios. Secondly, external wall renovation increased environmental impact. Thirdly, GSHP increased greenhouse gas emission when old windows were kept. On the other hand, when windows were replaced and GSHP was installed, GWP was decreased.

The two paragraphs above conclude two opposite conclusions. From the perspectives of primary energy and LCC, windows should not be replaced if GSHP is included. However, from the perspectives of LCA and LCC, these two renovation measures should be carried out together. This divergence is caused by different angles of consideration.

References

Aquino, A., Bonamente, E., Rinaldi, S., Nicolini, A., Medaglia, C.M., n.d. Life cycle assessment of a ground-source heat pump including an upstream thermal storage 13.

Belaïd, F., Ranjbar, Z., Massié, C., 2021. Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector. Energy Policy 150, 112122. https://doi.org/10.1016/j.enpol.2020.112122

Boverket's mandatory provisions and general recommendations, BBR, BFS 2011:6 with amendments up to BFS 2018:4, n.d. 154.

Boverkets föreskrifter om ändring av verkets föreskrifter och allmänna råd (2016:12) om fastställande av byggnadens energianvändning vid normalt brukande och ett normalår, BFS 2017:6, n.d. 16.

CELLPLAST S200 2400X1200X200MM 8,64 M^2 3ST PER PAKET [WWW Document], n.d. URL https://www.bauhaus.se/cellplast-s200-2400x1200x200mm-8-64-m-3st-per-paket (accessed 5.11.21).

Cuce, E., 2017. Role of airtightness in energy loss from windows: Experimental results from in-situ tests. Energy and Buildings 139, 449–455. https://doi.org/10.1016/j.enbuild.2017.01.027

Documentation EnergyMachines™ | Energymachines, n.d. URL https://energymachines.com/en/products/energy-machines/documentation-energymachines/ (accessed 5.11.21).

Dodoo, A., Gustavsson, L., Sathre, R., 2011. Primary energy implications of ventilation heat recovery in residential buildings. Energy and Buildings 43, 1566–1572. https://doi.org/10.1016/j.enbuild.2011.02.019

Energy Efficient Design Software | Green Design | Sefaira [WWW Document], n.d. . SketchUp. URL https://www.sketchup.com/products/sefaira (accessed 5.11.21).

EnergyPlus | EnergyPlus [WWW Document], n.d. URL https://energyplus.net/ (accessed 5.11.21).

Fjärrvärmepriser - Energiföretagen Sverige [WWW Document], n.d. URL https://www.energiforetagen.se/statistik/fjarrvarmestatistik/fjarrvarmepriser/ (accessed 6.2.21).

GreenDelta, 2020. openLCA.

Hjortling, C., Björk, F., Berg, M., Klintberg, T. af, 2017. Energy mapping of existing building stock in Sweden – Analysis of data from Energy Performance Certificates. Energy and Buildings 153, 341–355. https://doi.org/10.1016/j.enbuild.2017.06.073

Johansson, P., n.d. Assessment of the Risk for Mold Growth in a Wall Retrofitted with Vacuum Insulation Panels 8.

Liu, S., Shukla, A., Zhang, Y., 2014. Investigations on the integration and acceptability of GSHP in the UK dwellings. Building and Environment 82, 442–449. https://doi.org/10.1016/j.buildenv.2014.09.020

Nyckeltal till din hållbarhetsredovisning [WWW Document], n.d. . Kraftringen. URL https://www.kraftringen.se/om-kraftringen/hallbarhet/miljo/nyckeltal/ (accessed 5.11.21).

Priser på el för hushållskunder 2007– [WWW Document], n.d. . Statistiska Centralbyrån. URL http://www.scb.se/hitta-statistik/statistik-efter-amne/energi/prisutvecklingen-inom-energiomradet/energipriser-pa-naturgas-och-el/pong/tabell-och-diagram/genomsnittspriser-per-halvar-2007/priser-pa-el-for-hushallskunder-2007/ (accessed 6.2.21).

Ramírez-Villegas, R., Eriksson, O., Olofsson, T., 2016. Assessment of renovation measures for a dwelling area – Impacts on energy efficiency and building certification. Building and Environment 97, 26–33. https://doi.org/10.1016/j.buildenv.2015.12.012
Ridley, I., Fox, J., Oreszczyn, T., Hong, S.H., 2003. The Impact of Replacement Windows on Air Infiltration and Indoor Air Quality in Dwellings. International Journal of Ventilation 1, 209–218. https://doi.org/10.1080/14733315.2003.11683636
Rønneseth, Ø., Holck Sandberg, N., Sartori, I., 2019. Is It Possible to Supply Norwegian Apartment Blocks with 4th Generation District Heating? Energies 12, 941. https://doi.org/10.3390/en12050941
Smart ventilation solutions [WWW Document], n.d. . Smartvent. URL https://smartvent.se/en/ (accessed 2.20.21).
Solar PV – Analysis [WWW Document], n.d. . IEA. URL https://www.iea.org/reports/solar-pv (accessed 2.17.21).
Solceller i 2021: Jämför pris och hitta installatörer [WWW Document], n.d. URL https://www.greenmatch.se/solceller (accessed 5.11.21).
S-P-01642 - Mortars for plaster, render coats and restoration, thermo-dehumidifying renders [WWW Document], n.d. URL https://www.environdec.com/library/epd1642 (accessed 5.11.21).
S-P-01969 - Wood- and wood aluminum clad windows and patio doors [WWW Document], n.d. URL https://www.environdec.com/library/epd1969 (accessed 5.11.21).
S-P-02035 - EPS 80 insulation board [WWW Document], n.d. URL https://www.environdec.com/library/epd2035 (accessed 5.11.21).
S-P-02325 - Risen Energy Single-glass Monocrystalline Photovoltaic Modules [WWW Document], n.d. URL https://www.environdec.com/library/epd2325 (accessed 5.11.21).
Stevson, S., Yinxin, L., 2020. Heating Energy Performance & LCC Analysis on Renovation Proposals of a Multi-Family Apartment Cluster. Lund University.
Swedish Standards Insutitute, 2000. Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurisation method (ISO 9972:1996, modified).
Uffelen, C. van, 2012. Passive Houses: Energy Efficient Homes. Braun Publishing.
Wikells Sektionsfakta [WWW Document], n.d. URL https://www.sektionsfakta.se/User/Byggdelar/ByggdelsKapitel?bok=ROT (accessed 5.11.21).
Yang, Y., Campana, P.E., Stridh, B., Yan, J., 2020. Potential analysis of roof-mounted solar photovoltaics in Sweden. Applied Energy 279, 115786. https://doi.org/10.1016/j.apenergy.2020.115786
Younes, C., Shdid, C.A., Bitsuamlak, G., 2012. Air infiltration through building envelopes: A review. Journal of Building Physics 35, 267–302. https://doi.org/10.1177/1744259111423085

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