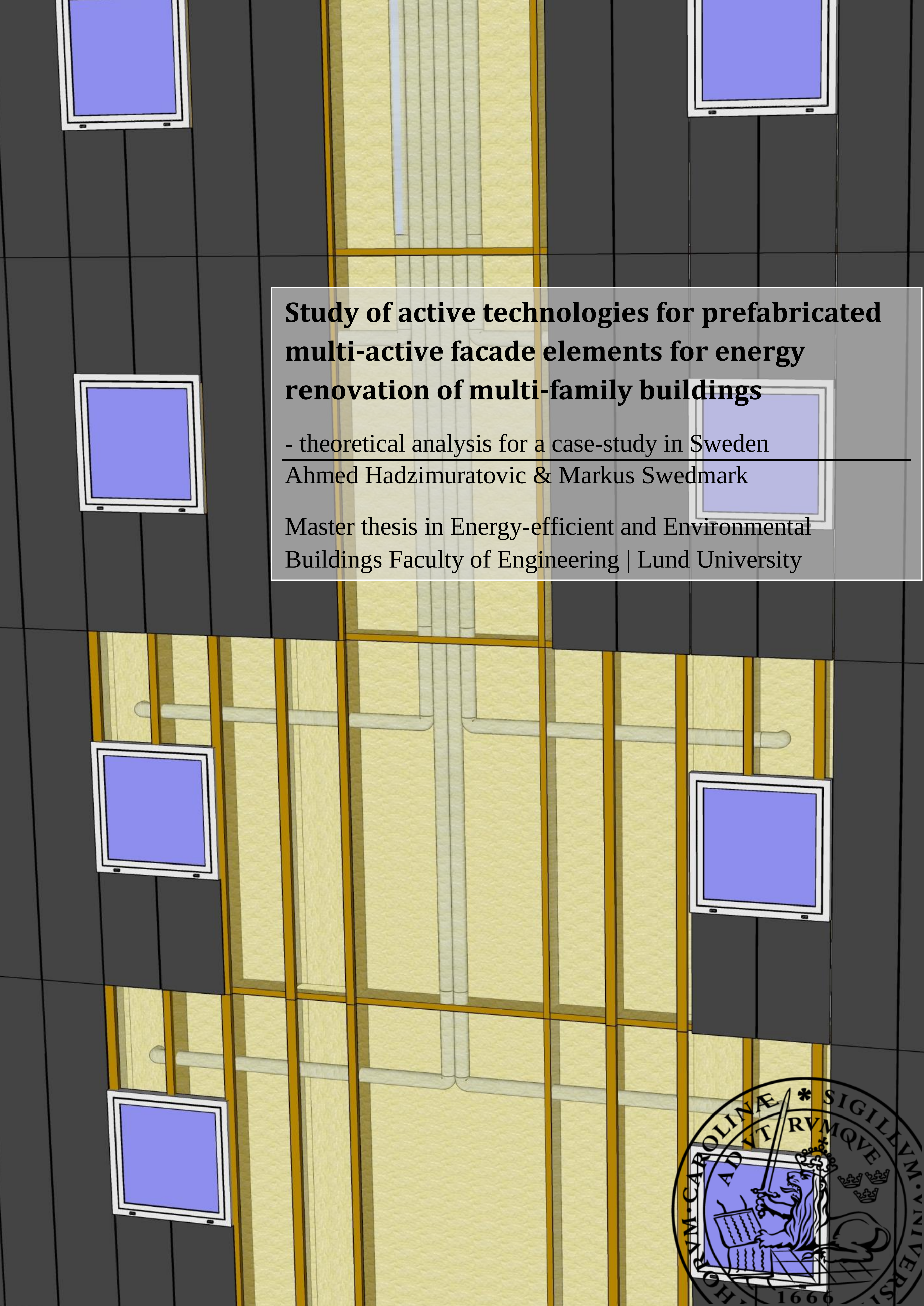

Study of active technologies for prefabricated multi-active facade elements for energy renovation of multi-family buildings

- theoretical analysis for a case-study in Sweden

Ahmed Hadzimuratovic & Markus Swedmark

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 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. 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.

Examiner: Åke Blomsterberg

Supervisor: Ricardo Bernardo, Stephen Burke

Keywords: Multi-active façade element, BIPV, LCC, heat losses from façade integrated ductwork

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Abstract

In Sweden, between 1964 and 1975, approximately one million dwellings were raised in the so called million programme. Due to their age and often neglected maintenance regarding both building envelope and installations, in many cases, comprehensive retrofitting is now required. The aim with this study was to theoretically investigate the energy saving potential and cost-effectiveness of integrating active technologies into a prefabricated insulating façade module, when retrofitting a Swedish case-study high-rise lamella multi-family building from the “Million Program”. The active technologies that were found most suitable in the Swedish context were; centralized supply- and exhaust air ducts with heat recovery where the supply air ducts are routed through the multi-active elements as well as facade integrated photovoltaics. To estimate their energy savings potential, various energy simulations were conducted in software tools such as, HEAT2, IDA ICE and Rhinoceros. To estimate the economic feasibility life cycle calculations were carried out. It was found that the heat losses as well as the annual energy losses from wall integrated ducts were minor even without high performing insulation materials applied. Furthermore, the decrease in the supply air temperate during the coldest hour in the year was acceptable. The results showed that by improving the building envelope and reusing the present exhaust air ducts as well as integrating the supply air ducts in the multi-active element the specific energy use can be lowered by 55 %, from 141 to 62.8 kWh/(m^2·yr). The combination of heat recovery from the exhaust air as well as the insulating properties of the multi-active elements are the main contributing factors to the energy savings. The multi-active façade solution with complementary energy saving measures (roof insulation, windows and heat recovery) was found to have a higher saving potential compared to traditionally insulate the building with or without a heat pump. Moreover, the integration of photovoltaic modules in the façade have a restricted potential due to limitations in the Swedish tax regulations. This makes the energy savings of installing photovoltaic modules in the façade roughly covering the investment during the lifetime only when the investment subsidy is awarded. The economic analysis showed that improving the building envelope and implementing a multi-active façade solution, resulted in a competitive alternative in comparison to traditionally insulate the building and as well as to previously documented retrofitting projects in Sweden.

Preface

This study was carried out as the final part of the master programme in Energy Efficient Building Design at Lund University. Further, the study was carried out as a collaboration between Lund University and NCC.

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We would like to thank our main supervisor Ricardo Bernardo for the given support, guidance and dedication during the entire work process of this master thesis.

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The authors gratefully acknowledge permission to use material from the following sources;

Figure 1: Lunos e², example of a regenerative micro air handling unit (Lunos, 2016).

Figure 2: Example of possible building integrated photovoltaics (Acc-glasrådgivare, 2016).

Figure 3: Illustration of a Hybrid PV/T (Newform Energy, 2014)

Finally, we would like to thank our families and friends for their understanding and support during the entire master studies.

Malmö, June 2016

Ahmed Hadzimuratovic & Markus Swedmark

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1 Introduction

1.1 Background

Global warming and climate change

It is commonly known that one of the greatest challenges of our time is to limit the effect of global warming. As a consequence of the global warming scientists now observe climate changes, which have resulted in retreating glaciers, an increased sea level, higher intensity of tropical storms and more frequent and severe heat waves (NASA, 2016). According to the Intergovernmental Panel on Climate Change (IPCC), "*The range of published evidence indicates that the net damage cost of climate change is likely to be significant and to increase over time*" (IPCC, et al., 2007). Furthermore, scientists strongly believe that the global temperatures will continue to rise in the future, this partly due to the greenhouse gas emissions caused by humans (NASA, 2016). The main greenhouse gas emission caused by humans is carbon dioxide (CO_2) where the primary source is fossil fuels (EPA, 2015). Further, fossil fuels like crude oil, natural gas and coal are currently the worlds primary energy source (EESI, 2016). To enable a sustainable life on the planet a reduction of the global energy use of fossil fuels is a requirement.

EU 2020 goals and directives

The European commission has, in order to limit and reduce the global climate change, set climate and energy targets for 2020 which consists of three key targets (European Commission, 2016a);

- Reduction of greenhouse gas emissions by 20 %, compared to the levels of 1990.
- 20 % of the energy used in EU is to be provided from renewable energy sources.
- An improvement in energy efficiency by 20 %, compared to future projections from 2007 in areas such as generation and final usage of energy.

One of the highest energy using and largest CO_2 emitting sectors in Europe is the building- and service sector which corresponds to approximately 40 % of the energy use and 36 % of the CO_2 emissions in the EU. At the moment approximately 35 % of the building stock in the EU is over 50 years old (European Commission, 2016b). The European commission (2016b) state that there is a potential to reduce the total energy usage up to 6 % in the EU by improving the energy efficiency of buildings. Furthermore, the Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive have been developed which briefly state that;

- By the 31 of December 2020 all new buildings must be Nearly Zero Energy Buildings (NZEB).
- Countries in the EU must set minimum energy performance requirements for new buildings and for energy retrofitting of the present building stock.

- Countries within the EU are obligated to energy efficiently retrofit 3 % of the buildings owned and occupied by the government and that long-term national building renovation strategies are developed (European Commission, 2016b).

An investigation has been carried out by the Swedish National Board of Housing (SNBH), at the request of the government, to propose what NZEB should mean in form of demands on the energy performance of buildings in Sweden (Boverket, 2015a). The SNBH propose that the energy performance of a new building in Stockholm is not to exceed the criteria, described in Table 1 for non-electrically heated buildings (Boverket, 2015b). Geographical location adjustments of the demands, due to difference in climate, will be established. The energy performance demand applies to specific energy use which is bought energy for; space heating, domestic hot water (DHW), space cooling and property used electricity. Moreover, if the building is electrically heated the bought energy for space heating, DHW and space cooling should be multiplied with a value of 2.5. If a larger effect for heating than 10 W/m^2 heated floor area is installed the building is considered as electrically heated (Boverket, 2015c).

Table 1: Proposed NZEB specific energy use criteria for new buildings situated in Stockholm after 2020 (Boverket, 2015b).

Building type	Multi-residential building	Multi-residential building (apartment size max 35 m^2)	Facilities	Single family houses
Spec. energy use / $kWh/(m^2 \cdot yr)$	55	65	50	80

Swedish building stock and energy performance

The Swedish residential building stock holds a great energy saving potential where an average of 138 $kWh/(m^2 \cdot yr)$ is used for space heating and domestic hot water (DHW) (Energimyndigheten, 2015). Furthermore, the housing segment built between the years of 1964 and 1975, where approximately one million dwellings were raised, have an energy use for space heating and DHW of approximately 165 $kWh/(m^2 \cdot yr)$ (Warfvinge, 2008). These buildings, which now are referred to as buildings from “The million programme”, are according to Warfvinge (2008), the most common multi-residential building type in Sweden, furthermore, they are generally constructed similarly and have a similar energy use (Blomsterberg, 2012). Due to their age and often neglected maintenance, comprehensive retrofitting is awaiting, including both replacement and refurbishment of plumbing, ventilation systems, windows, electrical installations and facades (Boverket, 2014). In conclusion, it is high time to address these buildings. Moreover, it would be a good opportunity to combine energy saving measures with the required retrofitting since some of the investment needs to be done in both cases anyway. However, such a retrofit has to be economically justifiable in order to be appealing for property owners at a large scale.

1.2 Swedish building code requirements

The current energy performance requirements, set by the SNBH, for new buildings are divided into four climate zones to account for differences in climate depending on geographical location. Climate zone one and four represents the north and south of Sweden respectively. Furthermore, the requirements are divided into if the building is electrically heated or non-electrically heated, for an example by district heating. Moreover, climate zone one represents the north of Sweden and climate zone four the south of Sweden respectively. The energy performance, expressed in the buildings specific energy use, of new multi-residential buildings and average heat loss coefficient (U_m) for the building envelope is not to exceed the requirements described in Table 2 (Boverket, 2015c). The energy performance requirements include bought energy for; space heating, domestic hot water, cooling and property used electricity.

Table 2: Specific energy use requirements by SNBH for new multi-residential buildings.

Climate zone	**1**	**2**	**3**	**4**
Specific energy use (electrically heated) / kWh/(m^2·yr),	85	65	50	45
Specific energy use (non-electrically heated) / kWh/(m^2·yr),	115	100	80	75
Average heat transfer coefficient (U_m) / W/(m^2·K)	0.4	0.4	0.4	0.4

To ensure a good indoor climate the minimum required ventilation flow in all buildings is 0.35 l/(s· m^2) in average for the heated floor area (Boverket, 2015c).

When retrofitting a building the aim should be to meet the energy performance requirements set by SNBH of a new building as far as possible. Moreover, no degradation of the energy performance is allowed after a retrofitting (Boverket, 2015c). Furthermore, if the requirements are not fulfilled after the retrofitting for various reasons, the aim should be, when retrofitting the climate envelope, to have at maximum heat loss coefficients of the climate envelope described in Table 3 (Boverket, 2015c). Moreover, it should be mentioned that the Swedish building code does not specify exactly what the definition of an extensive retrofitting is.

Table 3: Requirement on heat loss coefficients for the climate envelope after changes to the building envelope if the average heat loss coefficient of 0.4 W/(m^2·K) for the envelope could not be met.

Construction part	Roof	Exterior wall	Foundation	Window	Door
Heat transfer coefficient / W/(m^2·K)	0.13	0.18	0.15	1.2	1.2

Furthermore, if extensive changes are made to the present ventilation system, maximum specific fan power (SFP) according to SNBH is described in Table 4 (Boverket, 2015c).

Table 4: Maximum SFP of a retrofitted ventilation system, HR represents heat recovery.

Ventilation system type	Supply- and exhaust air with HR	Supply- and exhaust air without HR	Exhaust air with HR	Exhaust air without HR
SFP Ventilation system/ kW/(m^3/s)	2.0	1.5	1.0	0.6

Regarding air infiltration, the Swedish building regulations stipulates that the airtightness of the building should be so good that the requirements on building energy performance, described in Table 2, are met (Boverket, 2015c). Moreover, no definition is given regarding what good airtightness is.

1.3 The Swedish million programme

1.3.1 History

After the Second World War a steadily growing population in Sweden was recorded, this led to a general housing shortage. More people began to move from the rural parts of Sweden into the cities as a result of a growing prosperity (Vidén, 2012). The Swedish government was forced to take action to solve the overcrowded living conditions as well as the low housing standards. A parliamentary decision was made to build approximately 100 000 apartments yearly during a period of ten years. The buildings were raised over the whole country but with emphasis on the three largest cities; Stockholm, Gothenburg and Malmoe. They were generally located in the outskirts of the city, which resulted in a development of suburbs (Vidén, 2012). To enable a short production time, the variation of building and construction types were limited because of the immense amount of apartments to be built (Industrifakta, 2008). According to Industrifakta (2008) 85 % of the raised buildings were lamella buildings with a total of approximately 700 000 apartments. Moreover, about 300 000 of the apartments are in low-rise lamella buildings, illustrated in Figure 4, and 400 000 apartments in buildings with four or more storeys, illustrated in Figure 5. Moreover, approximately 10 % of the raised buildings were tower blocks, illustrated in Figure 6, and 5 % were lamellar buildings with exterior corridors (Industrifakta, 2008).

Figure 4: Example of a low-rise lamella building situated in Malmoe.

Figure 5: Example of a high-rise lamella building situated in Malmoe.

Figure 6: Example of a tower block building situated in Malmoe.

1.3.2 Construction

A summary of generally applied construction solutions for buildings raised during the million program is presented in Table 5. The information was obtained from Reppen & Vidén (2006) and Björk, et al. (1983).

Table 5: Generally applied construction solutions for buildings raised during the million program.

Construction part	Low-rise lamella	High-rise lamella	Tower block
Roof	Flat or low pitched roof	Flat roof	Flat roof
Attic	Cold attic, insulated with 15 cm of min.wool	Cold attic, insulated with 15 cm of min.wool	Cold attic, insulated with 15 cm of min.wool
Exterior walls	Concrete, brick and timber framework. Min. wool insulation, 5 cm to 10 cm.	Concrete cast on site with exterior light weight concrete as insulation or lightweight concrete blocks	Concrete cast on site with exterior light weight concrete as insulation or lightweight concrete blocks
Interior walls	Concrete, load bearing	Concrete, load bearing in lower floors	Concrete, load bearing in lower floors
Foundation	Slab on ground/crawl space/basement with reinforced concrete slab.	Slab on ground /basement with reinforced concrete slab.	Slab on ground /basement with reinforced concrete slab.

Generally, the inner walls were the loadbearing core of the building which consisted of reinforced concrete alternatively lightweight concrete blocks in low storey buildings. However, during the 1970s sandwich exterior loadbearing wall elements were also used for both the low- and high rise lamella buildings. Prefabricated elements were more commonly used during the later part of the million program (Björk, et al., 1983). Plaster was usually used on the concrete exterior walls while timber framework walls could have outer layers of metal sheeting, wood panels, eternite or facade brick. The foundation, depending on the site conditions, usually consisted of slab on ground, basement foundation or crawl space foundation. Approximately one third of the roof constructions were constructed almost completely flat, therefore, large attics are very uncommon (Björk, et al., 1983). It is common, for the buildings raised during this period, to not have an airtight envelope (Warfvinge, 2008).

1.3.3 Ventilation

Natural ventilation was the most common ventilation system used in apartment buildings, prior to the million program. Initially it was used for some low rise buildings during the period, although, in a small extent (Reppen & Vidén, 2006). Natural ventilation works by thermal forces and wind pressure, furthermore, the system is based on supplying air through valves in windows and walls to living-and bedrooms. Moreover, the air is exhausted through ducts in the kitchen, toilets and bathrooms (Warfvinge & Dahlblom, 2010). However, the most common installed ventilation system, used in over 70 % of the buildings dating from the million program, was mechanical exhaust air ventilation (Reppen & Vidén, 2006). This system works similarly to natural ventilation with the exception of deliberately creating an under pressure in the building by placing fans connected to the exhaust air ducts (Warfvinge & Dahlblom, 2010).

1.3.4 Space heating and domestic hot water

Approximately 60 % of the buildings raised during the million program were connected to district heating, 30 % were connected to a local heating central and about 10 % were heated by electricity (Reppen & Vidén, 2006). However, today, approximately 94 % of the buildings use district heating as the main heating source for space heating and DHW. Furthermore, 97 % of the buildings, connected to district heating, use a hydronic system (Boverket, 2010). The heat is distributed commonly through two-pipe connected radiators, although, some of the buildings installed one-pipe systems. Due to the often occurring problems with one-pipe systems, where the heat is unevenly distributed in the building, this type of system was quickly abandoned. The DWH is commonly connected to a hot water circulation pump to avoid waiting time and unnecessary pouring of water (Reppen & Vidén, 2006).

1.4 Previous comprehensive retrofitting projects in Sweden

Several retrofitting pilot projects have been carried out in Sweden, focusing on buildings from the million program. A short summary of five retrofitting projects with information regarding used energy reducing measures is presented in Table 6. Some information was not possible to obtain, for instance the air leakage after the retrofit as well as by how much thermal bridges were reduced, therefore, only yes or no is inscribed in these categories. The information was collected from the report "*Ekonomi vid ombyggnader med energisatsningar*" by Byman & Jernelius (2012).

In the report by Byman & Jernelius (2012) an economic analysis of the projects was conducted where some general conclusions were made. Generally, energy reducing measures are seldom profitable if only considering the savings in energy use even if the reduction is up to 70 %. All of the above mentioned projects include standard increasing measures, which is a factor to why some property owners consider the retrofitting in total to be profitable. This is due to an increasing value of the property as well as positive effects on the neighbourhood in terms of lower vacancies and improved reputation. Furthermore, Byman & Jernelius (2012) argue that the retrofitting is often considered by the property owners as a long term investment. The buildings which have been retrofitted are often in such a condition that a standard increase and renovation is inevitable. However, when a standard increase and renovation is carried out, the energy saving measures can contribute to a lower life cycle cost (LCC) and somewhat reduce the unprofitability. Contributing factors to why a certain property owner considers a retrofit profitable or unprofitable is highly depending on assumed interest rates, energy price increase and inflation. Generally, many of the owners reckon that retrofits would be more profitable if higher increases were made to the rent for the tenants. Moreover, a strategy to make the retrofit more profitable is to additionally add new floors to the buildings and have more apartments which in turn raise the revenue (Byman & Jernelius, 2012).

Table 6: Summary of five of the retrofitting projects carried out in Sweden.

<table>
<tr><th colspan="2">Retrofitting project</th><th>Backa röd</th><th>Gårdsten Solhus 1</th><th>Brogården</th><th>Nystad 7</th><th>Trondheim 4</th></tr>
<tr><td colspan="2">Building type</td><td>Tower block</td><td>Lamella</td><td>Lamella</td><td>Lamella</td><td>Lamella with exterior corridors</td></tr>
<tr><td colspan="2">Built / year</td><td>1971</td><td>1969-1971</td><td>1971-1973</td><td>1974</td><td>1974</td></tr>
<tr><td colspan="2">Building units / apartment units</td><td>1/16</td><td>10/255</td><td>16/300</td><td>1/99</td><td>1/24</td></tr>
<tr><td colspan="2">Additionally insulated façade / mm</td><td>200</td><td>150</td><td>430-480</td><td>80</td><td>50</td></tr>
<tr><td colspan="2">Additionally insulated attic / mm</td><td>500</td><td>150</td><td>500</td><td>300</td><td>200</td></tr>
<tr><td colspan="2">Additionally insulated basement walls, crawl space or slab / mm</td><td>Crawl space, 500</td><td>Basement, 200</td><td>Slab, 100</td><td>Basement, 80</td><td>Basement, 150</td></tr>
<tr><td colspan="2">Increased airtightness</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Installed Supply- and exhaust air ventilation with heat recovery</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Reduced thermal bridges</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Individual debiting of DHW after retrofit</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Change of windows and/or doors</td><td>Both</td><td>Windows</td><td>Both</td><td>Both</td><td>Both</td></tr>
<tr><td colspan="2">Standard increase, new bathroom, kitchen, floors etc.</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Rent increase after retrofit / %</td><td>35</td><td>7</td><td>40</td><td>17-24</td><td>17-24</td></tr>
<tr><td colspan="2">Evacuation of tenants</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td rowspan="2">Investment cost for energy saving- and standard increasing measures / (SEK/m^2)</td><td>Ene-rgy</td><td>3 000</td><td>1 000</td><td>5 600</td><td>2 140</td><td>3 490</td></tr>
<tr><td>Stan-dard</td><td>11 500</td><td>4 500</td><td>14 200</td><td>9 860</td><td>11 110</td></tr>
<tr><td rowspan="2">Energy use for DHW, space heating and property used electricity / (kWh/(m^2·yr))</td><td>Before</td><td>178</td><td>274</td><td>177</td><td>164</td><td>214</td></tr>
<tr><td>After</td><td>52</td><td>145</td><td>58</td><td>78</td><td>94</td></tr>
<tr><td colspan="2">Total energy use reduction / (%)</td><td>70</td><td>47</td><td>67</td><td>52</td><td>56</td></tr>
<tr><td colspan="2">Considered as a profitable investment</td><td>No</td><td>Yes</td><td>Yes</td><td>No</td><td>No</td></tr>
</table>

1.5 Multi-active facades

Multi-active facade or multi-functional facade is a concept, where emphasis is on integrating passive- and active technologies in a prefabricated wall element (Treberspurg & Djalili, 2010). These elements can also be manufactured and assembled on-site. Possible passive integrated technologies are thermal insulation and phase changing materials (PCM). Further, possible integrated active technologies are among others: micro heat pumps (mHP), micro air handling units (mAHU), building integrated solar thermal (BIST), building integrated photovoltaics (BIPV), centralized supply and exhaust ventilation, decentralized supply air ventilation etc. Furthermore, by adding extra functionalities to a typical facade renovation with extra insulation the cost-effectiveness might be increased. The retrofitting approach and process, when prefabricating multi-active façade elements, is illustrated in Figure 7.

The retrofitting approach is initiated by a geometric mapping of the building to be retrofitted. This enables the creation of a 3D-model which is used in the design process. The geometry is divided in to modular elements, in dimensions reasonable for transports. The second phase is the design process, where the actual planning and designing is carried out. For instance, solar irradiation analysis can be carried out in order to determine where solar technologies are suited to be integrated. Further, in this phase the actual designing of each wall element is performed, taking into consideration structural aspects as well as the integration of passive and active technologies (TES Energy Facade, 2016a). This phase culminates into drawings which are used in the next phase. The third phase consists of fabricating wall elements according to the drawings. Meanwhile, preparations on site are carried out regarding eventual demolishing of existing façades as well as preparing structural support for the elements. The last and final phase is assembly of the prefabricated wall elements on the site, inspecting them and initiating the active technologies (TES Energy Facade, 2016a). Multi-active façade systems have previously been applied in several demonstration projects in Europe, however, different concepts were applied. Some identified concepts are: SmartTES, GAP solution, and MeeFS.

SmartTES is a concept developed through an international research project, which is based on highly prefabricated timber wall elements containing building elements, such as windows, balconies as well as integrated active technologies (TES Energy Facade, 2016b). SmartTES has been applied in several pilot projects; one of them is “Risør Technical College” located in Risør, Norway. In this case, the prefabricated walls were timber frame walls with windows already mounted. The assembly process was performed by successfully removing the existing wall, following by mounting of the prefabricated walls. The whole assembly process was carried out within 24 hours i.e. only one day disturbance for the students/tenants (TES Energy Facade, 2016c).

GAP Solution is a concept based on a highly prefabricated wall made up of solar comb, illustrated in Figure 8, which is covered with a toughened glass panel. The benefit with the solar comb is that it allows solar irradiation to pass in and heat up the air within the solar comb. The result of this is an increased temperature in the exterior parts of the wall which in turn reduces the heat flux from indoors. The heat flux is reduced due to a reduced temperature difference, resulting in a lower effective heat loss, in comparison to the static heat losses. The GAP solution also allows installations of active technologies. Further, the GAP solution was used in a project in Austria where a 90 % reduction of the energy use for space heating of was achieved. (IEA ECBCS Annex 50, 2010).

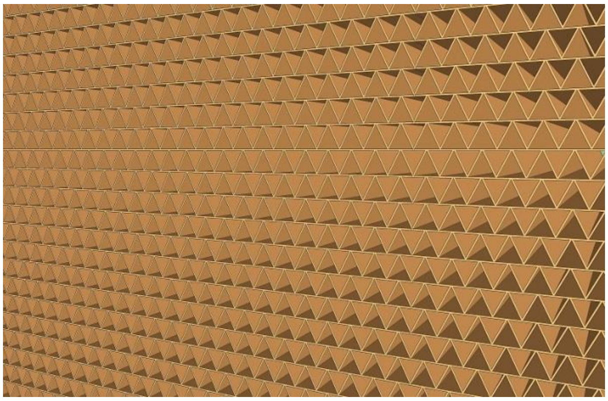

Figure 8: Illustration of solar comb (illustration inspired by Gap Solutions (2014)).

MeeFS is a concept based on highly prefabricated and standardized multifunctional panels consisting of structural panels and technological modules which are integrated within the structural panels, illustrated in Figure 9. The structural panels consist of composite materials and are anchored to the present wall. The technological modules can be either active or passive and are mounted on the structural panels. The active technological modules may consist of a glazing unit (window), solar protection unit (glazing and solar shading), solar thermal unit or green façade unit (MEEFS Retrofitting, 2016). However, the MeeFS concept is still in the development stage, it has not been demonstrated on a full scale building yet.

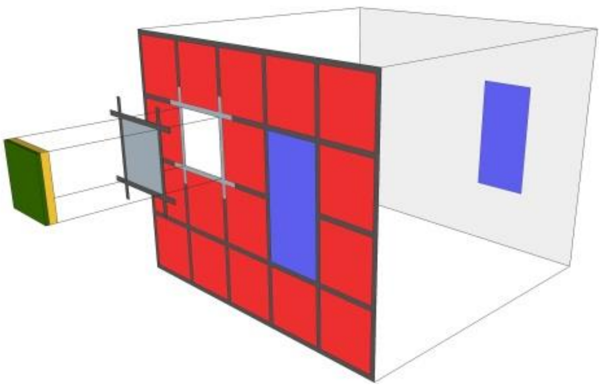

Figure 9: Illustration of the MEEFS concept where technological modules are assembled on a structural panel, which is anchored to the present wall, illustration inspired by MEEFS Retrofitting (2016).

An example of a cost effective retrofitting project, with prefabricated multi active façade elements, is a project carried out in Graz, Austria on a multi-residential building. A total yearly energy reduction from 140 kWh/m² to 14 kWh/m² for space heating was achieved. Furthermore, a short installation time and construction process allowed the tenants to stay during the retrofitting. The multi active façade element included heating- and DHW distribution pipes as well as, the previously mentioned, solar comb solution together with additional insulation (Blomsterberg, 2012).

1.6 Swedish application and research project

A multi active façade solution for retrofitting of buildings, has so far, not been used in Sweden. Further, a multi active façade element was planned to be used in a pilot retrofitting project in Malmoe, Sweden, of a building dating from 1970 consisting of 30 apartments. However, the retrofitting was never carried out due to high expected costs and the impossibility to raise the rents proportionally to the investment (Blomsterberg, 2012).

In order to investigate possible cost-effective multi active façade solutions, a research project has been initiated by Lund University together with NCC, a market leading contractor in Sweden, and several other firms. The research project aims to investigate whether the inclusion of added functionalities, beyond the traditional extra insulation, into a prefabricated façade module could improve the cost-efficiency in cases where a conventional façade renovation was required anyway due to aging. Furthermore, an investigation has to be carried out regarding the active elements in order to draw conclusions regarding the cost effectiveness and feasibility.

1.7 Goals & research questions

Objectives

- To investigate the energy saving potential of integrating active technologies for space heating, DWH, ventilation and solar energy into a prefabricated façade module for retrofitting of a Swedish multi-family house from the million program.

- By using relevant criteria, evaluate active technology solutions integrated into the facades of Swedish multi-family buildings in a Swedish context. Furthermore, to investigate centralised versus decentralised technical solutions when façade integrated in the Swedish building context.

- To investigate the economic feasibility from a life cycle perspective of a prefabricated multi-active façade solution against other renovation solutions. Initially, this was outside of the scope of this study, however, it was found necessary in order to base the conclusions on more than the energy saving potential. Therefore, the economic analysis is limited, not including a sensitivity analysis.

Questions to be answered

- Which active technologies (or combinations of technologies) have the highest potential regarding energy savings?
- Which active technologies (or combinations of technologies) have the highest potential regarding life cycle profitability?
- Where in the building envelope should the active technologies be integrated and how should they be designed?

1.8 Overall approach

The overall approach that was undertaken to conduct the study was divided into four primary parts, further described below;

- **Literature review**
A literature review was carried out in order to identify existing technologies and if they are adequate for integrating in multi-active facades. The aim with the literature review was to scope further investigations to only technologies considered relevant in the Swedish context.

- **Application of case study building**
To apply the further investigated active technologies, a case study building was used that represents a typical high-rise multi-family building raised during the million program. The same building was also used in the research project as a case study building. It was important that the building had documented energy use for space heating, DHW and property used electricity.

- **Computer simulations and life cycle costing calculations**
The active technologies considered important were thereafter simulated in various developed alternatives applied on the case study building. The result of the simulations gave an indication of the possible energy saving potential of implementing an active technology. This information, was a part of the input for the LCC calculations together with costs regarding initial investment, maintenance etc.

- **Analysis**
Finally, analyses were conducted based on the simulated energy saving potential and calculated life cycle costs to evaluate the economic feasibility of the investigated active technologies.

1.9 Limitations

This study focuses mainly on active technologies, therefore, a deep investigation regarding passive technologies was not carried out. Furthermore, assembly of prefabricated walls on top of an existing structure requires structural support as well as that they need to be moisture safe. Neither moisture safety nor structural solutions were investigated in this study. Fire safety is an important aspect when considering integration of technologies in walls, especially if the technology is of the type that may affect the present fire resistance between apartments. The study is limited to discussions of possible solutions, however, a detailed fire investigation is outside the scope of the study. Moreover, thermal comfort and daylight quality are aspects that can be influenced both positively and negatively by multi-active, prefabricated wall elements. However, they were not quantified for the various technologies due to the focus of the study being energy potential and economic feasibility. Moreover, a life cycle assessment was not included within this study.

2 Literature review

A literature review was carried out in order to identify which technologies exist and if they are adequate for integrating in multi-active facades. The aim with the literature review was to scope further investigations to only technologies considered important in the Swedish building context. The literature review was based on scientific papers, popular science articles, reports and books. It was initiated by identifying different types of active or semi-active technologies for integration in multi-active facades. A semi-active technology is defined, in this report, as a technology which relays on an additional technology to be able to fulfil its purpose such as ventilation radiators, which increase the thermal comfort but do not reduce the energy use.

A criteria specification for the technologies was developed in order to evaluate the feasibility of applying them individually or combined with other technologies in retrofitting projects of multi-family apartment buildings constructed during the million program. Moreover, the technologies were evaluated according to the developed criteria which resulted in raising advantages and disadvantages for every identified technology. Finally, the literature review was summarized with the purpose of phasing out technologies which showed important disadvantages when retrofitting the Swedish million program. The technologies that met the criteria best were further investigated within this report. The approach for the literature review is illustrated in Figure 10.

2.1 Criteria specifications

In order for a certain active or semi-active technology to be applicable in Sweden criteria were developed which were thought to be relevant based on the suitability in a Swedish context. Every technology was individually evaluated based on these criteria.

Energy saving potential

This criterion evaluates the energy saving potential of the active or semi-active technology. The consequence of the technology not possessing any energy saving potential is that economic feasibility might be difficult to achieve. The reason is that the retrofitting process entails high investments, which needs to be covered or at least partially covered by a reduction in the operation cost of the building.

Well-established and tested technology

This criterion describes if the active or semi-active technology is a well-established and tested technology in Sweden. The consequence of the technology not being well established and tested can be that it does not fulfil the Swedish building code and regulations, although it may correspond to building regulations in other countries.

High level of prefabrication

This criterion describes if the active or semi-active technology is possible to prefabricate in wall elements or not. Retrofitting of buildings might take a long period of time and can therefore imply a high cost if everything is carried out on the construction site. However, both time and cost can, in many cases, be reduced by prefabricating elements beforehand and assembling them on site, since construction time is reduced this will enable a reduction of labour costs (Buildings Designing, 2015). From a larger perspective this can result in that a greater number of multi-family buildings can be retrofitted in shorter period of time. The consequence of not having a high level of fabrication is that energy retrofitting projects might choose the common way of renovating the building, which in many cases has proven to not be cost effective (Byman & Jernelius, 2012).

Interference in apartments

This criterion state if the active or semi-active technology will result in a high or low amount of work inside the apartments. In general work within the apartment is considered as a disadvantage and inconvenient for the tenants. However, some work is inevitable. The limit of when the work becomes too extensive and forces an evacuation is difficult to identify and is a subjective parameter. Further, this criterion also describes if extensive work has to be carried out in every apartment, for example installation of internal exhaust air, or both supply & exhaust air ductwork. If the amount of work is limited, it will result in a reduction of the risk of tenant interference. The retrofitting process of multifamily apartment buildings is usually very extensive. Refurbishments generally include new installations as well as standard increasing measures like new flooring, painting and refurbishments of the kitchen and bathroom. This results in extensive work within the apartments and forces the tenants to be evacuated during the whole retrofitting process. Furthermore, standard rising measures entail rent increases (Lind, 2015). The consequence of a tenant evacuation, for the property owner, is that all rental income will be absent during the whole retrofitting process. Further, other costs for moving the tenants to temporary apartments will be introduced. Therefore, it is very beneficial if the retrofitting can be carried out in a way that no evacuation of tenants is required or with an insignificant amount of interference in the apartments. Furthermore, retrofitting measures can be scoped to energy saving measures which do not require any standard rising.

Easy access for maintenance or repairs

This criterion constitutes if the active or semi-active technology enables an easy access to the technical equipment that is required for the building to operate properly. Easy access is most likely a very important factor for property owners, since it enables eventual breakdowns to be easily repaired. Examples of these types of equipment are AHUs and heat pumps (HP). Normally, these types of equipment are centralized in buildings dating from the million program, as earlier mentioned. If technical equipment is placed inside an apartment it requires the permission from the tenant to access the apartment each time an inspection takes place. However, if an urgent repair must take place the property owner can access the apartment without the permission from the tenant according to the Swedish rental law (Hyreslagen, 2016). Moreover, if technical equipment is integrated in a prefabricated wall element it complicates eventual inspections, maintenance or repairs since the equipment can be located several stories above the exterior ground level. The consequences are most likely very high maintenance and repair costs.

Use present hydronic and/or ventilation system

Most buildings dating from the million program are connected to the district heating network as mentioned earlier with the heat distributed by a hydronic system to the radiators. This criterion describes if the active of semi-active technology enables the present hydronic and/or ventilation system to be kept. If a present installation is available, it is most likely beneficial to reuse it. Moreover, emphasis should lay in reusing as much as possible of the present installations, in order to avoid space issues with new installations. An example is to reuse the present exhaust air ductwork, if exhaust air ventilation has been applied earlier, which commonly is placed in kitchens and bathrooms (Warfvinge & Dahlblom, 2010). The consequence of not keeping the present hydronic and/or ventilation system is that extensive work has to be carried out in each apartment and which would increase the costs of the retrofitting.

Daylighting conditions affected by technology

The daylight conditions are of very high importance in dwellings since it reduces the amount of required artificial light. Installing a prefabricated façade on the exterior part of the present external wall implies in a thicker wall, which in turn equals in a lower amount of daylight transmitted into the living areas (Fontoynont, 1999). Active of semi-active technologies that require the windows to be reduced in size are highly recommended to avoid if possible. The consequence of reducing the glazing surface is reduced amount of transmitted light in to the dwelling. This decreases the visual quality in the apartments and increases the artificial lighting need as well as the fact that the window to floor area quote in the Swedish building code might not be fulfilled (Boverket, 2015d).

Moisture risk by eventual water leakage from technology

This criterion is of very high importance, since an eventual moisture risk located within a prefabricated façade element will be very difficult to detect before the damage is substantial. Therefore, active or semi-active technologies which imply obvious moisture risks are highly recommended to be avoided.

Sustainable energy source

This criterion describes if the technology utilizes a sustainable energy source. In this case solar energy is investigated. Using the sun as an energy source is highly recommended since the energy is sustainable. The consequence of neglecting the usage of solar energy is an increase of the usage of other energy sources which probably not are as environmental friendly as solar energy.

Thermal comfort

This criterion describes if the technology can affect the thermal comfort in the apartments. For instance, the backside of a solar collector can reach temperatures up to 200 °C on stagnation temperature during summers (Frank, et al., 2015) which can affect the thermal comfort negatively during the summer months.

2.2 Evaluation

The following subchapter briefly describes the identified technologies followed by a discussion regarding advantages and disadvantages. The identified technologies were mainly obtained from scientific papers and reports. Finally, a summary of the evaluation according to the developed criteria is presented.

Ventilation radiators

Ventilation radiators is a semi-active technology; it enables warming up of the outdoor air, which enters behind the radiators (Gustafsson, et al., 2013), illustrated in Figure 11. Further, this increases the level of thermal comfort and provides a value added to the tenants. It works as a complement to an active technology which means that it does not operate alone. Moreover, this technology does not reduce the buildings energy use, thus probably lack any direct economic feasibility. The conclusion is that since it only provides value added to the tenants and no economic feasibility can be quantified, it is dismissed from further studies.

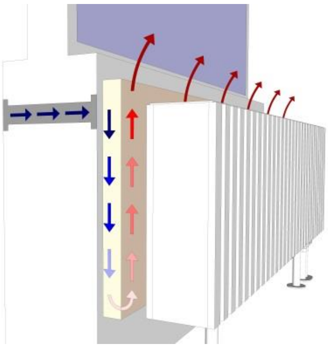

Figure 11: Illustration of ventilation radiators and how they operate.

Hydronic supply and return piping in the prefabricated wall

This active technology is based on integrating the supply- and return hydronic piping in the prefabricated wall element where heat can be distributed to heat exchangers, for example radiators (Schalk, et al., 2015). It can be advantageous if the building does not possess any hydronic system at all. However, as described in chapter one, buildings from the million program are generally connected to the district heating network and have hydronic systems installed. The disadvantages of replacing a fully functional internal hydronic system with one integrated in a façade element are, besides an unnecessary cost, that an obvious moisture risk is introduced. This moisture risk is of the kind that if a leak occurs, it becomes very difficult to notice or address it. Therefore, this technology is considered irrelevant for further studies.

Supply air diffuser integrated in windows

This technology is based on integrating supply air diffusers in the windows (Schalk, et al., 2015), illustrated in Figure 12. It is a semi-active technology, i.e. it can operate alone or as a complement to an active technology. For instance, cold outdoor air can be directly supplied to the room through the window diffuser if operating alone. Moreover, if operating as a complement to an active technology, the supply air can be delivered from an AHU, through ductwork in the prefabricated wall elements to the apartments through the window diffuser. It is well suited for buildings without any type of supply air valves or ducts. Supply air inlets in windows have been applied both in buildings with mechanical exhaust air ventilation and with natural ventilation. However, those system have not been tested with supply-and exhaust air ventilation enabling preheated air entering the living spaces.

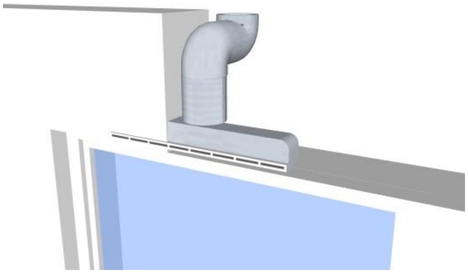

Figure 12: Supply air diffuser integrated in window module illustration, illustration inspired by Schalk, et al., (2015).

The strongest advantages of this semi-active technology are that windows can be mounted in the factory which means a limited disturbance for the tenants, except for when the old ones are dismantled. Further, no core drilling is required since the diffusers are integrated in the window module. However, the strongest disadvantage is that the glazing area within the window module is reduced due to the diffuser requiring space, which is a quality reducing measure in terms of daylight availability. Moreover, if windows have been changed recently, a second replacement is most likely not justifiable from an economic point of view. Furthermore, if operating alone the level of thermal comfort will remain poor since cold outdoor air will be supplied directly to the room. Disadvantages mentioned above are considered so strong that the technology was not further investigated.

Micro air handling unit with heat recovery unit adjacent to the window

The principle behind this active technology is to install a mAHU equipped with heat recovery in living rooms and bed rooms, next to the window or in the shutter box of the window (Schalk, et al., 2015), illustrated in Figure 13.

Figure 13: Micro-AHU with heat recovery integrated in the shutter box of the window, illustration inspired by Schalk, et al., (2015)

One significant advantage is that it enables the supply air to enter the rooms at a higher temperature in comparison to unheated outdoor air. Thus, the level of thermal comfort would probably be increased during the heating season. Another significant advantage is that this active technology is energy reducing in terms of lowering the heating demand for ventilation.

A disadvantage might be the limited space, which results in that no auxiliary heater is present in the mAHU in order to ensure a steady supply air temperature during the heating season. Furthermore, the AHU is powered by two small fans which might create noise disturbance for the tenants, which can be considered as a problem, especially in bedrooms. Moreover, as an additional disadvantage, installing the mAHU in the shutter box of the window requires either a smaller window or an enlargement of the shutter box. A smaller window would result in reduced daylight availability. An enlargement of the shutter box could cause problems from a structural point of view since the upper part of the shutter box usually contains reinforcement and would imply significant extra costs. Due to the above mentioned disadvantages the technology was not considered for further studies.

Centralized supply- and exhaust air ventilation with heat recovery

This active technology is based on upgrading the present exhaust air ventilation with supply air ducts and centralized heat recovery (Ott, et al., 2014), illustrated Figure 14. The new supply air ducts are located in the prefabricated façade elements, one duct for each apartment, with inlets to all bed rooms and living rooms. Further, this technology is reusing the present exhaust air ducts. Furthermore, a requirement for this technology is that a centralized AHU is installed, preferably in the attic where the existing exhaust air fan is located.

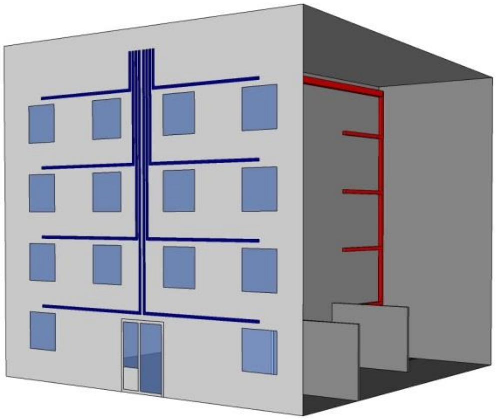

Figure 14: Illustration of a centralized supply and exhaust ventilation. Supply air ducts (blue) and present exhaust air ducts (red).

The strongest advantage is that heat recovery is enabled, i.e. a significant energy saving potential. Another significant advantage is that no internal ducting is required since existing return air ducts are reused. This means that the disturbance of the tenants is minimized to core drilling in the exterior walls for the supply air diffusers. Also, since the supply air is preheated, the indoor thermal comfort is significantly improved.

The disadvantages with this active technology are that the supply air temperature will gradually decrease since the ducts are routed through the outermost part of the wall. Furthermore, routing ducts through the external wall may increase heat losses due to thermal bridges (Ott, et al., 2014). This is an example where this active technology can be combined with the semi-active technology, ventilation radiators. In this case, air will be re-heated before entering the living spaces.

Moreover, small duct diameters are required in order for the ductwork to fit within the façade elements as well as the quantity of ducts being unknown. This will most probably result in higher specific fan power (SFP) in comparison to energy efficient ventilation systems where emphasis is to minimize the pressure drop per volume unit of air and length of duct (Santamouris & Wouters, 2006). An additional disadvantage can be lack of space for the AHU since, as earlier mentioned, the typical roof construction is flat and lacks space for large installations. However, the possibility exists of placing the AHU on top of the existing roof. The conclusion of this active technology is that it is considered relevant for further studies.

Centralized ventilation, with supply- and exhaust air ducts routed through prefabricated façade elements

This active technology is based on replacing the present exhaust air ventilation with a centralized supply and exhaust ventilation where both supply and exhaust ducts are located in the prefabricated façade elements (Ott, et al., 2014), illustrated in Figure 15. This requires new exhaust air ducting from kitchen and bathroom to connections in the prefabricated façade elements.

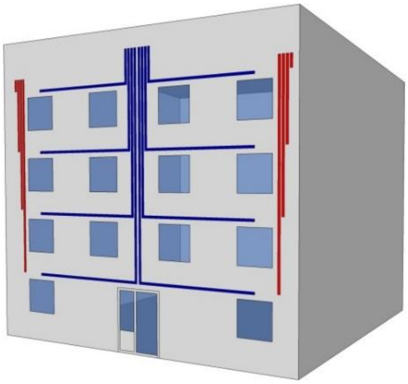

Figure 15: Illustration of a centralized supply and exhaust ventilation system with routed ducts through the prefabricated façade elements. Supply air ducts (blue) and exhaust air ducts (red).

One of the advantages of this active technology is its energy saving potential, like the previously described technology. The strongest disadvantages are that a present fully functional exhaust air ductwork is not reused as well as heat losses will occur from both supply and exhaust ducts. Further, extensive work might be required within the apartment in order to install new exhaust air ductwork. Also, most probably, there is lack of space in the façade for both exhaust and supply ductwork. Hence, this technology was not investigated further.

Decentralized air handing/micro heat pump with supply- and exhaust air ducts

This active technology is based on replacing the present exhaust air ventilation with a decentralized supply and exhaust air ventilation, where the micro AHU/HP can be placed inside the apartment, alternatively integrated in the prefabricated wall element (Dermentzis, et al., 2014). This requires new exhaust air ducting from kitchen and bathroom to connections in the prefabricated façade elements. The distribution of supply air to bed- and living rooms will be routed through the prefabricated wall elements. Micro AHU and micro HP are illustrated in Figure 16.

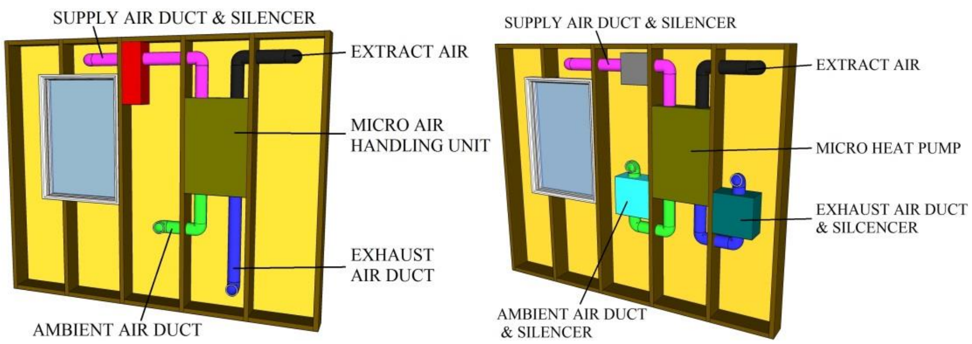

Figure 16: Wall integrated micro AHU (left), and wall integrated micro HP (right) illustration inspired by Dermentzis, et al., (2014).

The advantage with this technology is that heat recovery is enabled from the exhaust air.

The disadvantages are, except for not reusing a fully functional exhaust air ductwork, that placement of the AHU/HP is required within the apartment or wall element. Further, required space for the AHU/HP might not be available although the smallest AHU/HP is considered. The supply air ducts need to be routed through the prefabricated wall elements, to each room. This will most probably result in major work in the apartment since new exhaust air ductwork is required from kitchen, bathroom and toilet to the micro AHU/HP. Another aspect is that maintenance issues will arise due to the required permission to access each apartment, since the landlord is only allowed access without permission in emergency cases (Hyreslagen, 2016). Furthermore, a decentralized system will probably require a higher quantity of maintenance since there are multiple AHU/HPs instead of one or a few centralized. In addition to this, several small units will most likely have a lower efficiency in comparison to a large, centralized unit. The technical lifetime of smaller units is most likely lower. Decentralized units are located within the living spaces or directly adjacent; therefore, noise issues might occur since space for silencers might not exist. Besides this, this solution is not generally applicable, if the ambition is to limit the amount of work inside the apartments and avoid internal ductwork. It suits gable apartments better than apartments in the centre of the building, as illustrated in Figure 17 and Figure 18.

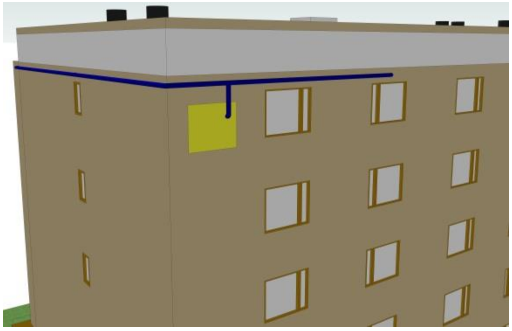

Figure 17: Illustration of possible supply air ducting (blue) in a gable apartment. Yellow represents a possible placement of the AHU/HP.

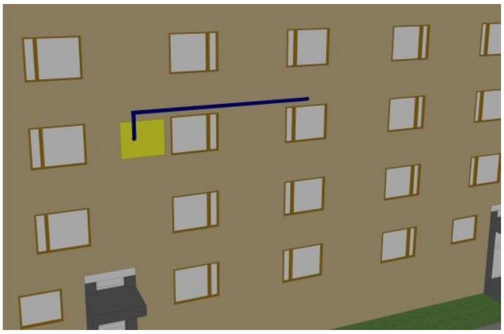

Figure 18: Illustration of possible supply air ducting (blue) in an apartment located in the centre of the building. Yellow represents a possible placement of the AHU/HP.

It can be observed that the ductwork can be routed to all bedrooms in the gable apartment (Figure 17). However, this is not applicable in the apartment in the centre of the building (Figure 18). Another disadvantage is the technical life time of small decentralized AHU/HP, which is most probably shorter compared to the technical lifetime of a prefabricated wall element. Lastly, noise issues from the AHU/HP might cause disturbance among the tenants. The conclusion is that the disadvantages are considered so strong that this technology was not further investigated.

Regenerative micro air handling unit

This active technology is based on replacing the present exhaust air ventilation with small regenerative mAHU, distributed in rooms in contact with the facade. It is installed by core drilling a hole in the façade and sealing around it. Regenerative heat exchangers work by switching flows in cycles. Firstly, air is exhausted through the heat exchanger which adsorbs heat. Secondly, after a certain amount of time the fan in the mAHU switches direction so that the outdoor air adsorbs the heat from the heat exchanger, before entering the room. One example is the Lunos e^2 which is illustrated in Figure 19 (Schalk, et al., 2015).

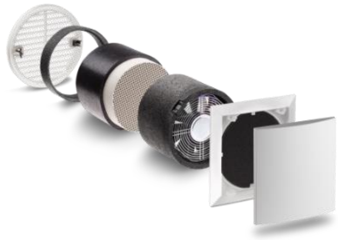

Figure 19: Lunos e², example of a regenerative micro air handling unit (Lunos, 2016).

The advantage is that the active technology has a high energy saving potential as well as not requiring extensive work for installation. Another advantage is that it does not require external ducting. A disadvantage is that it might create noise issues since it is located in each room. Furthermore, the mAHU is not equipped with an auxiliary heater which means that the supply air temperature is not guaranteed to reach desired temperature.

Furthermore, another disadvantage with this technology is the problem with heat recovery from the exhaust air from bathrooms and kitchens.
As previously mentioned maintenance issues will arise, since this technology is decentralized, due to the required permission to access each apartment as well as the high quantity of regenerative mAHU that most probably require more maintenance compared to a centralized system.

No information regarding previous utilization in Sweden of these active technologies in a large context such as multi-residential buildings has been found. Therefore, this active technology is currently considered less important for further studies since the criterion well established and tested is not fulfilled.

Building integrated solar thermal

This active technology consists of integrating solar thermal modules in the prefabricated wall elements, replacing façade materials. The strongest advantage is that Building Integrated Solar Thermal (BIST) BIST is a sustainable source of hot water that can be utilized for heating of DHW or as a complement for space heating. Furthermore, it can be made highly prefabricated. Besides this the cost of installing it is reduced compared to stand alone solar thermal installation since it decreases the required façade material. An aspect to take into consideration is that solar thermal modules become very warm during operation, where the stagnation temperature can reach up to 200 °C (Elimar , et al., 2015). Hence, the thermal comfort inside the apartment will most probably be affected negatively, due to the highest output during the summers, illustrated in Figure 20. Further, if any kind of profitability should be taken into consideration district heating prices, which is the replaced energy, must also be taken into account. The energy output from a flat plate collector as well as the variation in the district heating price is presented in Figure 20. The district heating prices were obtained for the year 2015 from Öresundskraft (Öresundskraft, 2015).

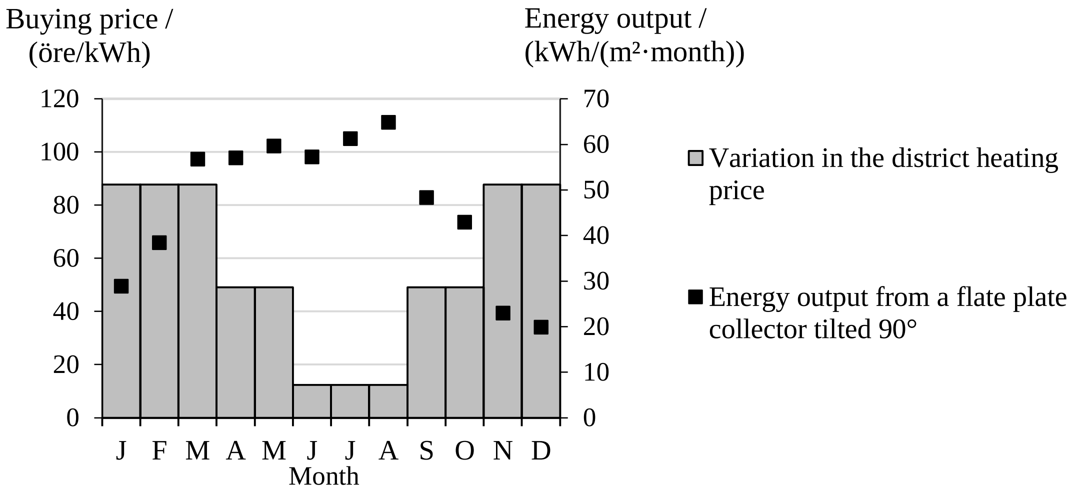

Figure 20: Variation in the district heating prices and the monthly energy output per square meter of solar thermal modules vertically orientated towards south.

It can be observed that the highest energy output from the solar collector is obtained during the summer. However, this is when the district heating price is the lowest. Furthermore, when the district heating price is the highest, the energy output is lowest. Another disadvantage is that an obvious moisture risk exists if the collector is integrated in the wall elements since an eventual leakage cannot be easily noticed nor repaired.

Due to the above mentioned, it is difficult to achieve any profitability in this case. Therefore, this active technology is not considered for further studies.

Building integrated photovoltaics

This active technology consists of integrating PV modules in the prefabricated wall elements, illustrated in Figure 21. The PV modules generate electricity, replacing the otherwise bought electricity with sustainable solar electricity. This electricity can be used to power commonly used electrical equipment in the building like AHU, elevators and lights.

Figure 21: Example of possible building integrated photovoltaics (Acc-glasrådgivare, 2016).

The strongest advantage is that the generated electricity originates from a sustainable source. Furthermore, the cost of installing BIPV is reduced compared to standalone PV installations since it decreases the required façade material. Moreover, the price for modules is steadily decreasing in Sweden (Lindahl, 2014), which is considered as an advantage. However, the disadvantages are that PV modules are sensitive to shading which can result in reduced electricity output if inadequately placed. Further, PV is not limitlessly profitable, the key is to generate electricity and self-consume it. This requires a properly sized installation. The conclusion of this active technology is that it is considered relevant, however, a case study must be carried out for each and every building in order to determine the quantity PV modules and the feasibility.

Building integrated photovoltaic/thermal solar collector

Building integrated photovoltaic/thermal solar collector (BIPTV) is a combination of two active technologies; BIST and BIPV where they are integrated in one single module. The BIPVT modules generate electricity and hot water (Anderson, et al., 2009). An illustration of a PV/T that can be integrated in the building envelope is presented in Figure 22.

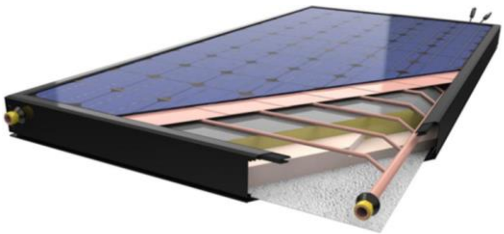

Figure 22: Illustration of a Hybrid PV/T (Newform Energy, 2014).

The strongest advantage is that the BIPVT modules generate both electricity and hot water from a sustainable energy source.

Even in this case, the disadvantage is, like for BIST, that a moisture risk will be present, further, the profitability is most likely low. Another disadvantage is, like for the BIPV, is the sensitivity of shading. Moreover, the investment cost is higher in in comparison to BIST and BIPV by themselves (Schalk, et al., 2015). Due to the present district heating prices which are very low during the summers this technology probably do not show any profitability since the heat output from the solar thermal part is the highest during summers. Therefore, this active technology is considered not suited for further studies.

2.3 Summary of the technology evaluation

Each identified technology was evaluated based on the criteria specification described previously. The evaluation of the identified technologies is summarized and presented in Table 7. The evaluation is subjective and the goal was to point out towards which technologies should be further investigated based on a technology screening. The evaluation is based on a qualitative grading in three scores, positive (1 credit), negative (-1 credit) or not affected (0 neutral credit). The purpose was to identify technologies that show significant disadvantages that disqualify them from further investigation and to point out those with the most relevant advantages. Further studies are carried out for technologies which have the highest positive, summarized scores. However, some technologies with positive summarized score are not further investigated, a short explanation to why is presented below.

The semi-active technology “ventilation radiators” has a positive summarized score; however, it does not have any energy saving potential. Therefore, it is considered as less important for further studies.

The active technology “building integrated solar thermal” also has a positive summarized score, however, it entails a moisture risk. Moreover, profitability is most likely low. Therefore, it is considered as less important for further studies.

Finally, the active technology “centralized ventilation, with supply and exhaust ducts routed through prefabricated façade elements” also possessed a positive score although it was considered as less important for further studies. The reason is that extensive work within the apartments is most likely required. Furthermore, the fact that the heat losses are probably doubled compared to only having supply air ducts routed through the prefabricated façade elements makes even this technology less important for further studies.

The result of this literature review, illustrated in Table 7 is that further research will be conducted for the technologies;

- “Centralized supply- and exhaust air ventilation with heat recovery” where supply air ducts are routed through the prefabricated wall elements and exhaust air ducts kept.
- “Building integrated photovoltaics” where PV is a part of the building envelope.

Table 7: Summary of the qualitative evaluation in a Swedish context where technologies relevant for further studies are illustrated in blue.

Score colour	Score	Score description
	1	Positive
	0	Not affected
	-1	Negative

Criterion	Ventilation radiators	Hydronic supply and return piping in the prefabricated wall	Supply air diffuser integrated in windows	Micro air handling unit with heat recovery unit adjacent to the window	Centralized supply- and exhaust ventilation with heat recovery	Centralized ventilation, with supply and exhaust ducts routed through prefabricated façade	Decentralized air handing/micro heat pump with supply- and exhaust air ducts	Regenerative micro air handling unit	Building integrated solar thermal	Building integrated photovoltaics	Building integrated photovoltaic/thermal solar collector
Energy saving potential	0	0	0	1	1	1	1	1	1	1	1
Well-established and tested technology	1	-1	1	-1	-1	-1	-1	-1	1	1	-1
High level of prefabrication	1	1	1	1	1	1	1	1	1	1	1
Interference in apartments	-1	-1	-1	-1	1	-1	-1	1	1	1	1
Easy access for maintenance or repairs	-1	-1	0	-1	1	1	-1	-1	-1	-1	-1
Use present hydronic and/or ventilation system	1	-1	0	-1	1	-1	-1	-1	0	0	0
Daylighting conditions affected by technology	0	0	-1	-1	0	0	0	0	0	0	0
Moisture risk by eventual water leakage from technology	0	-1	0	0	0	0	0	0	-1	0	-1
Sustainable energy source	0	0	0	0	0	0	0	0	1	1	1
Thermal comfort	1	0	-1	1	1	1	1	1	-1	0	-1
Accumulated score	2	-4	-1	-2	**5**	1	-1	1	2	**4**	0

3 Case study

3.1 High-rise lamella building

The case study building, used in the research project and in this study, is a high-rise lamella building with nine storeys above ground and a basement, situated in a city located on the south western coast of Sweden, which is a part of climate zone four (Boverket, 2015c). It was raised in 1963 and consists of 105 apartments distributed over eight storeys and a couple of facilities at the ground level as well as a storage space in the attic including a technical room with fans etc. The case study building as well as associated data regarding the building was provided by NCC. Because of confidentiality the case study building will not be specifically named with property name nor address within this report. It should be mentioned that more buildings were available in the research project. However, it was considered a more challenging task to implement the chosen technologies to a high-rise lamella compared to a low-rise lamella.

3.1.1 Technical description

The properties of the building envelope are presented in Table 8**.**

Table 8: Building envelope properties for the case study building.

Part of building envelope	Description and build-up
Roof	Concrete 150 mm, 95 mm insulation, asphalt membrane
Exterior walls	Sandwich element: Concrete 120 mm, 100 mm insulation, light weight concrete 60 mm
Basement walls	120 mm concrete
Foundation	200 mm concrete
Windows	Double pane windows
Doors	-

The building is ventilated by mechanical exhaust air ventilation (exhaust air ducts located in kitchen and bathroom) without any type of heat exchanger with an assumed air flow of 0.35 $l/(s \cdot m^2)$ (demanded by the building code) corresponding to a total exhaust air flow of approximately 3.2 m^3/s. Further, the SFP for the exhaust air ventilation system was assumed to 1.5 $kW/(m^3/s)$. The average airtightness is measured to 1.2 $l/(s \cdot m^2)$ enclosing envelope area at 50 Pa pressure difference. Furthermore, average indoor dry bulb temperature is measured to 21.5 ºC. The building is connected to the district heating network and distributes the heat by a two-pipe hydronic radiator system. Moreover, the heated floor area (A_{temp}) is 9235 m^2. The building has a window to wall ratio of 32.7 % and a form factor of 79 %, which is the relation between the envelope area and heated floor area.

3.1.2 Energy performance of the case study building

The measured annual average specific energy performance of the case study building is presented in Table 9.

Table 9: Average normalized annual specific energy use for the case study building.

Category	Energy use / kWh/(m²·yr)
Space heating & DHW	132.3
Property used electricity	8.7
Total	141

No separate meter is installed to measure the energy used to heat the DHW, therefore, energy used for space heating and DHW is combined in Table 9. Further, approximately 9 800 m^3 cold water is used yearly, which was used to estimate the energy for DHW. Property used electricity includes energy powering fans in the ventilation system, pumps, lighting in the stairwell and other energy used for the property.

3.2 IDA ICE model corresponding to the case study building

A calibrated base case (BC) model in IDA Indoor Climate and Energy (IDA ICE) (Equa, 2016) was provided by NCC which represents the case study building in the research project as well as in this study. IDA ICE is a dynamic software which is used to study the energy use in buildings as well as thermal comfort (Equa, 2016). Input data for the BC model in IDA ICE is presented in Table 10. The geometry of the building was created according to original drawings. Furthermore, the model served as an indicator only for the space heating need and the average heat transfer coefficient (U_m) of the building envelope. Weather data for Gothenburg, which is the closest city to the case study building, was used in the energy simulations in IDA ICE.

Table 10: Base case model input in IDA ICE.

Description	Data	Method
Heated floor area / m^2	9235	Measured
Enclosing envelope area / m^2	7311	Measured
Indoor temp / ºC	21.5	Measured
Airtightness / $l/(s \cdot m^2)$, enclosing envelope area at 50 Pa pressure difference	1.2	Measured
Ventilation system	Mechanical exhaust air ventilation, without heat recovery	-
Exhaust air flow/ $l/(s \cdot m^2)$	0.35	Estimated
Thermal bridges / %, of total transmission losses	15	Estimated
Construction part	**Heat transfer coefficient (U-value) / $W/(m^2 \cdot K)$**	
Roof	0.48	Approximated
Exterior walls	0.47	Approximated
Basement walls	0.9	Approximated
Foundation	0.31	Approximated
Windows & Doors	2.4	Approximated

Occupancy schedules and internal heat gains from appliances and tenants were set according to *"Standardize and verify the energy performance of buildings"* (SVEBY) (Sveby, 2012). An additional 4 $kWh/(m^2 \cdot yr)$ was added to the space heating need to account for airing

(Sveby, 2012). Regarding the DHW, an assumption was made that 40 % of the bought cold water was heated. This corresponds to a DHW need of approximately 20 kWh/(m^2·yr) which was considered low but reasonable since most of the tenants are elderly. Regularly 25 kWh/(m^2·yr) is assumed for DHW in multi-residential buildings (Sveby, 2012). Moreover, losses from the hot water circulation in the building were assumed to be included in the space heating need.

Property used electricity, which was measured to 8.7 kWh/(m^2·yr), was divided according to assumptions and estimations as follows;

- 4.84 kWh/(m^2·yr) for ventilation fans, corresponding to the SFP of 1.5 kW/(m^3/s) for the system and a constant airflow of 3.2 m^3/s.

- An assumption was made by NCC that hydronic pumps use approximately 2.3 kWh/(m^2·yr). However, to estimate the energy use for each hour, an assumption was made that 2 % of the energy used for space heating (when required) is used for hydronic pumps, this corresponds to 2.68 kWh/(m^2·yr). The estimation was considered reasonable due to the small difference between the estimated energy use and assumed energy use by NCC.

- 1.18 kWh/(m^2·yr) for lighting in the staircase and other equipment.

Further, such division was necessary in order to enable the possibility to estimate the potential for energy reducing measures for the property used electricity. A comparison between the BC model and the average measured energy use annually is presented in Table 11. Note that the property used electricity for the BC model is the same as for the measured to enable a complete comparison. Further, the IDA ICE model was not used to calculate the property used electricity. A monthly based comparison of the space heating- and DHW need between the BC model and measured specific energy use is presented in Figure 23.

Table 11: Comparison of the yearly average measured specific energy use and the specific energy use for the BC model.

Category	**Energy use / kWh/(m^2·yr)**	
	Measured	BC model
Space heating & DHW	132.3	133.1
Space heating	-	109.1
Additional space heating need caused by airing	-	4
DHW	-	20
Property used electricity	8.7	8.7
Total	141	141.8

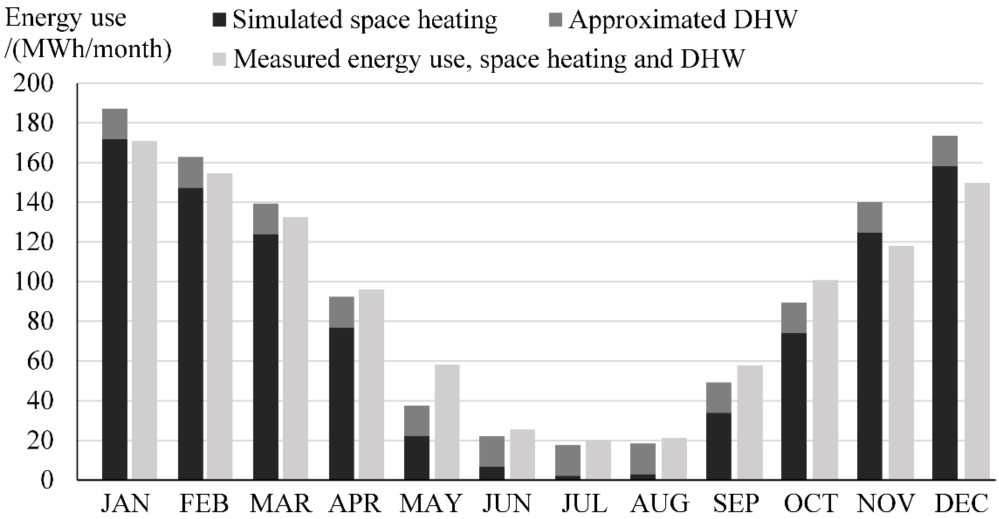

Figure 23: Comparison of monthly energy use for the base case model and actual measures.

It can be observed that the BC model does not match the measurements completely, however, it does follow the same pattern. In Table 12 the distribution of heat losses of the building envelope is presented for the BC model. Furthermore, the U_m was calculated to 1.18 W/(m^2·K). A further calibration of the BC model was not carried out within this study.

Table 12: Transmission losses through the building envelope for the BC model.

Building envelope	**Area (A) / m^2**	**U / (W/(m^2·K)**	**UA / (W/K)**	**Part of total losses / %**
Walls above ground	2920.7	0.47	1367.5	15.9
Walls below ground	415.0	0.90	374.8	4.4
Roof	1276.0	0.48	1753.2	20.4
Floor towards ground	1272.3	0.31	387.4	4.5
Floor towards crawl space	10.9	3.48	37.7	0.4
Windows	1404.0	2.40	3369.6	39.2
Doors	12.6	2.38	30.0	0.4
Thermal bridges	-	-	1285.9	14.9
Total	**7311.5**	**1.18**	**8606.1**	**100**

It can be observed that the most influencing construction part on the heat losses is the windows. They represent approximately 40 % of the total transmission losses. Furthermore, the exterior walls only stand for approximately 16 % of the transmission losses even though they represent the largest share of the building envelope. However, probably a significant part of the thermal bridges is located in the façade due to the large amount of windows and other connections.

4 Methodology

4.1 Overview

In order to investigate the energy saving potential and estimate the economic feasibility for the active technologies, several parameters were needed to be taken into consideration. Due to the active technologies being dependent on several variables, a plan for the approach for simulations and calculations was created and is illustrated in Figure 24. Furthermore, several alternatives were developed in order to compare the economic feasibility of retrofitting the building in different extents.

Moreover, it was considered within this study that by implementing a multi-active façade the maximum average heat transfer coefficient (U_m) would be 0.4 W/($m^2 \cdot K$) for the building envelope. This was set to comply with the Swedish building code regulations for new buildings.

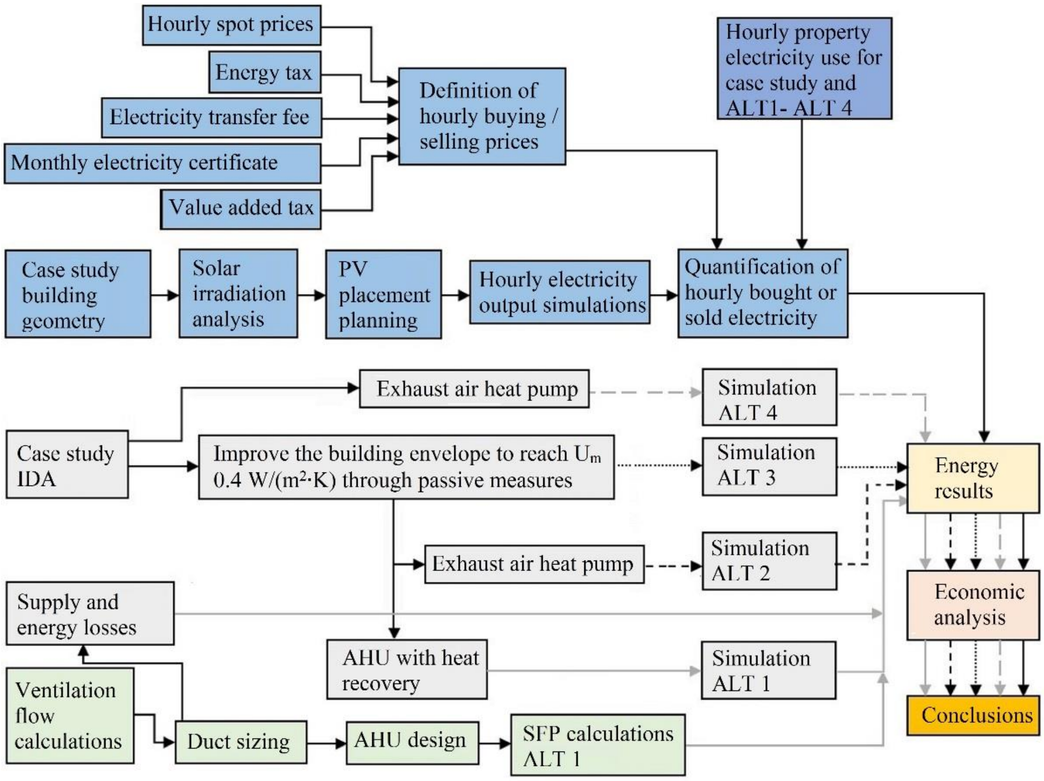

Figure 24: Plan for the approach for simulations and calculations.

All developed simulation alternatives presuppose the exhaust air ventilation is in good condition and airtight and therefore can be completely reused. This study is based on four alternatives;

- Alternative one consists of implementing a multi-active façade solution. It includes an improvement of the building envelope to reach an U_m of 0.4 W/($m^2 \cdot K$) and integrates the supply air ductwork in the new wall element. Moreover, this alternative also includes the installation of an AHU. The AHU is equipped with heat recovery by an air-to-air heat exchanger where heat in the extract air is partially transferred to the supply air. A simplified illustration of an AHU with HR is presented in Figure 25.

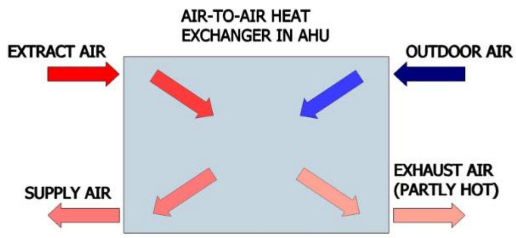

Figure 25: Illustration of an air handling unit with heat recovery.

- Alternative two corresponds to improving the building envelope to reach an U_m of 0.4 W/(m^2·K), as the first alternative. However, this alternative does not include any ductwork in the façade. Instead, exhaust air heat pump (EAHP) is installed to the present hydronic installation in the building as illustrated in Figure 26, covering only the space heating demand and not the DHW need.

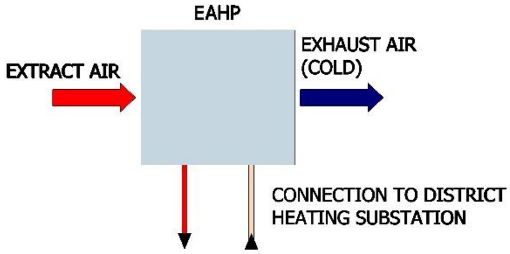

Figure 26: Illustration of an EAHP with extract air as heat source, connected to the hydronic system.

- Alternative three consists of improving the building envelope in order to reach an U_m of 0.4 W/(m^2·K). This alternative does not include any type of active measures such as heat pumps, PV, supply air ducts integrated in the exterior wall elements etc. This alternative is therefore used for comparison purposes with other alternatives.

- The fourth alternative consists of installing an EAHP to the present hydronic installation in the building. This alternative does not include any other retrofitting measures and is also used comparison purposes with other alternatives.

The methodology chapter has been divided into four sections;

Passive measures

This section describes the methodology used to determine required properties of the building envelope to reach an U_m of 0.4 W/(m^2·K). Moreover, the work process of determining the properties of the multi-active façade is described in this section in terms of insulation thickness, conductivity etc.

Active measures

This section describes the methodology used to investigate and apply the chosen active technologies for the multi-active façade. Moreover, it should be mentioned that since the evaluation of the PV is highly dependent on the economic aspect, it was separated from the main economic analysis chapter.

Specific energy use

In this subchapter the methodology used to simulate the space heating need and estimate the specific energy use for alternatives one to four is described. Additionally, the method of implementing an EAHP is presented in this section.

Economic analysis

The economic analysis section describes the methodology used to compare the economic feasibility between the developed alternatives from a life cycle perspective. This part does not include the economic analysis for PV which was included under the active measures.

4.2 Passive measures

4.2.1 Average heat transfer coefficient

A summary of the work process to calculate, and determine necessary measures to meet an U_m of maximum 0.4 W/(m^2·K) is presented in Table 13. Furthermore, the calculations were also carried out to determine the maximum transmission losses for the multi-active façade. A more detailed description follows in the subchapters.

Table 13: Work process of calculating the average heat transfer coefficient and requirements on the external wall.

Stage	Description
1	Calculation of the maximum transmission losses of the enclosing envelope area with the requirement to not exceed U_m of 0.4 W/(m^2·K).
2	Determination of heat transfer coefficients (U-value) for parts of the building envelope that are considered realistic and reasonable to retrofit beyond the external walls. This enables establishing requirements on the external walls (façade element) regarding the thermal performance.
3	Investigate required heat transfer coefficients for various conductivities for the external walls above ground to estimate the additional insulation thickness and the required thermal resistance properties of the insulation to not exceed an U_m of 0.4 W/(m^2·K).

4.2.2 Transmission losses

The average heat transfer coefficient was calculated by applying Eq. 1 (Boverket, 2015c).

$$U_m = \frac{Q_t}{A_e} = \frac{\left(\sum_{i=1}^{n} U_i \cdot A_i + \sum_{k=1}^{m} l_k \cdot \psi_k + \sum_{j=1}^{p} \chi_j\right)}{A_e} \qquad [\mathrm{W/(m^2 \cdot K)}] \quad (1)$$

In Eq. 1 Q_t represents the total transmission losses in W. Moreover, U_i represents the heat loss coefficient for construction part i expressed in W/(m^2·K), the area for the construction part i against heated indoor air is denoted A_i and expressed in m^2, the heat loss coefficient for the linear thermal bridge k is denoted ψ_k and expressed in W/(m·K).
Further, l_k represents the length against heated indoor air of the linear thermal bridge k expressed in meters, X_j represents the heat loss coefficient for the point shaped thermal bridge j expressed in W/ K. The enclosing envelope area is denoted as A_e and expressed in m^2 with 7311m^2 as input for the calculation.

4.2.3 Determination of heat transfer coefficients

The first step of the second stage was to determine the required heat transfer coefficients for the different parts of the building envelope of the case study building. Parts of the building envelope considered realistic to retrofit for the case study building, beyond the external walls, were the roof, windows and doors. Thus, no changes to the foundation or the basement walls were investigated. Maximum heat loss coefficients (U-values) were set for the retrofitted building envelope parts according to the recommendations in Table 3 (see Chapter *1.2*).

Furthermore, the second step was to improve the U-values for the roof, windows and doors iteratively, starting with the recommended U-values by the Swedish building code. Since the windows and the roof account for approximately 40 % respectively 20 % of the present transmission losses the emphasis were put on reducing their U-values. However, it was early discovered during the iterative process that by just lowering the individual U–values to the recommended value in the building code, the maximum value of U_m was still exceeded. Therefore, high performance windows with a U-value of 0.80 W/(m^2·K) were chosen which also correspond to windows used in low energy buildings (Swedish centrum for zero energy buildings, 2012). Moreover, a U-value of 0.10 W/(m^2·K) was set for the roof which was considered necessary in order to allow reasonable transmission losses through the exterior walls. Adding insulation to the existing roof was considered as a relatively simple measure to improve the building envelope. The U-value of the doors were only lowered to the recommended U-value of 1.2 W/(m^2·K) considering their low impact on the total transmission losses of the building envelope. In Table 14 a summary of the established U-values of the building envelope is presented as well as the recommended U-values by the Swedish building code.

Table 14: Established and recommended U-values for parts of the building envelope to be retrofitted.

Envelope part	**Established U-value / W/(m^2·K)**	**Recommended U-value / W/(m^2·K)**
Roof	0.10	0.13
Windows	0.80	1.20
Doors	1.20	1.20

Moreover, since the average heat loss coefficient take thermal bridges into account, see Eq. 1, additionally 20 % of the total transmission losses through the building envelope was added to account for the thermal bridges that will affect the building after the retrofitting. This procedure is recommended for U_m calculations of new buildings by Sweden Green Building Council (Sweden Green Building Council , 2014). The final step was to apply the established U-values and 20 % additional transmission losses to account for the thermal bridges in order to determine the maximum allowed transmission losses from the retrofitted external walls (multi-active façade), in order to not exceed an U_m of 0.4 W/(m²·K).

4.2.4 Required properties for the multi-active façade layer

Stage three consisted of determining the required properties of the insulation for the new wall layer part. With the results from stage two the maximal transmissions losses through the external walls were obtained. To calculate the required total U-value of the modified external wall in order to not exceed the maximum allowed transmission losses for the external walls of the building Eq. 2 was applied.

$$U_{ext.wall} = \frac{Q_{t-wall}}{A_{walls}} \quad [\text{W/ (m}^2\cdot\text{K)}] \tag{2}$$

In Eq. 2 the maximum allowed transmission losses for the external walls (obtained from stage two) is denoted Q_{t-wall} and expressed in W/K. A_{walls} represents the envelope area consisting of external walls in m^2 where 2920 m^2 was used as input. The resulting U-value obtained from Eq. 2 was thereafter recalculated into thermal resistance of the new wall by inversing the U-value. The difference between the present thermal resistance of the wall and the new required thermal resistance in the retrofitted wall was set as the required additional thermal resistance to be applied by the new wall part (multi-active layer). By applying Eq. 3 the required additional thermal resistance of the insulation in the new wall part was obtained.

$$R_{insul.} = R_{new} - R_{old} - R_{si} - R_{se} \quad [(\text{m}^2\cdot\text{K})/\text{W}] \tag{3}$$

In Eq. 3, $R_{insul.}$ represents the required additional thermal resistance of the insulation in the new wall part, expressed in $(m^2\cdot K)/W$. The total thermal resistance of the proposed retrofitted wall is denoted as R_{new} and expressed in $(m^2\cdot K)/W$. Further, R_{old} represents the thermal resistance of the present wall expressed in $(m^2\cdot K)/W$, the interior and exterior surface resistance is donated as R_{si} and R_{se} respectively, and are expressed in $(m^2\cdot K)/W$. As previously described, the current exterior wall thickness is 280 mm, and has a U-value of 0.47 $W/(m^2\cdot K)$. An upper limit of the total thickness of the exterior wall after the retrofitting was set to 500 mm to avoid too thick walls and a possible daylight reduction in the living spaces. Furthermore, an assumption was made that the new facade would consist of facade panels, having a total thickness of 40 mm including an air gap. This resulted in that the additional layer of insulation could have a maximum thickness of 180 mm.

With a maximum insulation thickness of 180 mm and a requirement on thermal resistance of the new wall part, conductivities from 0.01 W/(m·K) to 0.04 W/(m·K) with increments of 0.001 were investigated in order to determine possible thicknesses of the insulation. By applying Eq. 4 the insulation thicknesses were calculated as a function of the conductivity in order to find the most feasible alternative. Generally, the aim was to use as little as possible of high performing insulation materials, which are defined in this report as insulation materials with conductivities lower than 0.030 W/(m·K), to not introduce any obvious high costs for the exterior wall.

$$d = R_{insul.} \cdot \lambda \quad [\text{m}] \tag{4}$$

In Eq. 4, d represents the required insulation thickness expressed in meters, $R_{insul.}$ represents the required additional thermal resistance of the new wall part, expressed in $(m^2 \cdot K)/W$ which was obtained from the Eq. 3. Thermal conductivity of the insulation material is denoted as λ and expressed in $W/(m \cdot K)$.

4.3 Active measures

4.3.1 Integrated ventilation ducts

The work process of developing a ventilation concept with supply air ducts integrated in the façade elements, suitable for the case study building, is presented in Table 15. A more detailed description follows in the subchapters. The proposed ventilation concept was based, on reusing the existing exhaust air ducts located in kitchens and bathrooms for extraction of air. Furthermore, only the apartments were included for the ventilation concept, i.e. the ground floor facilities are not included.

Table 15: Work process of developing the ventilation concept.

Stage	Description
1	3D modelling of the case study building in SketchUp.
2	Investigating solutions for ductwork placement and paths.
3	Dimensioning of the ventilation system.

4.3.1.1 3D modelling of the case study building

Stage one consisted of creating a 3D model in SketchUp (SketchUp, 2016) of the building, to easily visualize ducts and take measurements of the building envelope. Original drawings were used as basis for the model.

4.3.1.2 Ductwork placement and paths

Stage two consisted of investigating possible solutions of where to place the ducts on the façade, however, some prerequisites were first established;

- Individual ducts to each apartment to limit noise distribution between apartments (Ott, et al., 2014).
- Use of both vertical and horizontal ducts in the façade to limit ductwork inside the apartments (Ott, et al., 2014), thus reducing the installation work and disturbance of the tenants.
- Route the supply air ducting to living-and bedrooms to enable fresh air in rooms where the predominant time is spent, complying with the Swedish building code (Boverket, 2015c).

Moreover, the aim was to supply the air adjacent to the windows and to limit the ductwork as much as possible in the façade to minimize areas with inhomogeneous insulation layer. With the building model obtained from stage one, measurements were taken from the building envelope where ducts were considered suitable and/or necessary to place in order to supply the living rooms and bedrooms with air. The measurements were later used in stage three to determine the duct dimensions.

Two main alternatives were investigated regarding the duct path in the façade from the AHU and quantity of AHUs;

Path alternative one – one central AHU located in the technical room in the attic, with all duct routing through the storage and roof to reach the façade and distribute the supply air to respectively diffuser.

Path alternative two – two central AHUs, one located in the technical room at the roof, as Path one, and one centrally located at the ground floor. The point with this alternative was to reduce the heat losses in the supply ventilation air since the maximum length of the ductwork was reduced to approximately half, compared with Path one. Each AHU supplies four stories, the AHU on the first floor supplies apartments located on the first four stories and the AHU on the roof supplies the top four stories.

It was outside the scope of this study to analyse the duct routing through the roof, therefore, the path leading from the suggested placements of AHU to the façade was only estimated through measurements of the 3D model.

4.3.1.3 Dimensioning of proposed ventilation system

Stage three consisted of dimensioning the ventilation system with the proposed ductwork paths from stage two, the task was divided into several subtasks which are described in Figure 27. A more detailed description follows.

Calculation of required air flows

The supply air flow for each apartment was calculated by applying the requirement of 0.35 $l/(s \cdot m^2)$ which is the minimum air flow allowed according to the Swedish Building code when people are present (Boverket, 2015c). Furthermore, the ventilation system was designed to have a constant air volume (CAV). A variable air volume (VAV) system was not considered within this study since it would be difficult to upgrade present exhaust air ducts or include extra equipment in the façade ductwork. The size of the apartments was obtained by measuring the original floor plan since all floors follow the same floorplan.

Ductwork dimensioning

The equal friction method was used to size the ducts, a method where the ducts are sized in order to have a certain pressure loss per meter duct (Warfvinge & Dahlblom, 2010). A pressure loss of 1 Pa/m is, according to Warfvinge & Dahlblom (2010), commonly applied and recommended and was therefore used in this study. Furthermore, 1 Pa/m generally results in low air velocities near supply- and exhaust air terminals (Warfvinge & Dahlblom, 2010). Moreover, an aim was to keep the same duct sizes through the whole duct path and to not use large variation in ducts sizes for different apartments in order to enable a more efficient production and assembling (Warfvinge & Dahlblom, 2010) of the multi-active façade. Therefore, 1 Pa/m was only used for the dimensioning of the first part of the duct, since the aim was to keep the same duct size, the pressure loss per meter duct changed where the duct has a different air flow but same dimensions.

In order to simplify further analysis regarding the placement of the ducts in the façade, rectangular ducts were used, an illustration of a rectangular duct is presented in Figure 28 together with definitions used in this study for; height, width and length of the duct. Furthermore, Ott, et al. (2014) recommends a minimum of 50 mm insulation between the duct and outermost façade layer to reduce heat losses from the supply air. It was therefore strived for to have ducts with a minimized height to enable as much space for insulation between the duct and outermost façade layer in the wall as possible. Also, the ducts were designed with the same height in order to use an even distribution of insulation in the wall where the ducts were considered.

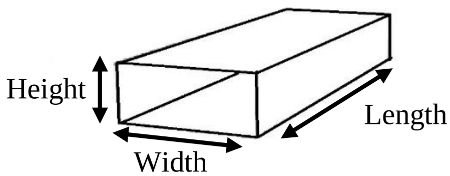

Figure 28: Rectangular duct, height, width and length definitions used in this study.

VariTrane Duct Designer (Trane, 2016), was used to determine suitable duct sizes according to the required air flow, pressure drop and space limits.

Calculation of pressure drops

With data obtained from stage two and the previous subtasks in stage three, pressure drops for the ductwork were calculated in order to enable further SFP calculations. VariTrane Duct Designer (Trane, 2016), was used to estimate pressure drops for junctions, elbows, fire dampers and silencers. Although fire safety was not covered within this study, pressure losses for fire dampers were included. Pressure drops for supply air terminals were estimated from a Fläktwoods product sheet (Fläktwoods, 2016). Moreover, an excel spread sheet was used to summarize the pressure drops for each path leading to respective apartment. The calculation was divided into two parts, the first part was a calculation of the pressure drop from the AHU at the roof to the façade, and the second part consisted of calculating the pressure drop from the top of the façade to each apartment including a silencer, diffuser and fire damper. The apartment with the largest pressure drop was further used as dimensioning pressure drop for the supply air.

4.3.2 Specific fan power

In order to quantify the energy use of the entire ventilation system, the SFP was necessary to be calculated. The first step consisted of quantifying the pressure drops in the supply- and exhaust air ductwork. Since the exhaust air ductwork is to be kept, the exact pressure drops were not possible to quantify since the duct sizes and exact routing are unknown at the moment. Therefore, the pressure drop in the exhaust air ductwork was initially assumed to be equal to the pressure drop in the roof- and wall integrated supply air ductwork. The next step consisted of calculating the SFP for the entire ventilation system. This was carried out using the AHU dimensioning software “Systemair - Air Handling Unit Design” (SystemAir, 2016). By using this software, it was possible to calculate a realistic SFP. This is due to that the software is based on real units in the market consisting of components which have tested properties regarding fan efficiencies etc. This means that pressure drops through the supply and exhaust filters, heating coil as well as through the heat recovery unit could be included. The SFP calculations were based on the results of the pressure drop calculations in the supply air ductwork. Furthermore, since the available space in the attic is limited a rotating heat exchanger was used as a basis for the SFP calculations. The rotary heat exchanger is relatively small in comparison to a cross-flow heat exchanger.

In all SFP calculations a moderately dirty filter was used which possess a higher pressure drop in comparison to brand new ones. The SFP is calculated by the software which applies Eq. 5 (Schild & Mysen, 2009).

$$SFP = \frac{W_{sup}+W_{exh}}{\dot{V}_{max}} \qquad [\mathrm{kW/(m^3/s)}] \tag{5}$$

In Eq. 5 W_{sup} and W_{exh} represent the power need from the supply respectively exhaust air fans in kW. $\dot{V}_{max}$ represents the highest air flow rate in m³/s.

However, in order to apply Eq. 5, equations Eq. 6-9 were required to be calculated first due to the SFP being a function of those (Schild & Mysen, 2009).

$$W_{sup} = \frac{\dot{V}_{sup} \cdot \Delta p_{sup}}{\eta_{sup}} \qquad [\mathrm{kW}] \tag{6}$$

$$W_{exh} = \frac{\dot{V}_{exh} \cdot \Delta p_{exh}}{\eta_{exh}} \qquad [\mathrm{kW}] \tag{7}$$

$$\Delta p_{sup} = \Delta p_{sup-ductwork} + \Delta p_{sup-filter} + \Delta p_{HR} + \Delta p_{Heating\ coil} \qquad [\mathrm{Pa}] \tag{8}$$

$$\Delta p_{exh} = \Delta p_{exh-ductwork} + \Delta p_{exh-filter} + \Delta p_{HR} \qquad [\mathrm{Pa}] \tag{9}$$

In Eq. 6 and Eq. 7 $\dot{V}$represents the supply air flow rate in m³/s for the supply respectively exhaust air ductworks. Δp represents the total dimensioning pressure drop in Pascal in the supply respectively exhaust air ductworks. η represents the efficiency of the supply respectively exhaust air fans, located in the AHU. Eq. 8 and Eq. 9 consist of several sub pressure drops which are summed into the total dimensioning pressure drops. The total dimensioning pressure drop consist of the pressure drops through the ductwork, filters, heat recovery unit and heating coil.

The next step was to calculate an annual energy use for the ventilation system. Since the ventilation system was of the type constant air volume (CAV) Eq. 10 was applied.

$$E_{ventilation} = \frac{\sum_{h=1}^{8760} SFP \cdot \dot{V}_{max}}{A_{temp}} \qquad [\mathrm{kWh/m^2}] \tag{10}$$

In Eq. 10 the SFP represents the specific fan power in kW/(m³/s). $\dot{V}_{max}$ represents the air flow rate in m³/s and A_{temp} represents the heated floor area of the building, which is 9235 m². However, the assumption of the pressure drop in the exhaust air ductwork being identical to the supply air duct is a source of error. Therefore, a sensitivity analysis was carried out by varying the pressure drop in the exhaust air ductwork by 50 % in each direction. Furthermore, the calculations were carried out for several AHU sizes in order to determine in what interval the SFP might be in depending on which size of the AHU is installed. This was carried out in order to investigate if the maximum SFP of 2 kW/(m³/s), set by the building code, will be fulfilled independently of the pressure drop in the exhaust air duct and the AHU size.

Furthermore, another reason for carrying out the sensitivity analysis was to investigate how a varying pressure drop in the exhaust air duct will affect the annual energy use for ventilation of the building.

4.3.3 Supply air and energy losses

In order to evaluate the placement of ventilation ductwork in the façade, the heat losses from the supply air alone were required to be quantified in order to estimate the supply air temperature. The evaluation consisted of an analysis of the heat losses from the supply air when transported between the AHU and the living spaces.

The hourly climate data, compiled by the Swedish Meteorological and Hydrological Institute (SHMI), obtained from SVEBY (Sveby, 2016), was used as a basis for the calculations. The climatic data contains, among other data, the dry bulb temperature and the relative humidity.

The work process of analysing the energy losses from the supply air ductwork in the façade was carried out on hourly basis and consisted of the stages described in Table 16.

Table 16: Work process of analysing the energy losses from the roof- and wall integrated supply air ductwork.

Stage	Description
1	Calculation of the power of the air exiting the AHU.
2	Simulation of the heat losses from the heated supply air to ambient air.
3	Calculation of the power of the air entering the living spaces, considering the heat losses through the entire duct length.
4	Calculation of the variation in supply air temperature for the duct located the furthest away from the air handling unit.
5	Calculation of the annual energy losses, from the supply air when transported from AHU to living spaces, for the entire roof- and wall integrated ductwork.

The first stage was to calculate the power of the air exiting the AHU. The outdoor air is heated in the AHU by a heat exchanger, as well as a heating coil as auxiliary heat source, ensuring a constant supply air temperature of 19 °C, thus, no additional moisture is introduced. This equals in an unchanged moisture content of the air. The power of the heated air exiting the AHU was therefore calculated by applying Eq. 11. A supply air temperature of 19 °C was chosen to have a lower temperature of the air entering the room than the indoor room temperature to enable the possibility for the air to mix.

$$P_0 = \dot{V} \cdot \rho_{air} \cdot h_0 \qquad [\mathrm{W}] \tag{11}$$

In Eq. 11, $\dot{V}$ represents the air flow rate and is expressed in m³/s. The density of air is denoted as ρ_{air} and has the value 1.2 kg/m³. The enthalpy of the air, when heated by the heat recovery is denoted as h_0 and expressed in J/kg of air.

The second stage was calculating the equivalent heat loss factors for each duct composition. They were simulated, using the software HEAT2 which is a heat transfer software (BLOCON, 2016), and calculated by applying the simulation results in Eq. 12. An illustration of the outgoing heat flux from the wall section is presented in Figure 29.

$$\Psi_{\mathrm{air}} = \frac{Q_{\mathrm{external\ incl.duct}} - Q_{\mathrm{internal\ excl.duct}}}{\Delta T} \qquad [\mathrm{W/(m \cdot K)}] \tag{12}$$

In Eq. 12, Ψ_{air} represents the heat loss factor from the heated ventilation air as well as the minor thermal bridge that occurs as a result of the duct being placed in the wall. It is expressed per length unit of duct in W/(m·K). Q represents the heat flux flowing out of the wall to the ambient air in W/m. It is divided in two cases, including and excluding ducts. ΔT represents the temperature difference between the indoor air and ambient air. Note that the calculations include even the minor thermal bridges that occur between the indoor air and duct.

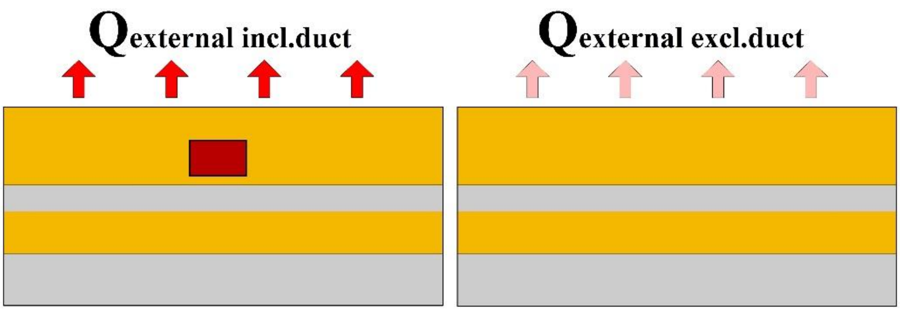

Figure 29: Illustration of the outgoing heat flux from the wall in the cases with and without a duct.

Furthermore, in order to identify the most favourable placement of the wall integrated duct, where the lowest heat losses from the supply air were strived for to be found, a sensitivity analysis was conducted. The sensitivity analysis was based on two thermal conductivities in front of the duct, facing the ambient air;

- λ =0.032 W/(m·K), corresponding to high performing mineral wool, as other parts of the façade element consist of.
- λ =0.021 W/(m·K), corresponding to Polyisocyanurate (PIR).

Moreover, the sensitivity analysis was based on the placement of the ductwork in the wall, illustrated in Figure 30, expressed as distance from the outermost part from the insulating layer in the interval from 0 to 100 mm. The upper limit was set to 100 mm in order to not exceed the maximum wall thickness of 500 mm since the ducts are 80 mm in height.

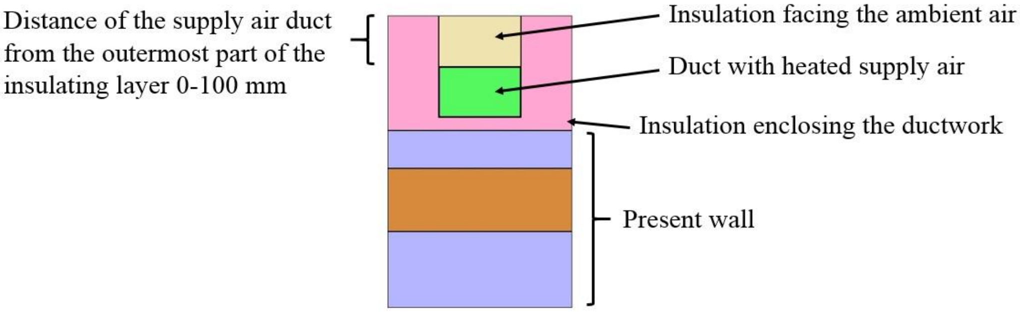

Figure 30: Illustration of the wall section where a duct is located and the parameters varied.

The third and fourth stages were, to calculate the power and temperature of the supply air when entering the living spaces. This was carried out for the entire year in order to quantify the variation in supply air temperature as well as identifying the peaks.

The work process of calculating the total heat loss from the supply air and resulting supply air temperature, for the ducts possessing the longest path in the multi-active wall- and roof were carried out by initially calculating the heat transfer rate for each duct size and duct composition in the wall.

Further, a weighted heat loss factor was manually calculated for all types of duct compositions obtained from the results of the investigation regarding the placement and paths for the ductwork. Moreover, this was carried out since the path from the AHU to the diffuser, exposed to the ambient air, consist of supply air flowing through various duct compositions.
This means that the heat loss factor is varying on the path. However, to simplify the calculations duct compositions with more than one type of duct dimension was individually calculated.

The power of the air that enters the living spaces was calculated for each hour in the year by applying Eq. 13.

$$P_{out} = P_{in} - (DL \cdot \Psi_{\text{air-w}} \cdot (T_{in} - T_{amb})) \qquad [\text{W}] \qquad (13)$$

In Eq. 13, P_{in} represents the power of the air entering the duct in W. For the first cell, P_{in} is equal to P_0, that is the power of the heated air exiting the AHU. *DL* represents the duct length in meters. The weighted heat losses from the ventilation air alone are denoted as Ψ_{air-w} and expressed in W/(m·K). The temperature of the air entering the cell is denoted as T_{in} and expressed in °C. The ambient temperature, which influences the heat losses is denoted as T_{amb} and also expressed in °C.

The power of the air that leaves the ductwork was converted into a corresponding enthalpy of the air by applying Eq. 11. Further, in order to convert the enthalpy to a supply air temperature, Eq. 14 was applied (Nevander & Elmarsson, 2008).

$$h = 1000 \cdot T + 1000 \cdot x \cdot (2500 + 1{,}86 \cdot T) \qquad [\text{J/kg}] \qquad (14)$$

In Eq. 14 *h* represents the enthalpy in J/kg of air. Further, *T* represents the temperature in °C. However, to solve this equation *x* must be known, which is the moisture content of the air expressed in kg of water per kg of air. The moisture content was possible to calculate due to the climate file containing the relative humidity and dry bulb temperature. The moisture content was therefore calculated by applying equations Eq. 15, Eq. 16, Eq. 17 and Eq. 18 (Nevander & Elmarsson, 2008).

$$x = \frac{\varphi \cdot v_s(T)}{\rho_i} \qquad \text{[kg/kg]} \tag{15}$$

$$\rho_i = \frac{352{,}9}{T+273.15} - 1.607 \cdot \varphi \cdot v_s(T) \qquad \text{[kg/m}^3\text{]} \tag{16}$$

$$v_s(T) = p_s(T) \cdot \frac{M_v}{R \cdot (273.15+T)} \qquad \text{[kg/m}^3\text{]} \tag{17}$$

$$p_s(T) = a \cdot (b + \frac{T}{100})^n \qquad \text{[Pa]} \tag{18}$$

In Eq. 15 to Eq. 18 *x* represents the moisture content of the air expressed in kg of water per kg of air. φ represents the relative humidity expressed in % and $v_s(T)$ represents the saturated moisture content of air expressed in kg/m³.ρ_i represents the density of moist air, expressed in kg/m³. *T* represents the temperature of the air expressed in °C and $p_s(T)$ represents the saturated moisture pressure expressed in Pa. M_v represents the molecule weight of water which is 18.02 kg/kmol and *R* represents the gas constant which is 8314.3 J/(kmol·K). *a* is a constant, its value is 4.689 Pa in the temperature interval -20°C ≤T≤0°C and 288.68 Pa in the temperature interval 0°C ≤ T ≤ 30°C. *b* is a constant, its value is 1.486 in the temperature interval -20°C ≤T≤0°C and 1.098 in the temperature interval 0°C ≤ T ≤ 30°C. *n* is a constant, its value is 12.3 in the temperature interval -20°C ≤T≤0°C and 8.02 in the temperature interval 0°C ≤ T ≤ 30°C.

The fifth and final step, was to estimate the energy losses of the ventilation air inside the ducts. The heat losses from the ventilation air vary depending on the temperature difference between the supply and ambient air. This heat loss factor was calculated by applying Eq. 12 as earlier mentioned. A weighted heat loss factor was calculated for each duct path, which consists of different duct compositions. By applying Eq. 13 a corresponding power loss was calculated, this was carried out for all ducts and for their entire duct lengths in order to quantify how much energy is lost from the entire roof- and façade integrated ductwork. Further, this was carried out for each hour in the year. The annual energy loss from the ventilation air in the wall integrated ducts, for each duct path was calculated by applying Eq. 19. Values where P_{supply} is greater than P_0 were not included in the summary since energy gained during the summer cannot compensate for heat losses during the winter.

$$E_{loss-duct\ N} = \frac{\sum_{h=1}^{8760}(P_0 - P_{supply})}{A_{temp} \cdot 1000} \qquad \text{[kWh/m}^2\text{]} \tag{19}$$

$$Total\ losses = E_{loss-duct\ 1} + \cdots + E_{loss-duct\ N} \qquad [\text{kWh/m}^2] \qquad (20)$$

In Eq. 19 P_0 represents the power of the heated air exiting the AHU. P_{supply} represents the power of the air when reaching the supply air diffuser, that is, all heat losses from the AHU to diffuser subtracted. The total heat losses are summarized in Eq. 20.

4.3.4 Photovoltaics

The evaluation of the active technology PV was carried out with the purpose to find the most suitable placement and to investigate the cost effectiveness. The work process is described in Table 17.

Table 17: Work process of evaluating PV systems.

Stage	Description
1	Importing the previously created 3D geometry to Rhinoceros 3D and carrying out an annual solar irradiation analysis for the entire building.
2	Creating hourly electricity profiles for the property used electricity, for all studied alternatives.
3	Simulation of the electricity output for each system studied. This was carried out in System Advisor Model (SAM) (NREL, 2010).
4	Calculation of the hourly bought or sold electricity for each studied PV system in order to estimate a summarized annual cost for the bought electricity.
5	Estimation of the investment cost and eventual subsidies.
6	Calculation of the Life Cycle Cost (LCC), Life Cycle Profit (LCP) and breakeven point for each studied alternative.
7	Conclusion if there is any profitability in installing a PV system, and which system is the most suited.

In order to identify adequate placements for PV modules, a solar irradiation analysis was carried out for the external walls and roof. Another purpose was to identify highly shaded surfaces to be avoided which could significantly constrain the output of the PV array.

The first step to carry out the solar irradiation analysis was to import the 3D building model with surrounding buildings to the software Rhinoceros 3D (Rhinoceros, 2016). The geometry on which the solar irradiation analysis was based on is presented in Figure 31.

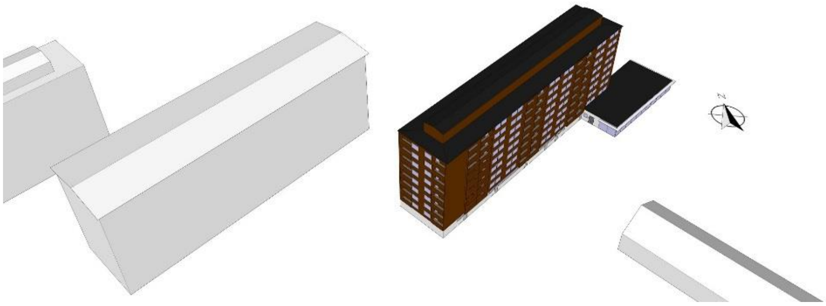

Figure 31: 3D model of the case study building and surroundings. Note that the length of the building is orientated 37 ° from south.

The solar irradiation analysis was carried out with the Rhinoceros 3D plugins Grasshopper, (Grasshopper, 2016) and Diva for Rhino (DIVA4Rhino, 2016). Grasshopper is a graphical algorithmic plugin (Grasshopper, 2016) that was used to integrate the 3D model and to enable the building surfaces to be analysed. Diva for Rhino is a daylight and energy modelling plugin (DIVA4Rhino, 2016) used in this study to quantify the annual solar irradiation that is received by the building.

The simulations were based on climate data from the city the case study building is located in and were carried out with a grid size of 0.1 x 0.1 m in order to achieve a high accuracy. The optical input data for the solar irradiation analysis is presented in Table 18.

Table 18: Input data to the annual solar irradiation analysis.

Element	Reflectance / %
Case study building facade	35
Case study building roof	10
Surrounding building walls	35
Surrounding building roofs	10
Surrounding ground	20

The third step was to create an hourly electricity profile over the property used electricity for each alternative which was used as a design benchmark in the further steps of the analysis. The electricity profile includes the electricity use for the eventual supply- and exhaust air fans in the AHU, hydronic pumps as well as eventual heat pump, depending on the alternative. The electricity use for the eventual fans in the AHU was based on the SFP value calculated in the SFP-analysis.

Since the electricity profile is not constant it was calculated by Applying Eq. 21. The electricity profile was carried out on hourly basis during the entire year.

$$P_{property} = SFP \cdot \dot{V} + P_{HP} + P_{pumps} \quad [\mathrm{W}] \tag{21}$$

In Eq. 21 SFP represents the specific fan power in kW/(m³/s). $\dot{V}$ represents the mass flow rate of the air through the AHU in m³/s. For the alternatives where no supply-and exhaust air ventilation was considered this was set to zero. P_{HP} represents the power the heat pump requires to operate in W which was retrieved from IDA ICE. P_{pumps} is the power the hydronic pumps are assumed to require during the heating season in W.

In order to take PV into account, the available area of the sur faces were required to be quantified with the purpose to set the boundaries of how many modules that physicaly can fit. This was carried out for the roof surfaces with the highest annual solar irradiation as well as for the unshaded facades and balcony railings but excluding windows.

To determine which placement is the most favorable, simulations of the electricity output from a 1 kW_p PV system was carried out and analysed. The simulations were based on roof mounted modules, and façade integrated modules. Further, a simulation of the optimal placement (module inclination 35°, directly towards south (Warmec, 2016) was also carried out for comparative purposes.

The fourth step was to simulate the electricity output on hourly basis for the various studied PV systems focusing on façade integrated PV as well as traditionally, roof mounted PV.

This was carried out using SAM which is a PV system designing software, based on real PV products available on the market, and on their performance. Further, SAM accounts for the following system losses:

- Module losses.
- Inverter losses, when converting from direct current (DC) to alternative current (AC).
- Inverter losses at standby which occurs during nights when no power is generated.
- Wiring losses.
- Losses in various type of diodes and connectors (NREL, 2010).

The simulations were based on the climate data closest to the city where the case study building is located which is Gothenburg. Furthermore, the PV simulations were based on *SweModule 265x* modules with the peak power of 262 W_p, efficiency 16 % and open circuit voltage 38.6 V which are polycrystalline solar modules. Moreover, the simulations were also based on inverters with the maximum DC voltage of 600 V that is with the capacity to handle 15 series connected modules.

Thereafter, a calculation of bought or sold electricity was made on hourly basis (same resolution as the electric meters). This means that the electricity need profile was compared to the electricity output from the various PV systems studied. This was carried out in order to quantify the summarized annual cost for the electricity that needs to be bought from the grid. This was also used as the basis for the further economic analysis. The average buying price and selling prices for the year 2015 are presented in Figure 32.

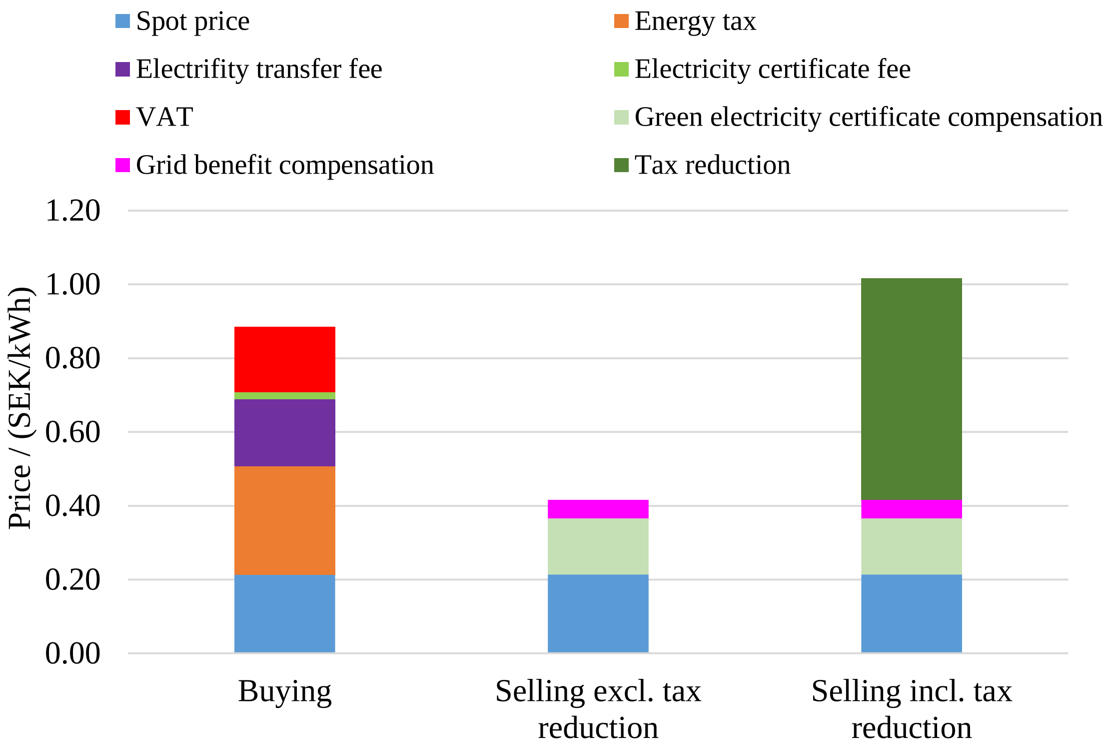

Figure 32: Average buying and selling prices in the year of 2015, excluding fixed charges.

It can be observed that the selling price without tax reduction is significantly lower in comparison to the selling price with included tax reduction.

The hourly bought and sold electricity were calculated by applying Eq. 22 and Eq. 23 (Lindahl, 2014).

$$E_{buy} = SP + ET + ETF + ECF + BVAT \quad [\text{SEK}] \tag{22}$$

$$E_{sold\ to\ grid} = SP + GECFS + GECFU + GB + TR + SVAT \quad [\text{SEK}] \tag{23}$$

In Eq. 22 and Eq. 23, *SP* represents the spot price in SEK/kWh excluding VAT and was obtained from Nord-Pool, which complies the market electricity prices in Sweden (Nord-Pool, 2015). Spot price is the cost for the electricity which is either sent out or received from the grid. Since the case study building is located in the south-western part of Sweden, hourly spot prices for electricity price zone SE4 were used in the calculations. The spot price varies on hourly basis, for the year 2015, in the interval from 0.00295 to 1.39271 SEK/kWh.

ET represents the energy tax in SEK/kWh which at present is 0.294 SEK/kWh excluding VAT for the zone the case study building is located in (E-ON, 2016).

ETF represents the electricity transfer fee in SEK/kWh. It has the value 0.18 SEK/kWh for fuses above 16A (E-ON, 2015). *ECF* represents the electricity certificate fee when buying electricity in SEK/kWh. At present, it has the value of 0.0195 SEK/kWh (E-ON, 2015).

GECFS represents the green electricity certificate compensation on sold electricity while *GECFU* represents the green electricity certificate compensation on self-used electricity and was obtained from Ekonomifakta (Ekonomifakta, 2016). The green electricity certificate is applicable for all generated electricity, both sold and self-used. It varies on monthly basis, and for the year 2015 it varied from 0.139 to 0.167 SEK/kWh.

GB represents the grid benefit compensation in SEK/kWh. This is the compensation for the usefulness the power generation has to the grid and varies between the power companies. In this case, the compensation 0.05 SEK/kWh from E.ON was used which is a power company established in south-western Sweden (E.ON, 2016).

BVAT represents the value added tax on bought electricity and consists of additional 25 % of the other cost summed together in SEK/kWh.

TR represents the tax reduction which is given in SEK/kWh. It enables the solar power producer to receive 0.6 SEK/kWh as compensation by tax reduction for the power fed into grid. However, the tax reduction is only valid for electricity up to 30 000 kWh/year fed into the grid and for systems with a fuse of maximum 100 Amperes (Skatteverket, 2016). This means that the maximum electricity output P from the PV system, or the maximum bought electricity, may not exceed 23 kW under the conditions; voltage U = 230 volt and electric current I =100 ampere by applying Ohms law (P=U·I). Furthermore, if the quantity of generated electricity sold to the grid exceeds 40 000 SEK/year income tax will be added for the surplus profit (Skatteverket, 2016). This additional tax is represented as *SVAT* in SEK/kWh. Moreover, the tax reduction is valid for private households and legal entities.

Moreover, if the value of the sold electricity exceeds 30 000 SEK/year energy tax (ET) will be introduced (Skatteverket, 2016). This results in subtracting energy tax from the selling price as well as that the tax reduction is not applicable any more. This results in a minimal selling price due to the selling price (without tax reduction) will be lowered additionally by 0.294 SEK/kWh resulting in a selling price of approximately 0.118 SEK/kWh.

The economical assessment of the various studied PV installations was carried out in order to investigate the cost-effectiveness and calculate the breakeven point for the investment based on various prerequisites.

To calculate the Net Present Value (NPV) Eq. 24 and 25 were applied. The NPV was calculated with the geometric gradient series, which are cash flow series that either increases or decreases by a constant percentage for each period during the entire life cycle (Blank & Tarquin, 2011). The NPV was calculated for the running costs regarding electricity, maintenance cost and inverter change.

Furthermore, the NPV of the annual costs for the annual grid connection fee was calculated by applying Eq. 26 (Blank & Tarquin, 2011). The additional cost caused by system degradation in the PV system was calculated by applying Eq. 27. The total LCC for the studied PV systems is summarized by applying Eq. 28.

$$A_1 = C_0(1+i)^n \quad \text{[SEK]} \tag{24}$$

$$NPV = A_1 \left(\frac{1-\left(\frac{1+g}{1+i}\right)^n}{i-g} \right) \quad \text{[SEK]} \tag{25}$$

$$NPV_{gc} = P(1+i)^n \quad \text{[SEK]} \tag{26}$$

$$NPV_{rp} = ((PV_{savings} \cdot (1+SG)^{n-1}) - PV_{savings}) \cdot \frac{1}{(1+i)^n} \quad \text{[SEK]} \tag{27}$$

$$NPV_{total} = I_c + NPV_{run} + NPV_{inv} + NPV_{main} + NPV_{rp} + NPV_{gc} \quad \text{[SEK]} \tag{28}$$

In Eq. 24 and 25, A_1represents the accumulated costs in year one in SEK. C_0 represents the running cost in year zero, that is in the current money value in SEK. i represents the required rate of return of the investment in %. n represents the lengths of the life cycle. g represents, depending on the case, either the constant electricity price growth rate, growth rate of maintenance or inverter price change in %. NPV represents the net present value of the running costs in SEK. NPV_{main} represents the life cycle cost of maintaining the PV installation in SEK. NPV_{inv} represents the life cycle cost of replacing the inverter in the year 15 in SEK. NPV_{run}, NPV_{main} and NPV_{inv} were calculated with Eq. 24 and 25. NPV_{gc} represents the life cycle cost of being connected to the electricity grid in SEK. P represents the present worth of the money value the grid connection fee represents in SEK. NPV_{rp} represents the additional cost that occurs as a results of the system degradation in SEK. This means that the PV system will generate less energy for every year that passes, hence, the required electricity to be bought will increase. SG represents the system degradation rate in %. $PV_{savings}$ represents the annual savings that take place by installing the specific PV system in SEK. I_c represents the initial cost of the investment in SEK.

The net present value was calculated for a life cycle of 30 years since the PV installation is expected to last longer than the given warranty time of 25 years. The rate of return was set to be 5 % with inflation excluded (Statens-Fastighetsverk, 2014). The constant electricity price growth rate was assumed to be 2.5 % with inflation excluded (Statens-Fastighetsverk, 2014). The PV degradation rate was set to 0.5 % per year (Jordan, et al., 2010).

The annual cost of the inverter change which occurs at year 15 was set to be 100 SEK/ kW_p spread out during the whole life cycle (Lindahl, 2014). The inverter price change was assumed to be – 2 % since inverters are assumed to decrease in price. The inverters are to be changed after 15 years, this means that the second inverter change will occur after 30 years. This is outside of the life cycle and is therefore not included in the LCC.

The grid connection fee varies depending on the fuse and it is charged per month. However, in this case the monthly costs were grouped into one annual cost in order to simplify the cost estimation. The grid connection cost for various fuse sizes, based on the voltage 230 V is presented in Table 19, which were obtain from E.ON (E-ON, 2015). The grid connection fee was assumed to remain the same during the entire life cycle.

Table 19: Annual grid connection costs with E.ON as power supplier.

Fuse / Ampere	16	20	25	35	50	63
Annual cost excl. VAT / (SEK/kWh)	3 288	4 356	5 640	8 280	12 408	16 140

The initial cost I_c for each PV system was calculated based on the initial cost 13.9 SEK/W_p excluding VAT for systems smaller than 20 kW_p and 12.9 SEK/W_p excluding VAT for systems larger than 20 kW_p (Lindahl, 2014). For the cases with façade integrated PV, where PV replace façade material the initial cost was calculated by subtracting the cost of the façade material the PV replaces. This cost, including mounting cost, was set to 537 SEK/m² excluding VAT and corresponds to ordinary façade fibre cement façade panels. The cost was based on Wikells sektionsfakta (Wikells-Byggberäkningar, 2016) which is a price estimation software commonly used in the Swedish building sector. When placing 537 SEK/m² in perspective, it means that they stand for approximately 25 % of the initial cost for a PV system, regarding a system that has a 15 % efficiency and costs 13.9 SEK/W_p. Governmental investment subsidies are at present 30 % of the investment cost for companies, however, the highest amount possible to receive is 1 200 000 SEK (Energimyndigheten, 2016). The maintenance costs of the PV installation were set to be 1 % annually of the initial cost in order to account for eventual cleaning, system inspections and failures that are not covered by the warranty (Heinz. Ossenbrink, 2012). The price growth rate was set to 0 % regarding the annual maintenance costs since the maintenance cost was assumed to neither increase nor decrease.

The residual value of the PV installation, after the end of the life cycle was set zero, this is due to the residual value being unknown (Lindahl, 2014). Furthermore, the recycling cost was not included in the LCC. This is due to that the PV will most likely continue to generate electricity even after the end of the economic life cycle as well as that the recycling cost is unknown.

The LCP calculations were carried out by applying Eq. 29 where the difference between with and without PV represents the profit from a life cycle perspective. The breakeven point was quantified by interpreting the intersection between the accumulated NPV with and without a PV system.

$$LCP = NPV_{with\ PV} - NPV_{without\ PV} \quad \text{[SEK]} \tag{29}$$

The scenarios that were simulated, and on which the economic analysis was carried out are presented in Figure 33.

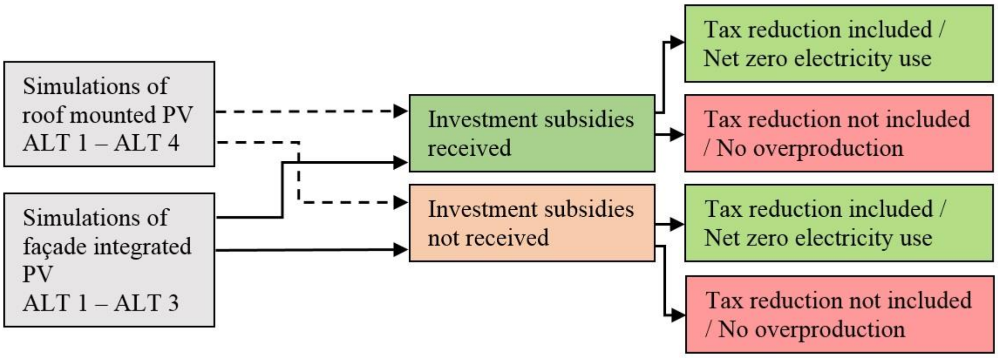

Figure 33: Simulation schematics of the various PV systems and calculation prerequisites.

Two scenarios were considered as basis for the evaluation, roof mounted and façade integrated PV. The economic evaluation for the roof mounted scenario was carried out for all four design alternatives. However, the façade integrated scenario was only carried out for alternative one, two and three. This is due to that the fourth alternative consists of only installing a heat pump and therefore will the present façade remain unchanged.

There is an uncertainty if subsidies are available since the governmental budget is limited (Energimyndigheten, 2016). Therefore, the economic analysis was divided in two groups depending if subsidies are available or not.

The case when no investment subsidies nor tax reduction are available represent a worst case scenario. In the worst case scenario, there is no incentive to sell any electricity to the grid and will result in smaller systems that self-consume as much as possible. In the case where tax reduction is available, an incentive is present for overproducing, as earlier mentioned, up to 30 000 SEK/ year. Moreover, by overproducing there is a possibility to reach net-zero electricity use (yearly production of electricity equal to yearly need of electricity), if required amount of PV modules can fit on the roof or façade.

4.4 Specific energy use

4.4.1 Space heating

To simulate the space heating need for the various developed alternatives described in the method overview chapter, IDA ICE V.4.7 was used (Equa, 2016). The work process of simulating the space heating need is described in Figure 34. A more detailed description of each alternative follows.

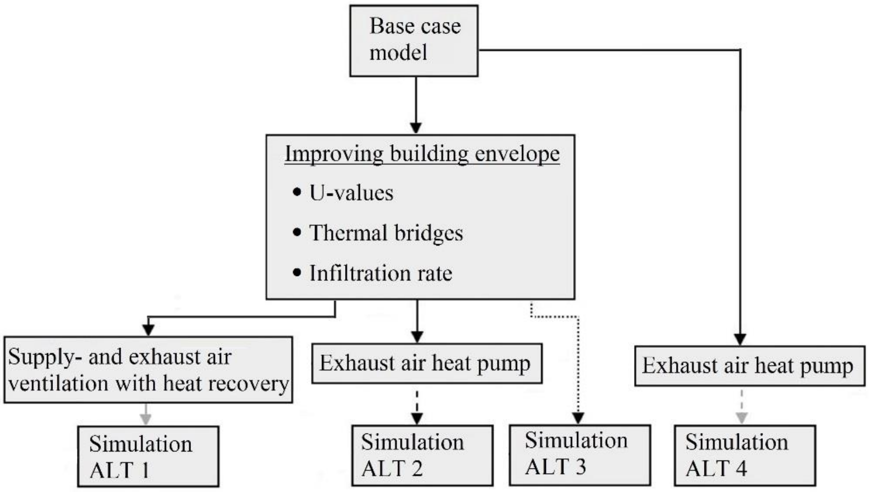

Figure 34: Work process of simulating the various alternatives in IDA ICE.

The first three alternatives include an improvement of the building envelope. The first step was therefore to change the U-values of the building envelope according to the set and obtained U-values from the results of the investigation of passive measures. Secondly, additional 20 % of the transmission losses were added to account for thermal bridges. With an improvement of the building envelope an assumption was made that the airtightness was improved by 50 %. Moreover, to account for airing, 4 kWh/(m^2·yr) was added to all alternatives and equally spread throughout the year because of the uncertainty of the amount of energy losses due to airing each month.

For the first alternative, which is corresponding to an implementation of a multi-active façade, supply- and exhaust air ventilation with heat exchanger was included. The heat exchanger efficiency was set to 80 % and a heating coil was included to ensure a supply air temperature of 19 °C from the AHU. Moreover, the result of the additional heat losses from having the ducts in the façade were added to the first alternative.

Exhaust air heat pump

The second and fourth alternatives include an EAHP as heat extraction technology on the exhaust air. Exhaust air heat pumps are usually sized for the dimensioning heating need and exhaust air mass flow rate. However, due to the unavailability to find exhaust air heat pumps with the capacity to handle exactly 3.2 m^3/s, a heat pump closest to the required airflow was chosen. The considered exhaust air heat pump was “Carrier 30RQSY-039” (Carrier, 2016). It is an exhaust air-to-water heat pump, therefore, it is well suited to be connected to the present district heating substation. The selected heat pump has a mass flow rate of 3.5 m^3/s.

The exhaust air heat pump has an integrated fan, however, it is not known if it can handle the quantified pressure drops. Moreover, the exhaust air heat pump was assumed to be turned off during the periods when the building does not have any space heating need. In order to ensure ventilation during the time the EAHP is shut off, a decision was made to include the existing exhaust fan and its power need for the entire year. The technical specifications of the selected exhaust air heat pump, which were used as the basis in the

IDA ICE simulations are presented in Table 20. The rating conditions, at which the technical properties of the heat pump were tested by the manufacturer was; an incoming temperature of 40 °C on the cold side and a leaving temperature of 45 °C on the hot side.

Table 20: Properties of the exhaust air heat pump

Coefficient of performance (COP) / (kW/kW)	Heating capacity / kW	Lower threshold of exhaust air temperature / °C
3.36	41.6	-15

The EAHP was modelled in IDA ICE and connected to the district heating substation in the software, which means that the energy extracted by the heat pump reduces the required specific heating need of the building, which would otherwise be required to be bought from the district heating network. The considered heat pump has a heating capacity of 41.6 kW which corresponds to approximately 5 W/m² when distributing the installed heating power on the heated floor area. Thus, the building is not considered as electrically heated (<10 W/m² installed power for heating) according to the Swedish building code (Boverket, 2015c). The analysed parameters, except for energy use for space heating were; the exhaust air temperature, electricity use for the heat pump as well as the seasonal coefficient of performance (SCOP). The electricity use for the heat pump was analysed in order to be able to calculate SCOP, which is a measure to describe how efficient the heat pump is on a yearly basis and was calculated by applying Eq. 30. The reason for analysing the exhaust air temperature was to distinguish the seasonal variations. Furthermore, the electricity use of the EAHP was logged on a separate energy meter in IDA ICE.

$$SCOP = \frac{EH_{without\ HP} - EH_{with\ HP}}{EHP_{el}} \qquad [-] \qquad (30)$$

In Eq. 30, $EH_{without\ HP}$ represents the annual energy use for space heating without any heat pump in kWh. $EH_{with\ HP}$ represents the annual energy use for space heating with the heat pump activated in kWh. EHP_{el} represents the annual electricity use of the heat pump in kWh.

4.4.2 Property used electricity use and DHW

Within this study no measures have been considered to lower the energy use for DHW nor the electricity use for lighting and other equipment in the building. Therefore, all developed alternatives have a DHW use of 20 kWh/(m^2·yr) and 1.18 kWh/(m^2·yr) for lighting and other equipment in the building. However, the energy use for the hydronic pumps was individually estimated for each alternative as for the base case, depending on the heating need.

No measures were taken to reduce the power to run the fans in the ventilation system for alternative two, three and four. Therefore, all alternatives except alternative one have an energy use of 4.84 kWh/(m^2·yr) for the ventilation system. The energy use for the ventilation system for alternative one was obtained from the results of the SFP calculations as described in chapter *4.3.2*.

4.5 Economic analysis

In order to investigate the economical aspect of the developed energy retrofitting alternatives, a LCC analysis was required to be carried out. The LCC analysis was initially outside of the scope of this study however, it was carried out in order to base the conclusions on not only energy results but economy as well.

The LCC analysis was based on quantifying the LCC, LCP as well as breakeven time for the investments the various alternatives required. The LCC analysis included initial costs, running costs for district heating and electricity as well as building maintenance cost. The purpose was to quantify the costs the various alternatives entail during their entire life cycle in the present money value, thus basing our conclusions on more than only comparing initial costs.

Furthermore, it was assumed that the case study building was in immediate need of renovation. Hence, an "anyway" renovation alternative was used, which corresponds to costs that cannot be avoided, covering renovations that are needed to restore the building to the previous functionality and quality. However, it was assumed that the renovation measures do not improve the energy performance of the building. Such an alternative is recommended by Annex 56 and is described in "*Methodology for Cost Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56)*" (IEA, 2014). The anyway renovation measures, that are required to be carried out, even if no energy improving measures take place, are presented in Table 21.

In the case of window replacement, two scenarios were studied. The first scenario was to assume a window replacement to new ones that meet the BBR requirement of a maximum heat loss factor of 1.2 $W/(m^2 \cdot K)$.

The second scenario assumes that the windows are to be replaced to new ones, with identical thermal properties as the present ($U=2.4\ W/(m^2 \cdot K)$). However, this scenario is an abstraction since these type of low performing windows are most likely not available on the market but is the recommended procedure when using an anyway renovation alternative by Annex 56 (IEA, 2014). The reason for this is to simply the comparisons.
The assumption on what this anyway renovation includes will strongly influence the conclusions regarding the energy renovation alternatives. The initial cost for the two anyway renovation cases were assumed to be identical.

Table 21: Breakdown of the initial costs categories for the various alternatives studied.

Element	ANYWAY	ALT 1	ALT 2	ALT 3	ALT 4
Repair of the present concrete façade elements as well as replacement of sealants.	X	X	X	X	X
Demolition and recycling of present windows.	X	X	X	X	X
Downspouts, gutters and window sheeting for rain management.	X	X	X	X	X
Replacement of the present roof waterproofing membrane.	X	X	X	X	X
Façade elements with the thermal resistance R= 7.69 $(m^2 \cdot K)/W$, resulting in a heat loss factor of U=0.13 $W/(m^2 \cdot K)$, consisting of; steel studs, high performing mineral wool, wind board, façade supporting studs, fibrocement façade panels.	-	X	X	X	-
Façade integrated ventilation ductwork consisting of ducts, silencers, fire dampers as well as supply diffusers.	-	X	-	-	-
Core drilling in present concrete façade for diffusers.	-	X	-	-	-
Air handling unit of type supply and return air with heat recovery.	-	X	-	-	-
Return air heat pump connected to the present district heating substation of the building.	-	-	X	-	X
Windows and glazed balcony doors featuring a heat loss factor U=0.8 $W/(m^2 \cdot K)$	-	X	X	X	-
Windows and glazed balcony doors equivalent to the present.	X	-	-	-	X
Roof elements with the thermal resistance R= 10 $(m^2 \cdot K)/W$, resulting in a heat loss factor of U=0.1 $W/(m^2 \cdot K)$, consisting of steel studs, mineral wool, board and water proofing membrane.	-	X	X	X	-
Other costs consisting of scaffolding, scaffold elevator for material transports, crane for lifting elements in place.	X	X	X	X	X
Other costs consisting of site establishment, subcontractor profit and main contractor profit.	X	X	X	X	X

The initial costs were quantified[1] by using the price estimation software Wikells sektionsfakta (Wikells-Byggberäkningar, 2016). Other costs, such establishing cost and contractor profit, were provided from a Swedish contractor that chose to be anonymous in this investigation. The annual maintenance cost for the various alternatives, viewed in the present value of money is presented in Table 22. Moreover, modification of the present roof overhang was not included in the economic analysis.

[1] With contribution from Rikard Nilsson, Construction Management - Lund University

Table 22: Division of the maintenance costs that the LCC analysis was based on.

Maintenance type	**Takes place**	**Maintenance cost / SEK**				
		ANYWAY	ALT 1	ALT 2	ALT 3	ALT 4
Filter change	Annually	1500	3000	1500	1500	1500
Heat pump refurbishment	In intervals of 20 years	-	-	480 000	-	480 000

The maintenance costs for the anyway renovation and the third alternative (only additional insulation reaching U_m = 0.4 W/(m²·K)) consist of a filter change in the exhaust air AHU, which is required to be changed annually at a assumed cost of 1500 SEK in the present money value. Alternative one (supply and exhaust air with heat recovery, ducts routed through the façade elements) consist of two separate filters; one for filtering the exhaust air and one for filtering the outdoor air. Therefore, the annual cost for filter replacement is doubled to 3000 SEK in the present money value.

The second alternative (installing an EAHP and additional insulation reaching U_m = 0.4 W/(m²·K)) and fourth alternative (only installing an EAHP) also have filters in their respective EAHP. These are also assumed to be replaced annually at the same cost.

Heat pumps have a technical lifetime of approximately 20 years (Thermia, 2010), therefore, a refurbishment was assumed to be required, which would be based on replacing worn out components instead of buying a new heat pump. The refurbishment cost was assumed to stand for 50 % of the cost for a new heat pump, viewed in present money value. The refurbishment will therefore take place, during the life cycle of 60 years, at year 20 and 40. The refurbishment at year 60 was considered at the end of the life cycle and therefore not included.

As base for the LCC calculations the energy results from each studied alternative were used. The approach for quantifying the annual cost for district heating and property used electricity was carried out by applying Eq. 31 and Eq. 32.

$$C_{heating} = \sum_{1}^{8760} P_h \cdot C_{dh} \quad \text{[SEK]} \tag{31}$$

In Eq. 31 $C_{heating}$ represents the annual cost for heating, bought from the district heating network in SEK. P_h represents the hourly energy demand for space heating of the building in kWh. C_{dh} represents the hourly cost of district heating in SEK/kWh. The price for district heating varies in the interval from 0.124 to 0.877 SEK/kWh, depending on the month (Öresundskraft, 2015), as presented in Figure 20 (Chapter *2.2*). The hourly energy demand for space heating was obtained from the results of the energy simulations for each alternative.

$$C_{electricity} = \sum_{1}^{8760} P_e \cdot C_{el} \quad \text{[SEK]} \tag{32}$$

In Eq. 32 $C_{electricity}$ represents the annual cost for property used electricity SEK. P_e represents the electricity use on hourly basis kWh. C_{el} represents the hourly cost of electricity in SEK/kWh.

The hourly electricity use, for the various alternatives, was obtained from the results of the creation of hourly profiles. The hourly cost for electricity, varies in the interval from 0.62 to 2.35 SEK/kWh incl. VAT as mentioned in *4.3.4*.

The LCC analysis was carried out by applying Eq. 33 and Eq. 34. The total LCC for the studied energy saving measured were summarized by applying Eq. 35.

$$A_1 = C_0(1+i)^n \quad \text{[SEK]} \tag{33}$$

$$NPV = A_1\left(\frac{1-\left(\frac{1+g}{1+i}\right)^n}{i-g}\right) \quad \text{[SEK]} \tag{34}$$

$$NPV_{total} = I_c + NPV_{heating} + NPV_{elect} + NPV_{mainten.} \quad \text{[SEK]} \tag{35}$$

In Eq. 33 and 34, A_1represents the accumulated costs in year one, either for heating or electricity in SEK. C_0 represents the running cost in year zero, depending on the case, either for heating or electricity in the current money value in SEK. i represents the required rate of return of the investment in %. n represents the lengths of the life cycle in years. g represents, depending on the case, either the constant electricity price growth rate or constant district heating price increase in %.

In Eq. 35, I_c represents the initial cost the actual investment entail in SEK. NPV_{total} represents the net present value of the life cycle cost of the initial cost and running costs in SEK.

The LCC calculations were based on an assumed life cycle of 60 years, meaning that the case study building was assumed to be able to stand for another 60 years when either retrofitted by anyway renovation measures or a specific energy saving alternative.

The LCC was only scoped on the energy use and the initial costs the various alternatives entail, therefore, the residual value of the building and building materials was set to zero. Moreover, the effect of the energy efficiency measures has on the property value was not included due to its complexity.
The rate of return was set to be 5 % with inflation excluded (Statens-Fastighetsverk, 2014). The constant electricity price growth rate was assumed to be 2.5 % annual with inflation excluded (Statens-Fastighetsverk, 2014). The constant district heating price growth rate was assumed to be 1.5 % annual with inflation excluded (Statens-Fastighetsverk, 2014). The LCP of each alternative was calculated by applying Eq. 36.

$$LCP = NPV_{specific\ alternative} - NPV_{anyway} \quad \text{[SEK]} \tag{36}$$

In Eq. 36 the LCP was calculated by subtracting the NPV for the anyway renovation, from the NPV for the specific alternative. As earlier mentioned, the anyway renovation was based on two separate scenarios, therefore the LCP is also presented for both scenarios. The breakeven times were quantified by graphically find the intersection between the accumulated LCC for the various alternatives in comparison to the anyway renovation.

5 Results

5.1 Passive measures

5.1.1 Average heat transfer coefficient

The maximum allowed transmission losses through the building envelope, in order to not exceed the average heat transfer coefficient U_m of 0.4 W/(m^2·K) is presented in Table 23.

Table 23: Maximum transmissions losses through the building envelope to not exceed U_m.

Average heat transfer coefficient, U_m / W/(m^2·K)	Total maximum allowed transmissions losses through the building envelope / W/K
0.4	2924.5

By applying the established U-values for the roof, windows, doors and 20 % additional transmission losses to account for the thermal bridges, the remaining allowed transmission loss through the exterior walls with an area of 2920 m^2 was calculated to 376 W/K. Furthermore, this corresponds to a required U-value of 0.13 W/(m^2·K) for the exterior walls. In Table 24, transmission losses through the building envelope is presented for the present building and for the retrofitted building with improved U-values (marked in grey).

Table 24: Transmission losses through building envelope, present (white) and retrofitted building (grey).

Building envelope	**Area (A) / m^2**	**U-value / W/(m^2·K)**	**UA / (W/K)**	**Part of total losses / %**
Walls above ground	2920.7	0.47	1367.5	15.9
Walls above ground	2920.7	0.13	376.0	12.9
Walls below ground	415.1	0.90	374.8	4.4
Walls below ground	415.1	0.90	374.8	12.9
Roof	1276.0	0.48	1753.2	20.4
Roof	1276.0	0.10	127.6	4.2
Floor towards ground	1272.3	0.30	387.4	4.5
Floor towards ground	1272.3	0.30	387.4	13.3
Floor towards crawl space	10.9	3.48	37.7	0.4
Floor towards crawl space	10.9	3.48	37.7	1.3
Windows	1404.0	2.4	3369.6	39.1
Windows	1404.0	0.8	1123.2	38.6
Doors	12.6	2.38	30.0	0.4
Doors	12.6	1.20	15.12	0.5
Thermal bridges	-	-	1285.84	14.9
Thermal bridges	-	-	487.0	16.7
Total	**7311.5**	**1.18**	**8606.1**	**-**
Total	**7311.5**	**0.39**	**2924.2**	**-**

It can be observed in Table 24, that the improved building envelope, with established U-values as well as calculated U-value for the exterior walls, does not exceed an U_m of 0.4

W/(m^2·K). Furthermore, it can be noticed that the windows still hold the largest transmission losses of the building envelope after the retrofitting. However, by replacing the windows two thirds of those transmission losses were reduced. By applying the required U-value for the external walls a reduction in transmission losses of approximately 70 % can be noted. The required thermal resistance for the insulation in the new wall layer part ($R_{insul.}$) was calculated to 5.56 (m^2·K)/W. In Figure 35, insulation thickness as a function of conductivity is presented for the required thermal resistance of 5.56 (m^2·K)/W.

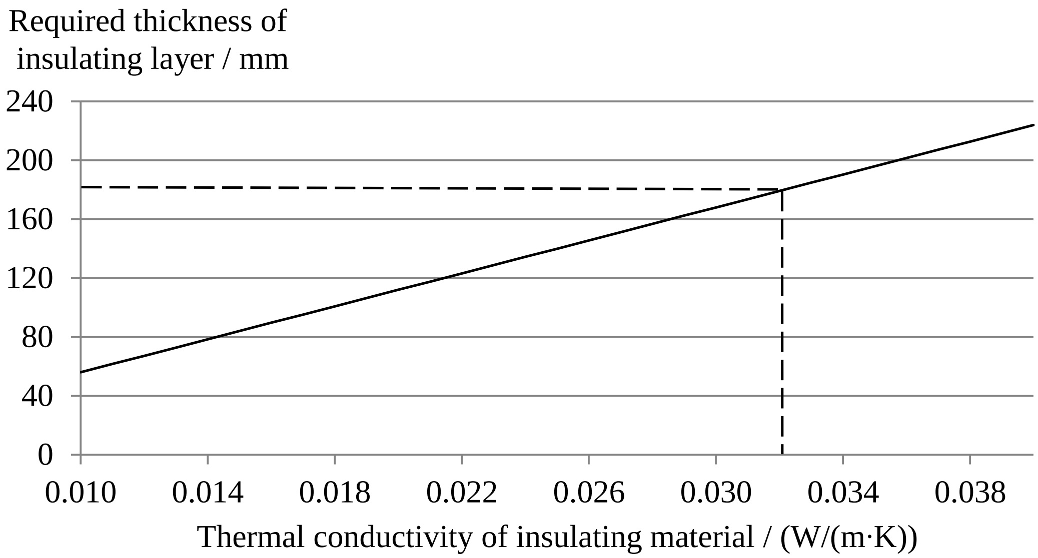

Figure 35: Insulation thickness as a function of conductivity, for the required thermal resistance. The maximum thickness of the insulation is 180 mm and is marked in the figure.

It can be observed in Figure 35, that in order to have a thermal resistance of 5.56 (m^2·K)/W well performing insulation materials are required. Moreover, if the maximum insulation thickness (180 mm) is utilized in the new wall layer part, an insulation material with a conductivity of 0.032 W/(m·K) can be used.

This was considered as the most feasible alternative since such insulation material features a thermal resistance corresponding to a well performing mineral wool thought to be commonly available in the market. Moreover, this thickness enables the largest space for implementing ventilation ducts. Therefore, further calculations in regards of the external wall are based on an insulation thickness of 180 mm with a conductivity of 0.032 W/(m·K).

5.2 Active measures

5.2.1 Integrated ventilation ducts

5.2.1.1 Ductwork placement and paths

The most suitable path for the ductwork in order to reach the living- and bed rooms of each apartment, as considered in this analysis, is presented in Figure 36 to Figure 38 for the façades and gables respectively. Large arrows denote main paths and smaller arrows denote individual paths.

Figure 36: Façade towards South-east.

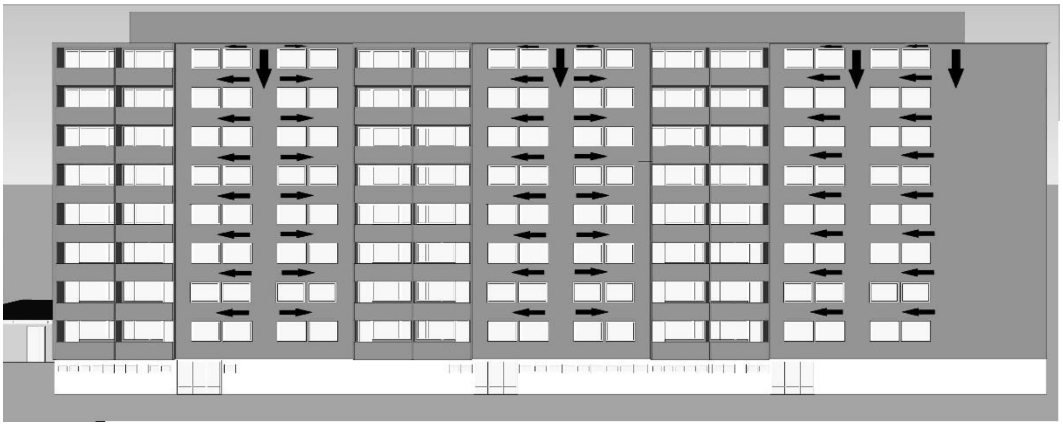

Figure 37: Façade towards North-west.

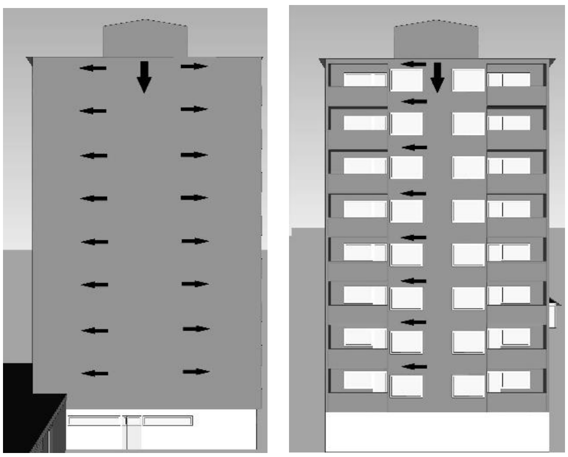

Figure 38: Gabel towards north-east (left) and south-west (right).

It can be observed that the chosen path is generally between the windows with the exceptions for the north gable and the unobstructed parts of the east and west façade. The width between the windows, on the considered suitable main path, was measured to 1.8 m on both the east and west façades and on the south gable. The ducts were sized to fit this main path. Moreover, the determined duct sizes for the main path were used consequently for the whole building in order to limit the variation of duct sizes.

5.2.1.2 Ventilation flows, ducts and routing

A description of the apartment sizes as well as the required air flow is presented in Table 25.

Table 25: Description of apartment sizes and corresponding requirement of supply air flow.

Apartment/ label	A	B	C	D	E	F	G	H	I	J	K	L	M
Area / m²	67	52	68	53	75	53	67	54	68	52	67	53	70
Req. air flow / (l/s)	23	18	24	19	26	19	23	19	24	18	24	19	25

The lager apartments require approximately 24 l/s respectively 19 l/s for the smaller. Therefore, only two duct sizes were considered. The floor plan of the case study building is presented in Figure 39 where each apartment and placement of supply air terminals are identified as well as the ducts for the supply air. Note that the floor plan at the bottom is a continuation of the floor plan above.

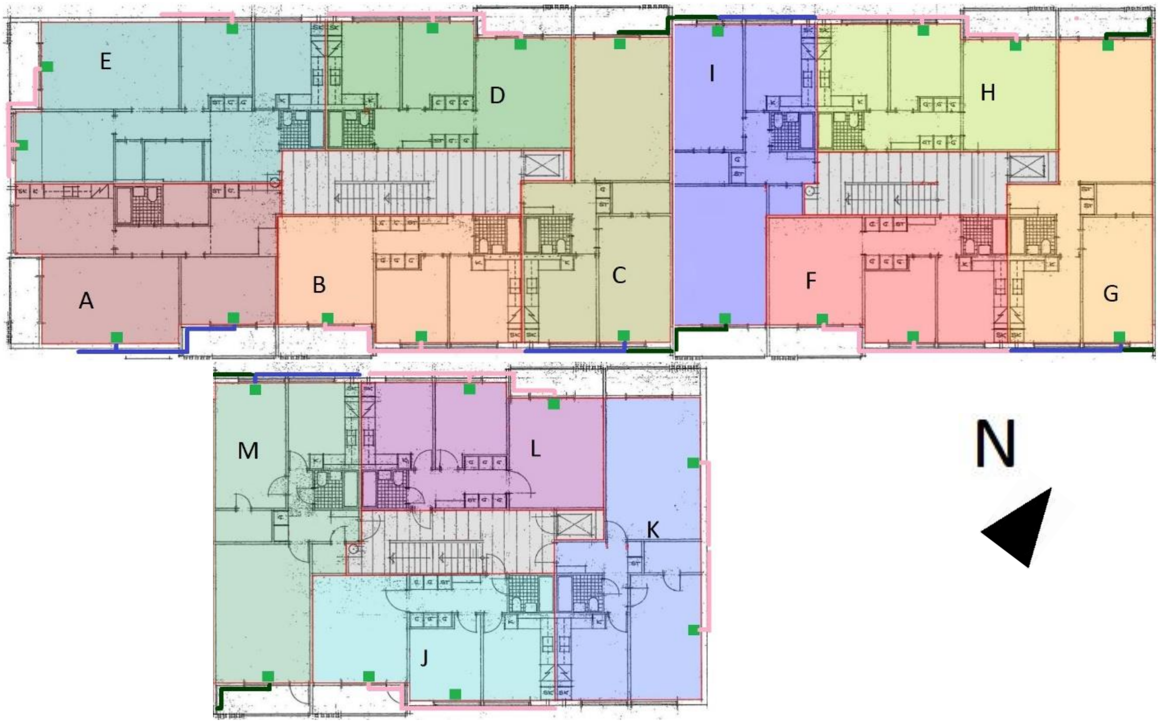

Figure 39: Floorplan of the case study building with marked apartments and suggested placement of supply air diffusers (light green squares). Pink lines represent supply air ducts for smaller apartments and blue lines represent supply air ducts to larger apartments. Dark green lines represents a duct which supplies more than one apartment .

It can be noticed in Figure 39, that in general, with the exception of apartment A and K, it was achievable to place the supply air terminals adjacent to the windows. Due to space restraints and the goal to have as little ductwork as possible, the routing only enabled supply air diffusers to be placed in the exterior walls not adjacent to the windows for apartment A and K. Since apartments C, I, G and M cut through the building, to avoid indoor ductwork, the duct supplying apartment C was required to supply the living room in apartment I. Also, ducts for apartment G were required to supply the living room in apartment M.

From the available 1.8 m of the main path a safety margin was set to 10 cm, which resulted in a useable width of 1.7 m for ductwork. Moreover, the main path was required to contain 14 ducts (seven stories, two apartments per storey, one duct each), the apartments on the top story did not have to use the main path. An illustration of one of the main paths with ducts is presented in Figure 40, pink ducts represent ducts for the required airflow of 19 l/s respectively blue for an airflow of 24 l/s. Further, red squares represent suggested placement of inlet to supply air terminals. With 14 ducts and a width of 1.7 m the maximum size for each duct was calculated to 120 mm, if equally large and barely any space in between. However, since two different air flows were considered, the required width of the ducts was different. Moreover, as earlier mentioned, the total width in between the windows was used as much as possible, in order to reduce the height of the duct between the existing wall and the new exterior façade and therefore have more space for insulation. Additionally, the same height for the two duct sizes was used in order to fit the same amount of insulation between the duct and outermost layer of the façade avoiding an uneven distribution of insulation. The suggested duct sizes, used for further analysis, are presented in Table 26.

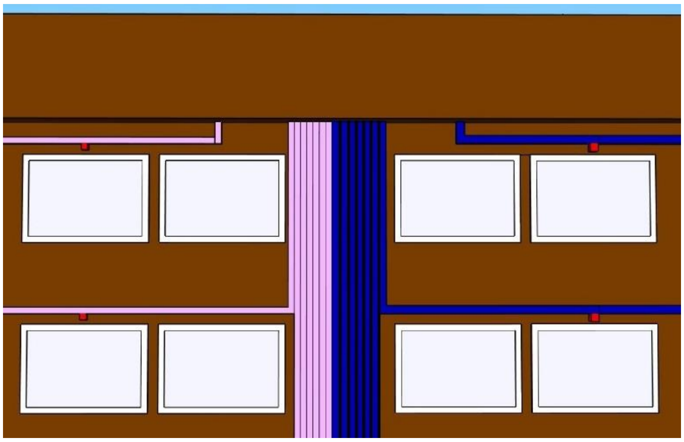

Figure 40: Ducts in one of the main paths, top two stories. Observe that the top apartments do not use the main path.

Table 26: Suggested dimensions of supply air ducts.

Dim. air flow / (l/s)	Width / mm	Height / mm
19	110	80
24	130	80

It can be observed in Figure 40 that the main path at the top has 14 ducts together with no space in between. Moreover, for each floor covered by the main path the duct quantity is reduced which also can be seen, in the Figure 40. A summary of the total lengths and duct compositions for the façade is presented in Appendix A.

Two alternatives were considered regarding the duct routing, path alternative one and path alternative two. In Figure 38 and Figure 39 the duct routing is presented for path one, respectively path two, both figures illustrating the South-east façade.

Figure 41: South-east façade, path alternative one.

Figure 42: South-east façade, path alternative two.

The routing for the North-west façade as well as for the gables is presented in Appendix B, for both path alternatives.

Initially, both alternatives were considered applicable, however, important constraints were encountered regarding path two. In order for the ductwork to reach all main paths for the first four stories, from the AHU at the ground floor, the ducts have to be routed along the façade on the ground floor or indoors. Due to the ground floor both having windows and entrances, routing along the façade was not considered an option. Moreover, routing the ductwork indoors at the ground level was also not considered an option due to space limitations. Additionally, the heat from the exhaust air from the first four stories would have to be transferred actively from the roof down to the ground floor AHU to enable heat recovery, since the exhaust air ducts are routed to the roof. Because of the above stated issues path alternative two was not further analysed in this study.

5.2.1.3 Pressure losses in the ductwork

A summary of the path with highest pressure drop (critical path) for each apartment is presented in Table 27. The calculation of pressure drop for the apartment with highest pressure drop is presented in Appendix C.

Table 27: Pressure losses in the critical path for each apartment.

Duct to apartment/ label	A	B	C&I	D	E	F	G&M	H	J	K	L
Floor	2	2	2	2	2	2	2	2	2	2	2
Pressure drop AHU – Façade / Pa	38.7	21.7	21.7	29.9	36.9	13.8	27.2	7.3	35.9	36.3	27.2
Pressure drop Façade / Pa	47.7	39.6	53.3	39.9	40.8	39.6	52.0	40.0	40.2	37.5	40.1
Total pressure drop / Pa	86.4	61.3	75.0	69.9	77.7	53.4	79.2	47.3	76.1	73.8	67.3

It can be observed that apartment type A on the second floor has the highest pressure drop, and is therefore used for further SFP calculations regarding the supply air pressure drop. Furthermore, the results show that the pressure drops in the façade does not vary significantly between the apartments, the variation lies in the pressure drops from the AHU to the façade.

5.2.2 Specific fan power

The results of the sensitivity study regarding the SFP and annual energy use of the property used electricity for the ventilation system are presented in Figure 43 and Figure 44.

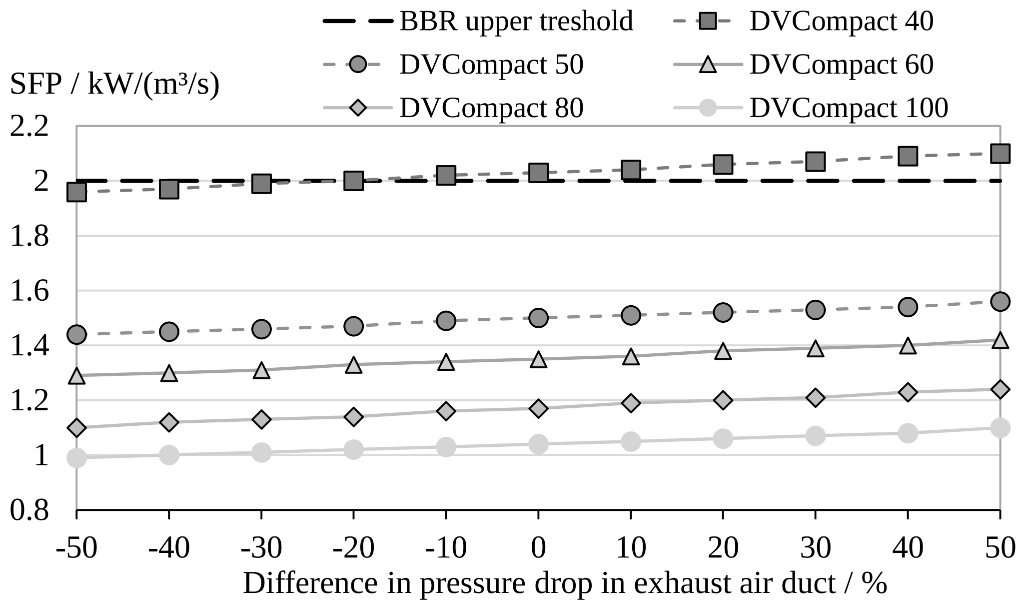

Figure 43: Result of the SFP calculations for various AHU sizes as well as for a variation in the unknown pressure drop of the existing exhaust ducts according to the estimated 86.4 Pa. Note that the vertical axis is broken.

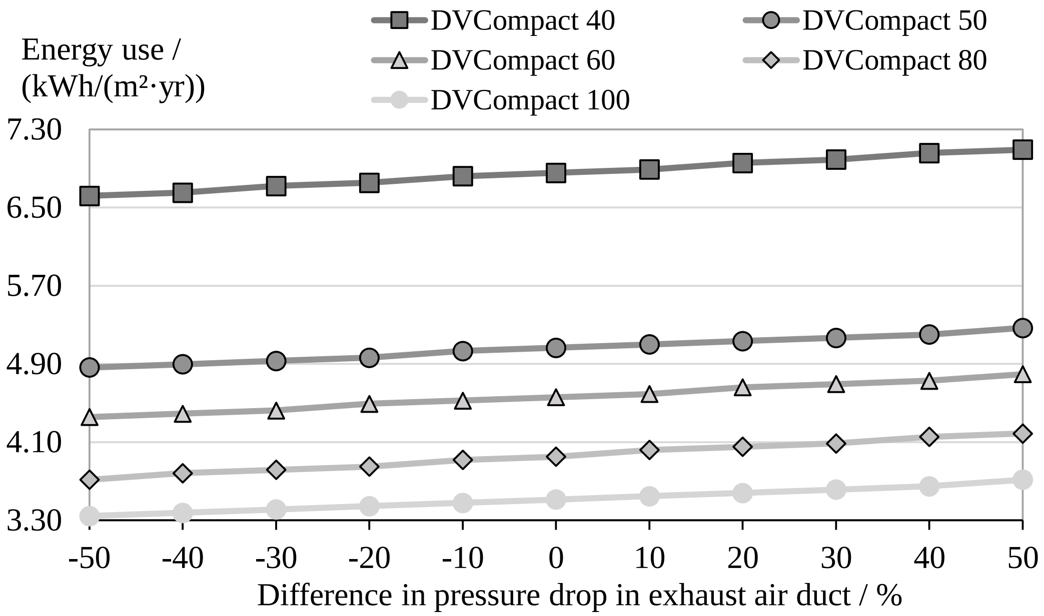

Figure 44: Result of the annual energy use calculations for various AHU sizes as well as for a variation in the unknown pressure drop of the existing exhaust ducts according to the estimated 86.4 Pa. Note that the vertical axis is broken.

It can be observed that the SFP lays in the interval from 0.99 to 2.1 kW/(m³/s) depending on what AHU size is used as well as the real pressure drop in the exhaust air ductwork. The annual energy use for ventilating the building lays in the interval from 3.34 to 7.09 kWh/(m²·yr). The average SFP of the investigated AHUs (under 2 kW/(m³/s)) was calculated to be 1.28 kW/(m^3/s). Moreover, no significant difference was observed for the SFP whether the pressure drop for the exhaust air duct was 50 % lower or 50 % higher than the one assumed and equal to the pressure drop in the supply air duct. Therefore, the AHU with closest SFP to 1.28 kW/(m^3/s) and with 0 % in difference in pressure drop for the exhaust air duct was chosen as the AHU for alternative one (multi-active façade solution), which was Compact 60 and has a SFP of 1.35 kW/(m^3/s).

5.2.3 Supply air and energy losses

The result of the sensitivity analysis, which was based on the placement of a single duct expressed as distance from the outermost façade layer is presented in Table 28 and
Table 29. The case where the insulation facing the ambient air has a conductivity of 0.032 W/(m·K) refers to only having one type of insulation in the multi-active façade element. Furthermore, the case where the insulation facing the ambient air has a conductivity of 0.021 W/(m·K) implies that two insulation materials are used in the façade element.

Table 28: Heat loss factors for various duct placements based on the ambient air facing insulation conductivity 0.032 W/(m·K). Values to left-hand side represent a placement close to the exterior and values to the right-hand side represent a placement closer to the existing wall.

Distance from outermost part / mm	0	10	20	30	40	50	60	70	80	90	100
Heat loss in the supply air / (W/(m·K))	3.263	0.440	0.254	0.181	0.140	0.114	0.096	0.082	0.072	**0.066**	0.068

Table 29: Heat loss factors for various duct placements based on the ambient air facing insulation conductivity 0.021W/(m·K). Values to left-hand side represent a placement close to the exterior and values to the right-hand side represent a placement closer to the existing wall.

Distance from outermost part / mm	0	10	20	30	40	50	60	70	80	90	100
Heat loss in the supply air / (W/(m·K))	3.262	0.326	0.190	0.137	0.107	0.087	0.073	0.062	0.055	**0.050**	0.054

It can be observed that the lowest heat losses take place, in each case independently on the conductivity, when placing the ducts 90 mm from the outermost part of the insulation. Furthermore, the heat losses are reduced when using insulation with lower conductivity. It can also be observed that the heat losses in the case with the conductivity of 0.021 W/(m·K) are approximately 25 % lower in comparison to placing the ducts in insulation like the surrounding wall (0.032 W/(m·K)).

Since the duct in the multi-active wall and roof does not consist of only one single duct, the respective heat loss factor were calculated in the interval from one to seven ducts placed next to each other as presented in Table 30. This was carried out for the duct dimension 130x80 mm since it has a larger area in the multi-active wall and roof. Furthermore, this applies for apartment types; C, I, G and M which are located on the second floor, see Appendix A.

Moreover, the heat loss factor is not constant through the duct path due to a constantly reducing number of ducts located next to each other. The weighted heat loss factors and the summary of them are presented in Table 30.

Table 30: Summary of duct composition lengths and heat loss factors for apartment types C, I, G and M, located on the second floor (total duct length 27 m).

Insulation conductivity λ / (W/(m·K))				**0.021**		**0.032**	
Duct quantity / pcs	Duct dimensions / mm	Duct composition length / m	Ratio of total lenght	Heat losses in duct / (W/(m·K))	Weighted heat loss factor / (W/(m·K))	Heat losses in duct / (W/(m·K))	Weighted heat loss factor / (W/(m·K))
1	130x80	11	0.407	0.051	0.021	0.072	0.029
2	130x80	2.6	0.096	0.066	0.006	0.108	0.010
3	130x80	2.6	0.096	0.080	0.008	0.143	0.014
4	130x80	2.6	0.096	0.093	0.009	0.176	0.017
5	130x80	2.6	0.096	0.105	0.010	0.210	0.020
6	130x80	2.6	0.096	0.118	0.011	0.243	0.023
7	130x80	3	0.111	0.130	0.014	0.276	0.031
Summed weighted heat loss factor / (W/(m·K))					**0.079**		**0.145**

It can be observed that the greatest part of the duct path is a single duct, for the ducts leading to the second floor (apartment types C, I, G, M). It can also be observed that the weighted heat loss for the lower conductivity are approximately half of the greater conductivity.

The variation in the supply air temperature, during the entire year, for the diffusers on the second floor, with the longest path in the multi-active wall- and roof elements (apartment types C, I, G, M) is presented in Figure 45 and Figure 46. This applies for the duct size 130 x 80 mm since they have a larger surface facing the ambient air.

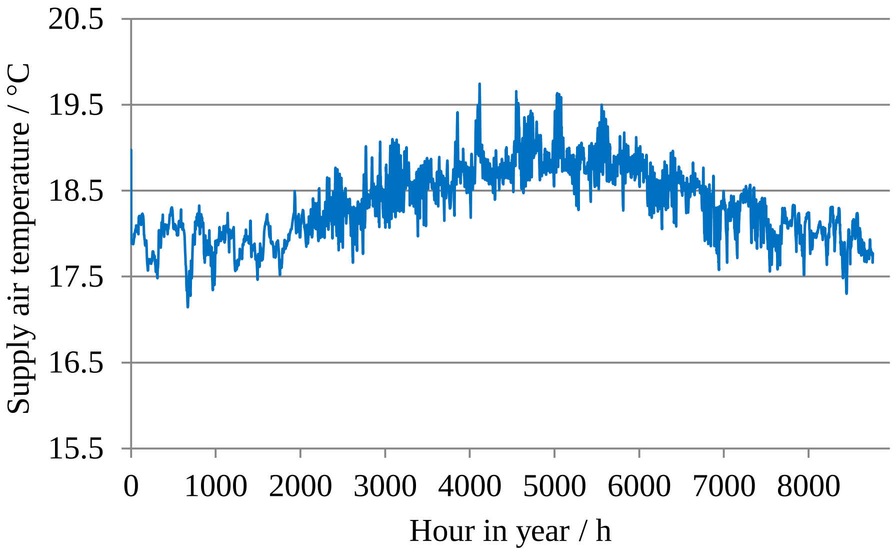

Figure 45: Variation in the supply air temperature for the diffusers on the second floor (apartment types C, I, G, M), based on enclosing insulation conductivity of 0.021 W/(m·K) which corresponds to PIR. The supply air temperature from the AHU in the attic does not drop below 19° C at any time. The vertical axis is broken.

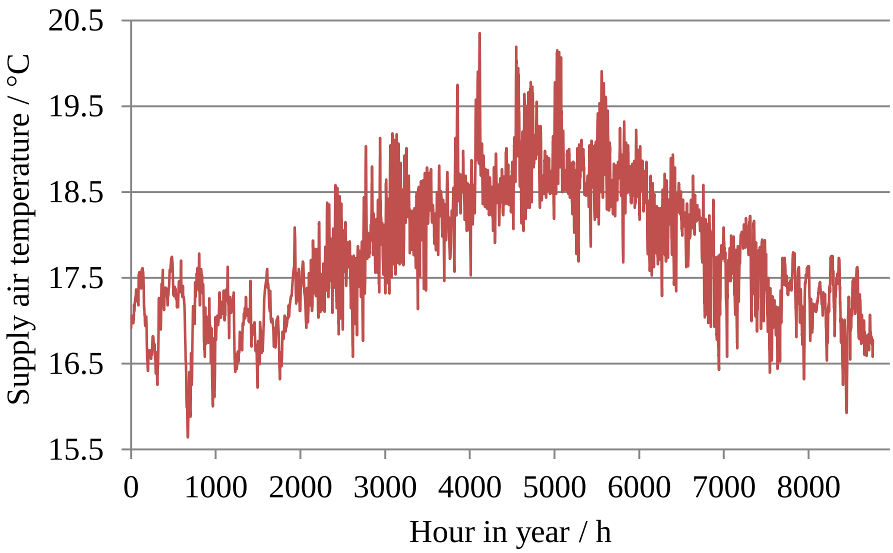

Figure 46: Variation in the supply air temperature for the diffusers on the second floor (apartment types C, I, G, M), based on enclosing insulation conductivity of 0.032 W/(m·K) which corresponds to high performing mineral wool. The supply air temperature from the AHU in the attic does not drop below 19° C at any time. The vertical axis is broken.

It can be observed that the supply air temperature never drops below; 17 °C for the PIR insulation and 15 °C for the high performing mineral wool, which occurs when the outdoor temperature is the lowest.

The summed annual energy losses, in the path between the AHU and respectively supply air diffuser is presented in Table 31, when routing the ventilation ducts, optimally placed through the façade.

Table 31: Annual energy losses from the entire supply air ductwork when routing the ventilation ducts through the façade when routing the ventilation ducts, optimally placed through the facade.

Conductivity λ / (W/(m·K))	Corresponding to	Energy loss / (kWh/yr)	Energy loss / (kWh/(m²·yr))
0.032	High performing mineral wool	1690	0.183
0.021	Polyisocyanurate (PIR)	771	0.083

It can be observed that the annual energy losses are below 0.2 kWh/(m²·yr) in both cases, when divided by the heated floor area which is 9235 m². Furthermore, it was considered within this study, that the difference in energy loss between having mineral wool or PIR enclosing the ducts was minor. Therefore, only using high performing mineral wool in the wall was considered for alternative one (multi-active façade solution).

5.2.4 Photovoltaics

The result of the annual solar irradiation analysis of the case study building envelope is presented in Figure 47.

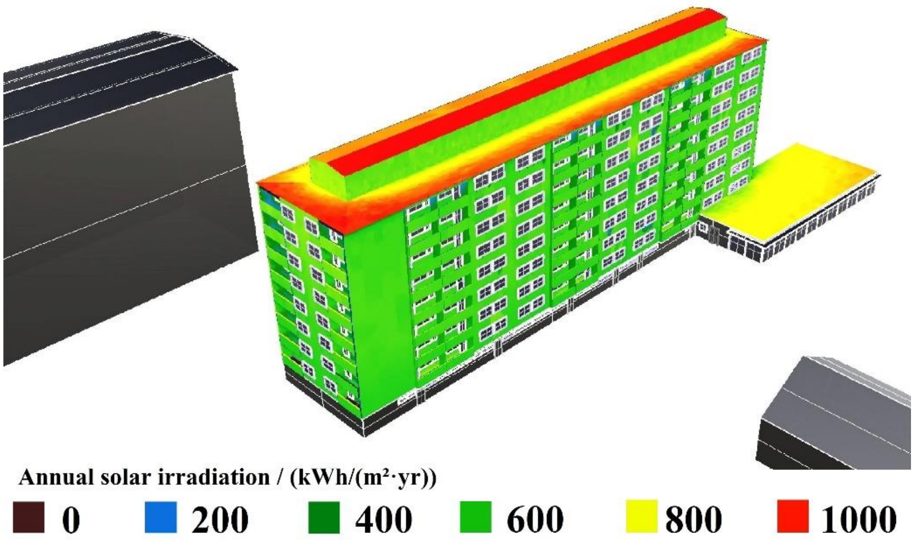

Figure 47: Annual solar irradiation analysis on case study building envelope.

It can be observed that the largest amount of solar irradiation is received on the higher roof surface (roof on attic), approximately 1000 kWh/(m²·yr) which is inclined 10 ° from horizontal with an azimuth of 143 °(37 ° East of South). Moreover, it can be observed that the vertical surfaces, where façade integrated PV is considered, receive approximately 600 kWh/(m²·yr), which means a reduction of 40% in solar radiation potential.

The result of the quantification of available surfaces, theire azimuths and tilts are presented in Table 32.

Table 32: Available surfaces for PV placements and their properties.

Available surface	Orientation towards	Azimuth / °	Available surface / m²
Roof	South-east	143	177
Roof	North-west	323	177
Facade	South-east	143	923
Facade	South-west	233	235

It can be observed in Table 32 that available surfaces on the roof are limited. However, there is significantly more available surface on the façade to integrate PV-panels. The result of the PV placement analysis, for a 1 kW_p system is presented in Figure 48.

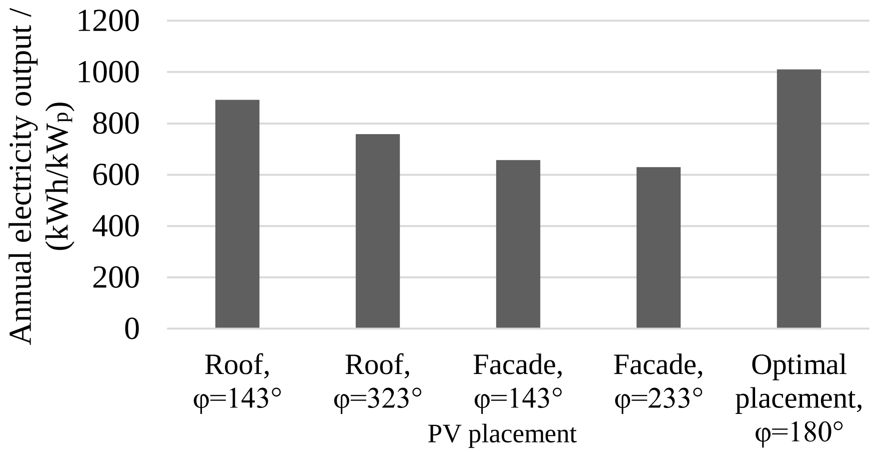

Figure 48: Results of the analysis of annual electricity output for the available surfaces as well as for the optimal placement, which is directly towards south and inclined 35 ° from horizontal. 180 ° corresponds to South and 0 ° corresponds to East.

It can be observed that the highest electricity output, on annual basis, is obtained from the roof mounted PV modules (inclined 10°) with the azimuth of 143°. For façade integrated modules (inclined 90°), the highest output is also obtained from PV modules with the azimuth 143°. This means that in eventual combinations, surfaces with the azimuth 143° should firstly be fully covered with PV before covering the available surfaces with other azimuths.

The property used electricity profiles for the various alternatives studied are presented in Figure 49. The electricity profiles are also presented separately in Appendix D.

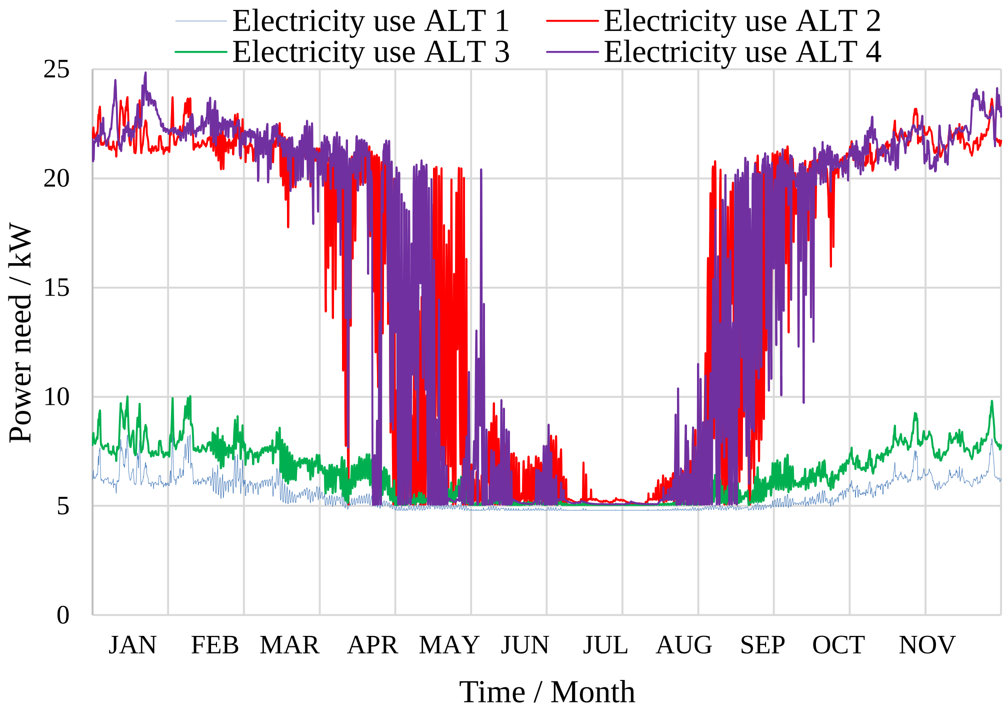

Figure 49: Compilation of the hourly power need for property used electricity for the alternatives studied.

It can be observed that the profile of the power need varies between the studied alternatives. Alternative one has the lowest power need for property used electricity, which includes, as earlier described, power for the AHU and hydronic pumps. Moreover, it can be observed that alternative four possesses the highest power need for property used electricity. In this case the power need for exhaust air fan, heat pump and hydronic pumps is included. Furthermore, the lowest required power need for the property used electricity (approximately 5 to 6 kW), occurs during the summer, for all the alternatives.

The comparison of the electricity profiles with the PV output for systems that do not overproduce substantially is presented in Figure 50 and Figure 51. In Figure 50 the electricity output from a 6.8 kW_p roof mounted PV system in comparison to the electricity profiles is illustrated. Further, in Figure 51 the electricity output from a 7.86 kW_p façade integrated PV system in comparison to the electricity profiles is illustrated.

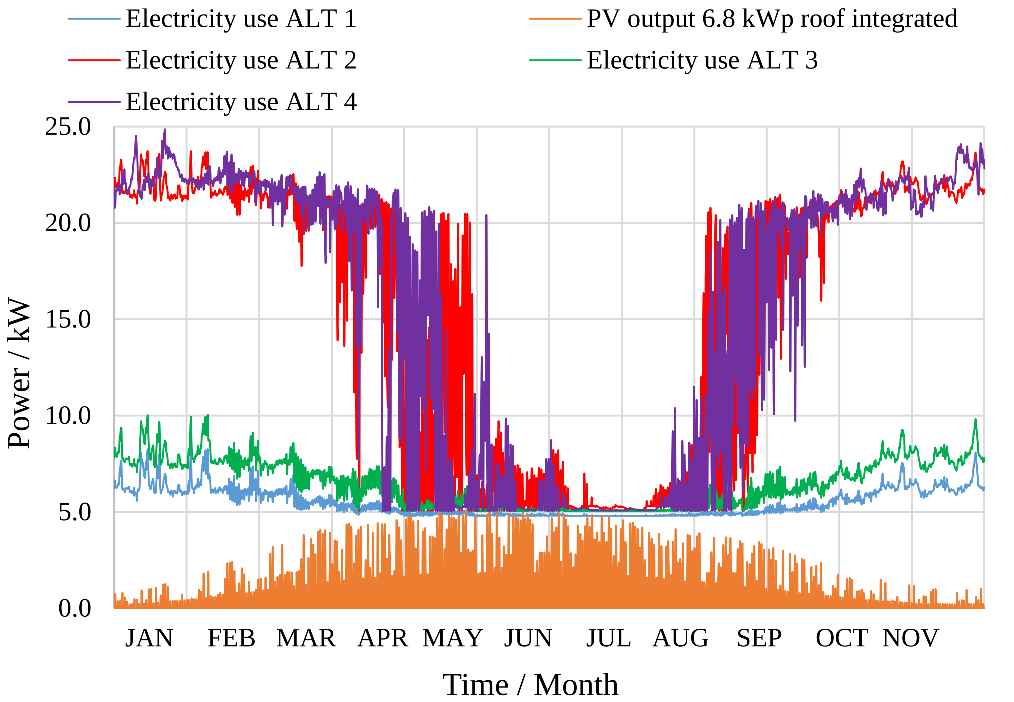

Figure 50: Hourly electricity use for the alternatives studied and the PV output from a 6.8 kWp (41.6 m²) roof integrated PV installation.

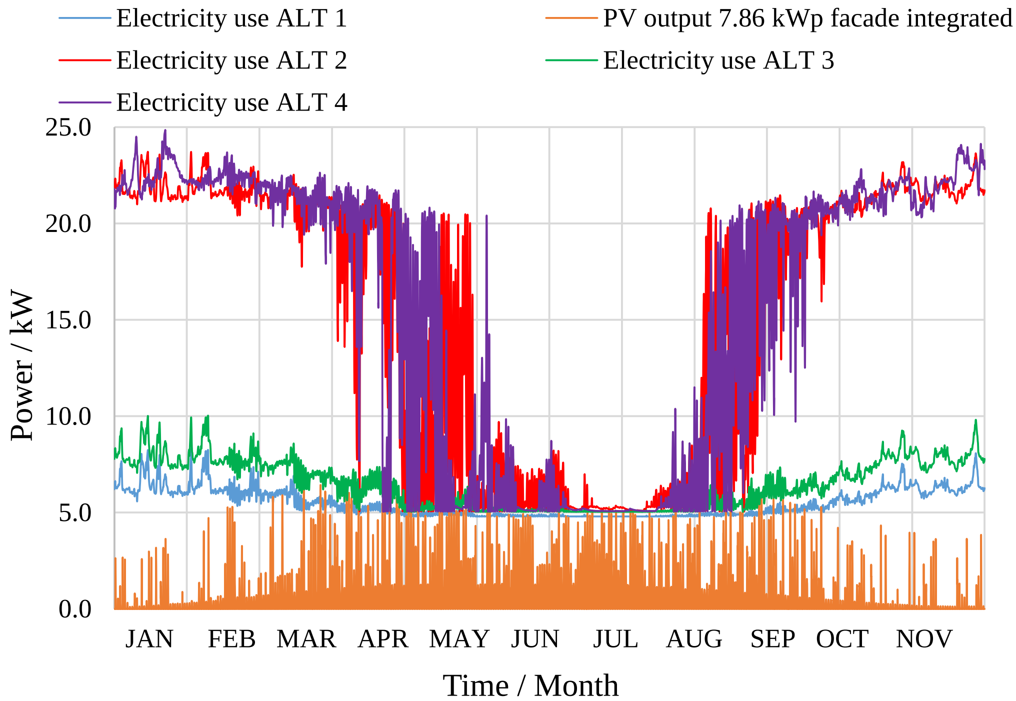

Figure 51: Hourly electricity use for the alternatives studied and the PV output from a 7.86 kWp (48 m²) facade integrated PV installation.

It can be observed that the peak output from the PV system is approximately the same as the electricity profiles for the four alternatives when the PV output is the greatest. The peak output occurs, for the façade integrated PV during spring and autumn due to its vertical position. Furthermore, for the roof mounted the peak occurs during the summer.
The results of the studied PV systems indicated that dimensioning a system with the aim to cover the yearly electricity demand would require a fuse size larger than 100 A, which in turn results in that tax reduction is not applicable. Therefore, it was considered not reasonable to suggest a PV-system dimensioned for covering the yearly property electricity need due to the investment being very unprofitable. Therefore, systems dimensioned to avoid overproduction were found to be the most appropriate and the only ones showed in the following LCC evaluation. The LCC and LCP results for the examined PV-system scenarios are presented in Table 33. Each examined scenario for all the alternatives is presented in Appendix E.

Table 33: Results of the LCC, LCP and break even time calculations for the systems that avoid overproduction.

Alternative	**PV system for all alternatives**			
PV placement	**Roof**		**Facade**	
Investment subsidies received (YES/NO)	YES	NO	YES	NO
Tax reduction included → cover electricity demand (YES/NO)	NO, no overproduction	NO, no overproduction	NO, no overproduction	NO, no overproduction
System size / kWp	6.8	6.8	7.9	7.9
Module area (15 % efficiency) / m²	41.6	41.6	48	48
Initial investment cost / SEK	82 851	118 359	76 478	117 449
LCC / SEK	1 096 099	1 131 606	1 118 286	1 159 257
LCP / SEK	19 743	- 15 765	- 2 445	- 43 415
Break even time / years	24	>life cycle	>life cycle	>life cycle

It can be observed that the only system that breaks even during the life cycle (after 24 years) is the roof mounted case where investment subsidies are received and where tax reduction is applicable but not used since no overproduction occurs. This alternative represents a reduction of the property used electricity by 0.67 kWh/(m^2·yr) on a yearly basis and generates a LCP of about 19 700 SEK during its life cycle. Furthermore, in no case the façade integrated systems were found to be profitable, independent of inclusion of investment subsidies and/or applicable tax reduction. However, when the investment subsidy is granted, the LCP result for the façade PV system is close to zero which means that the energy savings will approximately cover the investment.

5.3 Specific energy use

The results of the energy simulations, for the various studied alternatives are presented in Figure 52. The specific energy use for each alternative and category, on monthly basis is presented in Appendix F.

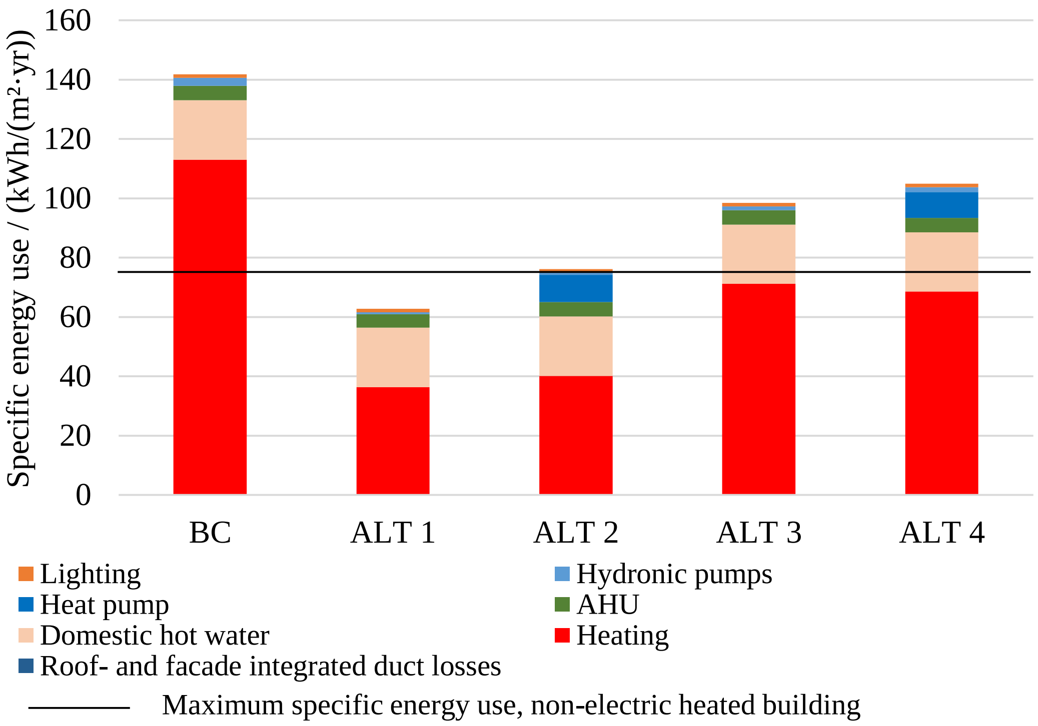

Figure 52: Results of the specific energy use for the base case and studied alternatives.

In Figure 52, the solid line represents the maximum allowed specific energy use by the building code for buildings heated in other ways than with electricity in climate zone four. It can be observed that alternative one (supply- and exhaust air ventilation with heat recovery, where supply air ducts are routed through the façade elements) has the lowest specific energy use (62.8 kWh/(m²·yr)) which is 55 % lower than the base case. Furthermore, alternative one is the only alternative complying with the building code regulation for new buildings while alternative two is very close.

The SCOP was calculated for alternative two and alternative four, which are alternatives including an exhaust air heat pump. The SCOP was calculated to 3.37 for alternative two and 3.27 for alternative four. The observed difference in SCOP is a result of that alternative two is an insulated building with slightly higher exhaust air temperatures which increases the effectiveness of the heat pump.

5.4 Economic analysis

The results of the LCC analysis, for the base case (anyway renovation) as well as for the studied alternatives is presented in Figure 53 to Figure 56. The accumulated LCC as a function of time for the scenario when the windows are replaced to new ones, fulfilling the BBR requirement of heat loss factor of maximum 1.2 W/(m²·K) is presented in Figure 53. In Figure 54, the LCP and initial cost for the studied alternatives are presented.

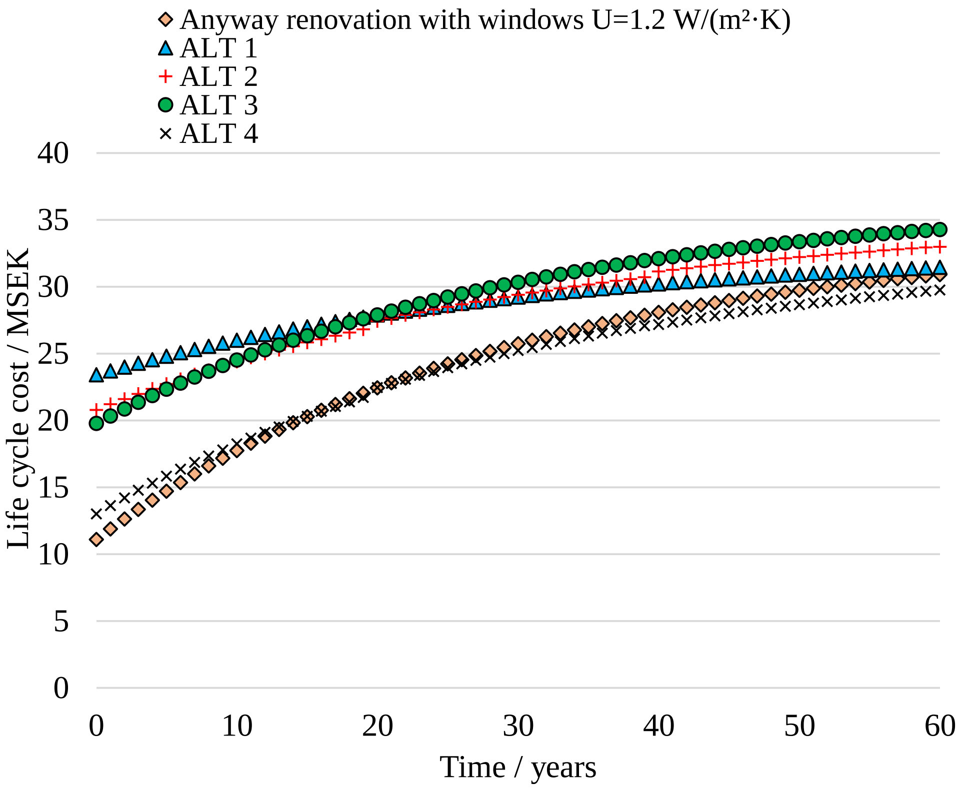

Figure 53: Accumulated LCC as a function of time for the scenario when the windows are replaced to new ones, fulfilling the BBR requirement of heat loss factor of maximum 1.2 W/(m²·K).

It can be observed that the initial investment the fourth alternative entail (only installing a heat pump) reaches the economical breakeven point after approximately 19 years, in comparison to an anyway renovation based on windows with the heat loss factor 1.2 W/(m²·K)).

Further, it can be observed that none of the other three alternatives reach their economical breakeven point during the life cycle of 60 years, in comparison to an anyway renovation based on windows with the heat loss factor of 1.2 W/(m²·K). However, if only an extensive renovation is considered by the property owner (anyway renovation is considered insufficient), in that case alternative one shows the highest cost effectiveness of the three types of extensive renovation (alternative one, two and three).

Furthermore, after 60 years the life cycle cost of the first alternative and the anyway renovation is approximately the same. However, the indoor thermal comfort during those 60 years is very different. The alternative which only implies an improvement of the building envelope has the highest life cycle cost.

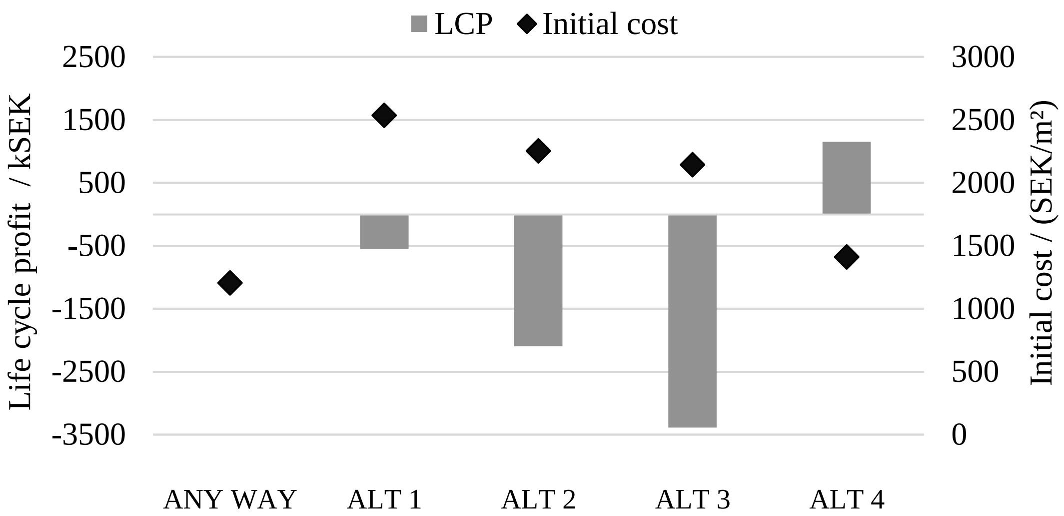

Figure 54: LCP (left y-axis) and initial costs (right y-axis) for the anyway renovation and studied alternatives, based on that the anyway renovation includes windows with the heat loss factor of 1.2 W/(m²·K).

It can be observed that the only positive LCP is generated by the fourth alternative, in the case when the anyway renovation is based on windows with the heat loss factor 1.2 W/(m²·K). The first three alternatives result in a loss from a LCP perspective.

The accumulated life cycle cost as a function of time for the scenario when replacing the windows to new ones, with identical thermal properties (U=2.4 W/(m²·K)) as the present ones is presented in Figure 55. In Figure 56, the LCP and initial cost for the studied alternatives are presented for this scenario as well.

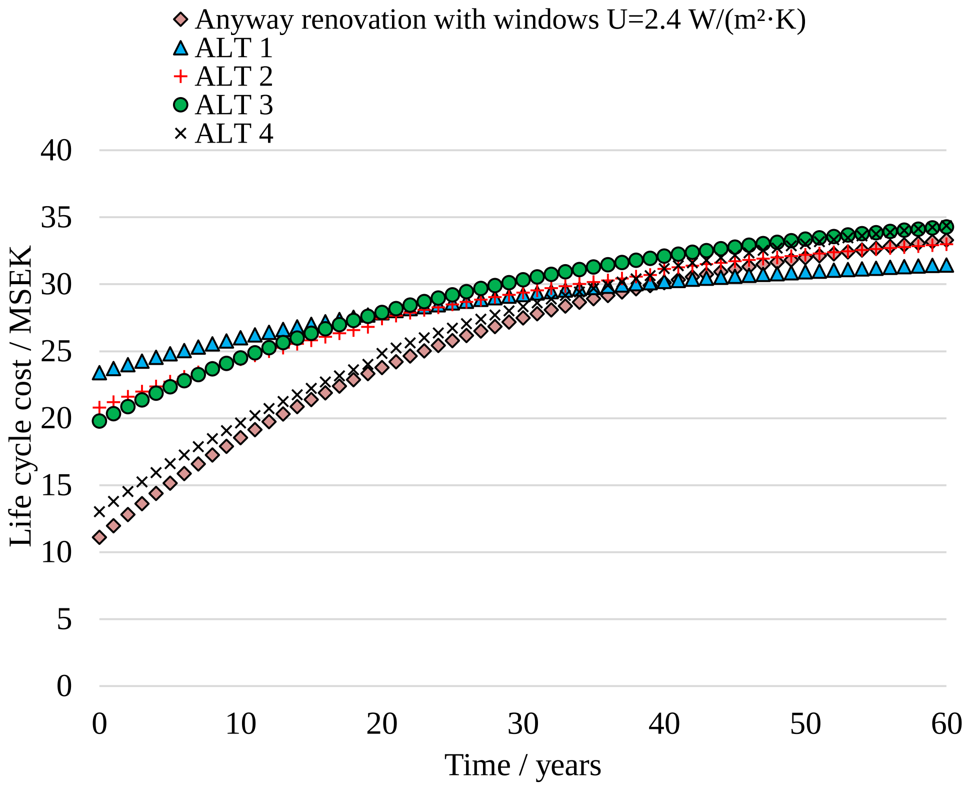

Figure 55: Accumulated LCC as a function of time for the scenario when replacing the windows to new ones, with identical thermal properties as the present

In this case, alternative one reaches the economical breakeven point first after approximately 40 years. Furthermore, it can be observed that alternative two (insulation of the building to reach U_m = 0.4 W/(m²·K) and installing an EAHP) reaches its breakeven point firstly after approximately 53 years.

In this case the first alternative showed the highest cost effectiveness by obtaining the lowest LCC. However, it can be observed that the first alternative has an investment cost, twice as high as for the anyway renovation. Furthermore, if comparing the three extensive renovation alternatives (alternative one, two and three) it can be observed that the initial cost for the first alternative is only slightly higher but has the highest cost-effectiveness and probably also the best thermal comfort.

Moreover, it can be observed that the third alternative (only additional insulating the building envelope, reaching U_m = 0.4 W/(m²·K)) does not reach the breakeven point during the life cycle of 60 years. Further, the fourth alternative (only installing a heat pump) does not reach the economical breakeven point in the life cycle which is a result of a high periodic maintenance cost for the heat pump.

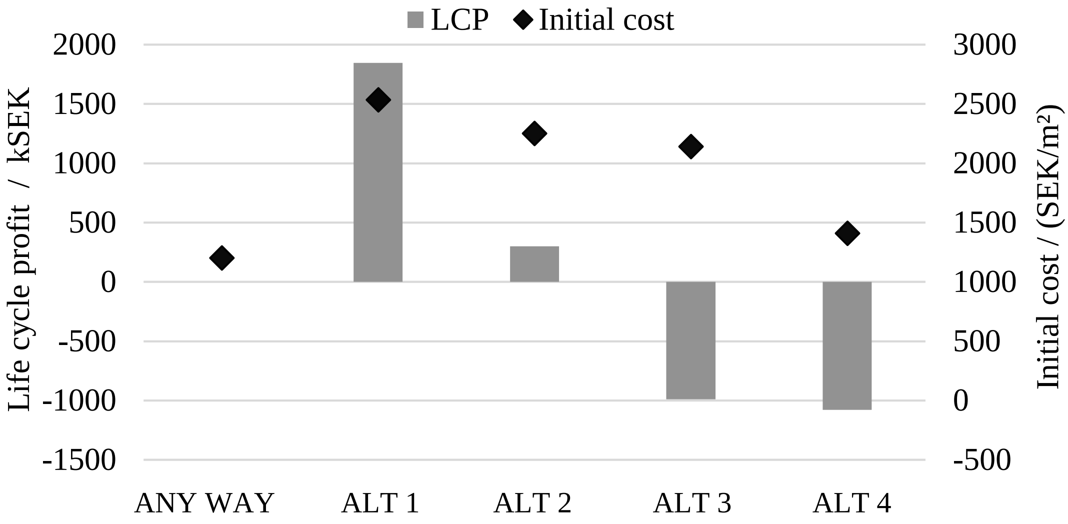

Figure 56: LCP (left y-axis) and initial costs (right y-axis) for the anyway renovation and studied alternatives, based on that the anyway renovation includes windows with the same heat loss factor as the current 2.4 W/(m²·K).

The highest LCP is obtained by the first alternative (supply and return air with heat recovery, ducts routed through the façade elements reaching U_m = 0.4 W/(m²·K)). However, this alternative features the greatest initial cost. Further, the second alternative (installing a heat pump and insulating the building envelope reaching U_m = 0.4 W/(m²·K)) also results in a positive LCP, although small. Furthermore, it can be observed that the initial cost for the second alternative is slightly lower than the first. Furthermore, it was observed that the initial cost for alternative one is approximately 2500 SEK/m², alternatives two and three have similar initial costs but vary in their LCP. The fourth alternative has the lowest initial cost of the developed alternatives and also the lowest LCP.

6 Discussion

This study started with a literature review based on a qualitative evaluation. This means that the technologies found to be relevant for the Swedish context in this study should not be seen as definite choices. However, the conducted evaluation consisted of thought to be relevant criteria for the Swedish context, developed in this study and therefore, the evaluation should be viewed as an indicator of suitable choices. This also means that the excluded active technologies should not be viewed as entirely irrelevant since the renovation requirement may vary between various buildings dating from the million programme. Moreover, the importance of the criteria may also change depending on priorities from the property owner, which may have a large impact on the outcome of the evaluation. Furthermore, there are most likely other criteria which were not identified within this study that may play a crucial role. Moreover, it was found, in the early stage of the study that decentralized systems are not to be recommended in the Swedish context due to the expected difficulties for maintaining and repairing as well as the additional costs they result in. This shaped the investigation quite much from the beginning. It should also be mentioned that the evaluation focused on solutions common on the market. Hence they can be more competitive regarding costs but they are also perhaps less innovative.

6.1 Passive measures

To reach a maximum average heat transfer coefficient U_m of 0.4 W/(m^2·K) significant improvements of the building envelope were required. Since the windows represent a dominating part of the envelope area their impact on the transmission losses was still the highest after introducing windows with a high thermal performance. Furthermore, by only improving the walls the building would not reach the U_m requirement. Therefore, it is important to point out that if a multi-active façade is to be used, it would for sure require other improvements of the building envelope if the aim is to reach the U_m requirement. Although the foundation represents approximately 15 % of the building envelope no improvements were suggested. This is due to the fact that the transmissions losses were low compared to the total losses as well as an assumption was made that it would be a rather complex undertaking to insulate the foundation beneath. However, insulating the foundation on top can be an option although it is not recommended due to the risk of moisture issues.

To have a higher accuracy when performing estimations of the transmissions losses, thermal bridges should be quantified individually and not by assuming a percentage of the total transmission losses. Since every building is unique thermal bridges should be viewed more in detail to achieve a more correct estimation. Moreover, it is reasonable that the impact of the thermal bridges increases in percentage when improving the building envelope since the total transmission losses are reduced.

It should be mentioned that the focus was put on using the total set thickness of the wall (maximum 500 mm), thus enabling an insulation material with a conductivity close to traditional mineral wool. However, if PIR or other high performing insulating materials would have been chosen instead, the wall thickness could have been reduced significantly although this would result in no space for any ventilation ducts. Furthermore, a maximum wall thickness of 500 mm was chosen to not introduce an obvious daylight reduction, however, this was only set to enable further calculations. It can be argued that, for example, 510 mm would not make a significant difference in terms of daylight, therefore, further studies should be made regarding what thickness is reasonable to have in total after the retrofitting.

6.2 Active measures

6.2.1 Ventilation

The aim with dimensioning the ventilation system was to estimate pressure drops to enable SFP calculations and to determine required duct sizes. However, no focus was put on investigating the velocity of the air before it reaches the supply air diffuser. It is therefore important to mention that when sizing the AHU after the highest pressure drop in the system, adjustments have to be made to all other paths with lower pressure drops to not have air with high velocity entering the apartments.

When sizing the ducts, it was favourable to have apartments with similar areas to limit the variation in required air flows and thus duct sizes. Moreover, if a large variation in duct sizes were required due to a large variety of demanded air flows between the apartments, it would most probably result in a more complex production and assembling of the multi-active façade.

It should be mentioned that by using rectangular ducts more material for the ducts is required, compared to circular ducts. This results in a higher cost, therefore it would be convenient to use circular ducts. However, it was found complex to model circular or close to circular ducts in HEAT2 due to limitations in the software.

To enable the ductwork to reach all apartments a main path was necessary. Having 14 ducts together in the main path without any insulation between the ducts, due to space limitations, will most probably result in noise dispersion between the apartments, therefore a suggestion for further studies is to look into this issue. Furthermore, practical aspects should also be considered like placement of façade material fixings. Additionally, fire safety measures should be considered when the ducts are installed next to each other. The suggested placement of supply air diffuser was above the windows, however, it could be advantageous to place the diffuser behind the radiators, beneath the windows to use some of the heat from the radiators to additionally heat the supply air. However, due to space limitations on the balconies this was not considered an option.

Since the building has apartments which cut through, some ducts were required to supply more than one apartment. In order to prevent fire gas spreading between the apartments a fire damper should be considered. A convenient place to install a fire damper could be where the duct passes the balcony, thus enabling easy maintenance if required.

Furthermore, it is important to mention that since the exhaust air ducts are reused, leakage through the ductwork most probably occur. This was not taken into consideration during the calculations, however, this would influence the total energy performance of the ventilation system and should be investigated for each building. It was also not considered that the existing exhaust air ducts might need renovation, which also should be investigated for each building.

No major difference in the results was observed for the SFP and annual energy use for the ventilation, for the case of supply and exhausts ventilation by wall- and roof integrated supply air ducts, depending on the pressure drop in the exhaust air duct. Moreover, the building code requirement of maximum SFP (2 kW/(m³/s)) is fulfilled in all cases except when using the AHU “DV Compact 40”. The reason for this is that this unit is undersized for the actual air flows. Therefore, the fans in the AHU will not be able to operate at their optimum efficiency range. Furthermore, this is also reflected on the annual energy use of the ventilation system.

The supply air temperature analysis was carried out in a way that it included the minor thermal bridge that occurs as a result of the insulating property deterioration of the external wall. Due to the temperature difference being minor between the indoor surface (21 °C) and the supply air duct (19 °C), the thermal bridge is considered minor. No method was found on how to separate this minor thermal bridge from the total heat flux. This is due to that the thermal bridge is defined between two temperatures. In this case there were three temperatures, indoor air temperature, ambient air temperature and supply air temperature in ducts.

The result of the sensitivity analysis, regarding the ducts placement in the prefabricated wall element indicated that a placement directly adjacent to the concrete increased the heat losses in the duct. This is because the concrete will conduct the heat, thus creating a larger thermal bridge. However, the difference is very low in comparison to placing the duct directly adjacent to concrete which might be better from a practical point of view.

Furthermore, the results also showed that the heat losses from the supply air ducts, located in the external walls were not as great as expected when distributed on the entire heated floor area since both are very small. The energy losses when enclosing the ducts with high performing mineral wool were approximately 25 % larger in comparison to the PIR. However, when distributing the energy losses with the entire heated floor area the difference was barely noticeable. The reason for the energy losses being relatively low is that they are separated from the outdoor climate as well as from the concrete (present outermost layer).

As earlier mentioned, the calculations were simplified to a weighted heat loss factor across the entire duct paths. This equals in higher power losses from the supply air to the ambient air than in reality due to that the temperature difference between the supply air and ambient air is continuously decreasing. This also means that the calculated supply air temperatures should most likely be slightly higher if the work process was not simplified with weighted heat loss factors.

Moreover, as mentioned earlier, the analysis of the supply air was scoped to two conductivities. There are other insulation types available such as aerogel (0.014 W/(m·K)) and vacuum insulated panels (VIP) (0.006 W/(m·K)). However, those products are fragile and most likely not suited for application in prefabricated facade elements due to the risk for damage during transportation and assembly. Furthermore, VIP panels do not have the same life length as other conventional building materials since its thermal properties decrease over time. VIP is more suited in products that have a shorter life expectancy, require low heat losses and little space such as refrigerators etc. Aerogel is relatively new on the market. No building where aerogel has been applied in Sweden was found, therefore, aerogel was not used in the further analysis. Furthermore, from an industrial prefabrication point of view, the energy losses are most likely too low in order to justify mixing of materials in the prefabricated elements. Moreover, if retrofitted on site it would only impose more work and make the retrofit more complicated.

Furthermore, enabling a controlled supply air to each apartment brings several added values. An example is that the supply air temperature increases significantly. The supply air temperature is increased from -12 °C to 15 °C during the coldest hour (worst case scenario) which enables a significant improvement to the thermal comfort. Another important aspect, which is not treated in this study is the fire safety. The fire issue was assumed to be possible to solve with fire dampers, preventing fumes spreading between apartments. For further studies, if PIR is considered, it is suggested to investigate such material from a fire perspective since PIR can be flammable. Alternatively, an investigation could be made if there are fire-preventing additives to PIR which prevent it to catch fire.

6.2.2 Photovoltaics

The PV simulations were based on climate data for the city closest to the case study building, Gothenburg, due to limitations in the SAM software. Therefore, the matching per hour is made by two different weather files which is a limitation of the PV investigation. However, the difference is most likely not significant since the case study building is close to the city the used climate data was obtained from.

The only profitable PV system was a roof mounted system with a module area of approximately 42 m^2. However, it can be argued if such a small system, only covering 0.67 kWh/m^2 (approximately 8 % of the yearly property electricity demand) on a yearly basis is of interest for a property owner. With an investment cost of almost 90 000 SEK and a LCP of approximately 19 000 SEK it seems to be difficult to motivate such an investment from an LCC point of view as well as the fact that the breakeven time is firstly reached after 24 years. Moreover, even though the façade integrated panels were less expensive compared to the roof mounted panels due to the saved cost for façade material, the energy saving are close to cover the investment cost. This is because the reduced investment cost is counter balanced by the reduced generated electricity due to the unfavourable 90° angle at the façade which also deviates from south. Without replacing façade material with PV, and receiving investment subsidies the investment cost of installing vertical modules will be higher than the energy savings.

However, it is important to emphasise that all scenarios were simulated with PV-modules not optimally tilted and not directly towards south, which could be observed in the table with compared outputs for a 1 kWp system optimally installed and, used direction and tilts for the case study building. This is, among others, a contributing factor to the low profitability presented in the results. Moreover, the calculations were conservative regarding the assumed life time, most PV systems will most likely continue to operate even after 25 to 30 years. By assuming a longer life cycle for the PV-panels the results would show a more favourable picture.

Furthermore, it can be argued that the maintenance cost was overestimated since many LCC reports of PV-systems tend to not include it in the calculations at all or argue that PV-systems are almost completely maintenance free. However, it was considered important in this study to include it due to a strong predication that a PV-system sometime during the life cycle most probably needs either repair, test or a cleaning etc. Moreover, the predicted maintenance is likely to not occur during the first years after the installation, which results in an overestimated initial maintenance cost. However, this can be seen as an insurance if the maintenance cost is underestimated when the system is older. Further, the fact that maintenance was included had a strong influence on the results because it increased the costs and thus increased the breakeven time.

Furthermore, VAT was included for the sold electricity in the calculations, which might often be neglected or forgotten since PV prices are given excl. VAT. Moreover, the payed VAT for sold electricity is important, since it decreases the profitability for systems which overproduces and sell more than 40 000 SEK/year. However, it should be mentioned that the systems found to be cost-effective did not overproduce, therefore, the additional VAT was not applied in these cases. Moreover, the fact that energy tax must be paid for sold electricity over 30 000 SEK/year decreases the cost-effectiveness of systems that overproduce even more. Regarding investment subsidies partially covering the initial cost, it should be mentioned that grant and processing time in some cases can take up to three years. During that period changes can be made to the regulations regarding the subsidy which in turn affect the whole economic analysis. Moreover, the PV prices can also decrease in the meantime. There is therefore an uncertainty regarding the subsidy which should be taken into account. Since the subsidy can cover up to 30 % of the investment it has a significant role in the calculation.

Further, the tax reduction is valid for private persons and legal entities, however an important factor to consider is that, for example, a municipal housing company often itself is a legal entity and not the individual buildings owned by the company. This means that only tax reduction up to 30 000 SEK/year can be received for a housing company, regardless of the quantity of PV installations on various buildings. This is a significant limitation to point out as it most probably would make an investment in PV-systems uninteresting for large property owners. Therefore, it would be favourable if the restriction is changed so that each building could be considered as a legal entity, or that a legal entity could apply the tax reduction for more than one building.

Moreover, tax reduction is advantageous for small electricity producers, however, with the limitation of a 100 A fuse size, a large overproduction is not economically feasible, which the studied case showed. Therefore, to make investments in PV installations more interesting in Sweden an increase of the fuse size limit would be advantageous. It would be interesting if the generated electricity could be distributed to the tenants in the building thus enabling the possibility to self-consume more and dimensioning a larger system. However, since the tenants cannot be forced to buy electricity from a specific supplier, an incitement for the tenants should be developed. Furthermore, such a system could be developed where the property owner sells the electricity for a favourable price to the tenants which can be an incitement, besides the positive environmental aspects. However, both the property owner and tenants would still be dependent on a power supplying company since the PV-system is dependent on weather conditions and of course if it is day or night.

Lastly, PV-modules, today, are still expensive if compared to the possible profitability they can generate, however since the modules are steadily decreasing in price PV-systems should be an investment to consider in the near future. However, with a decreasing PV-system cost the investment subsidy will most likely also be reduced.

6.3 Specific energy use

The results of the compilation of electricity profiles for the studied alternatives indicated that the lowest property used electricity was obtained by alternative one (Multi-active façade solution). The reasons for this, are among others, that the chosen AHU operates at lower power, enabling lower energy use. Additionally, it can be mentioned that the selected AHU for alternative one has a lower SFP than the present exhaust air fan which lowers the energy use although twice the mass flow rate of air is transported. Further, the fact that the buildings heating need is significantly lowered entail both lower power need for hydronic pumps as well as reducing the amount of time the building requires heating.

Furthermore, the alternative that showed the highest power need for property used electricity was alternative four that consists of only installing an exhaust air heat pump which is to be connected to the buildings present hydronic system. The first reason for this is that the exhaust air heat pump requires approximately a third of the amount of energy it recovers for powering itself, due to the SCOP being 3.27 in this case. Another reason is the decision was made to assume that the present exhaust air fan will need to operate all the time. The explanation to this assumption is that the heat pump is shut off when the building does not have any heating need, however, the building still requires ventilation in order to always fulfil the building code.

Moreover, a difference regarding the maximum power need between alternative two and four was observed. This is due to the power need for the heat pumps is different between the alternatives, which is a result of difference in their incoming extract air temperature. This was also shown in the results of the SCOP.

Further, the energy results also indicated that installing a heat pump instead of an AHU with heat recovery entails a higher specific energy use. The reason is that the heat pump uses more electricity in order to extract heat. Furthermore, in this case the old fans were assumed to be kept when installing a heat pump. This is due to provide the building with ventilation even if the heat pump shuts off during the summers. However, in this case the realistic solution would be to change the exhaust air fans if installing a heat pump. Furthermore, the results also indicated that conventional additionally insulation of the building does not provide a sufficient reduction of the specific energy use, in order to fulfil the building code.

Moreover, the results also indicated that the specific energy use is lowered by only installing an EAHP, in comparison to the base case. However, the specific energy use is only lowered by approximately 15 % which is considered not enough, even if a reduction in general is positive.
As earlier mentioned, a building is considered electrically heated if the installed power, driven by electricity for heating exceeds 10 W/m². Since the considered heat pump has a maximum power of 46.3 kW, corresponding to approximately 5 W/m² the building will

therefore not be considered as electrically heated. This also means that that the second alternative (additional insulation reaching U_m=0.4 W/(m²·K) and installing an EAHP) is not considered as electrically heated. The specific energy use of the second alternative was 76 kWh/m² which is close to fulfilling the building code requirement. However, perhaps there is another type of heat pump, with a higher COP which would manage passing the requirement.

Although alternative one complies with the present building code regulations regarding specific energy use, it does not reach the proposed NZEB level by the SNEB. Moreover, to lower the specific energy use further, it would require additional measures to the building envelope, in terms of lowering the heat loss factors for each part of the envelope. Furthermore, the total heat losses from all windows would be challenging to reduce since they already are at passive house level, the difficulty lays in that the façade has a high window to wall area (32.7 %).

Further, the building envelope should not only be considered since the maximum specific energy use consists of other parameters such as property used electricity and DHW use. Moreover, the energy use for heating the ventilation air as well as powering the fans can be further reduced by demand controlling the ventilation flows. However, this was not considered in this study due to expected difficulties fitting various dampers in the façade elements. A recommendation for further research is to investigate if these types of components can physically fit in a multi-active façade element.

Moreover, another suggestion for further research is to investigate how much the energy used by installations, property used electricity and DHW use can be individually lowered. This would simplify fulfilling the proposed NZEB requirement without unrealistic demands on the building envelope.

The possible sources of error for the energy simulations are multiple. Firstly, the hot water circulation losses were assumed to be included in the space heating need. However, they are complex to quantify and vary from building to building. In this study they were not quantified since required data was not available. Moreover, they can have a great impact on the specific energy use. Secondly, the assumption of the improved airtightness can also have a great impact on the specific energy use. Regarding the airtightness, it is complex to assess after a renovation, especially with multi-active façade elements, mounted on the outside of the present wall.

6.4 Economic analysis

Initially, it was only considered to study the energy saving potential of the active technologies considered suitable in the Swedish context. However, during the study it was found necessary to conduct an economic analysis, to base the conclusions on more than energy saving potential. Therefore, LCC calculations were carried out, however, no sensitivity analysis on the fixed parameters was included due to that the purpose was to only obtain a general overview. However, the assumed input parameters are thought to be credible and reasonable assumptions since they are suggested by the National Property Board of Sweden.

Furthermore, the level of the present energy tax was considered as a fixed parameter. Therefore, for further research, sensitivity analysis of the fixed parameters is highly recommended to be carried out in order to determine if the outcome of the results will change. A significant increase in district heating and electricity prices will result in more favourable results for the developed retrofitting measures.

The result of the LCC analysis for the energy saving measures indicated that the outcome varies, depending on the thermal properties of the windows considered in the two anyway renovation scenarios.

For the scenario where the anyway renovation was based on new windows with identical thermal properties as the present, the lowest LCC, shortest breakeven time as well as the highest LCP was obtained for the first alternative (supply and return air with heat recovery, ducts routed through the multi-active façade elements). Moreover, this alternative resulted in a LCP of approximately 1.8 million SEK, in comparison to refurbishing the building according to the anyway renovation, based on windows with identical thermal properties as the present. However, the first alternative also includes other important added values which makes the comparison with the anyway renovation inaccurate/very arguable. Such added values could be the end goal of the house owner which would make that comparison not useful. In such case the comparison would be more meaningful between alternatives one, two and three where extensive renovations were performed.

The high LCP obtained from alternative one is due to a significant reduction in energy use; both regarding district heating and property used electricity, since the LCP is the difference between the LCC of the specific alternative and the anyway renovation. Further, the annual savings will catch up the high initial cost within 40 years, with the premise that no rental increases take place. Added values like a higher level of thermal comfort would most likely also enable a rental increase which would mean that the time the investment catches up is decreased. However, rental levels were not included within the scope of this study and were therefore not considered in the economic analysis.

The scenario where the anyway renovation was based on windows complying with the building code for extensive renovations ($U=1.2\ W/(m^2\cdot K)$) which the anyway renovation is considered to be, the accumulated life cycle cost was significantly lower compared to the first scenario (identical windows as the present). Furthermore, it was observed that an anyway renovation with high running cost will result in higher LCP for the developed alternatives and a shorter breakeven time. This is a result of if no energy reducing measures is expected to be carried out, as for the first scenario, no reduction in running costs will take place.

It was found that the initial cost for the multi-active façade solution is competitive if comparing to previous retrofitting projects in Sweden for energy saving measures alone. However, the initial cost was estimated and difficult to confirm since no previous retrofitting project of this type has been carried out in Sweden before. Furthermore, the initial cost can also vary depending on the present economy and the geographical location of the building that is in need of retrofitting, since the transport costs may differ.

It is important to point out that the LCC analysis presented the economical point of view, however it did not include the co-benefits with each alternative. The four analysed retrofitting alternatives differ from each other in terms of co-benefits, an example of this is the thermal comfort, which implies that a comparison between the alternatives is not completely “fair” and could be argued that the alternatives are incomparable in such grounds. For the first alternative the supply air temperature is significantly higher in comparison to the other three cases where cold outdoor air directly enters the living spaces. This is most likely a co-benefit that improves the living value and could most likely entail an eventual rental increase, which in turn would enable reaching the breakeven point faster and result in a lower LCC and higher LCP. Therefore, a suggestion for further research is to quantify the thermal comfort for each case and investigate by how much the rent can be increased and how this affects the investment.

Another co-benefit is the increase of property value that the major renovation alternatives bring. Further, in the long term, such investments in buildings from the million programme can improve the general demand, thus lowering vacant apartments in areas not considered desirable. However, it is complex to quantify since the location of the building has to be taken into consideration.

7 Conclusions

An overall conclusion of this study is that, comparing the investigated solutions based on energy savings and profitability, the active technology found most suitable for the Swedish context consists on integrating supply air ducts in a prefabricated façade module while the existing exhaust ducts are retrofitted and heat is recovered in the centralized ventilation system. By implementing complementary energy saving measures like roof insulation and new windows a reduction of the specific energy use by 55 % (from 141 to 62.8 kWh/(m²·yr)) was possible to achieve. Further, it complies with the building code regulations regarding the specific energy use requirement and average heat loss coefficient for new buildings.

Moreover, when properly optimized, the energy loss of the ventilation air was only 0.2 kWh/(m²·yr)) and the temperature drop was, in the coldest day and for the apartment furthest away, only 4 °C (with a set supply air temperature of 19 °C after the air handling unit) and even though the heat losses were overestimated by the calculation method. Therefore, it is concluded that such ventilation system will work appropriately in an insulated façade module. Moreover, it was shown that the ventilation system is applicable on high rise lamella buildings. Therefore, such a system should also be applicable on low rise lamella buildings since the challenges are fewer.

Additionally, the above mentioned result was achieved without the use of extreme insulation materials around the ducts. The conclusion is therefore that PIR, Aerogel or VIP are not required when the duct is optimally placed. However, this is valid for the case study building, meaning that colder climates could change the results and demand other solutions.

Further, multiple ventilation ducts can be fitted in a façade element not forcing significant pressure drops due to duct size issues, however, this is highly dependent on the space available in the façade, required air flows and number of floors. It is also concluded that, for this case study, a ventilation system with supply air ducts in façade elements can manage the Swedish building code requirement on SFP (2.0 kW/(m³/s)). The SFP can, if the system is designed optimally, be in the interval from approximately 1 to 2 kW/(m³/s) corresponding to approximately 3 to 7 kWh/(m²·yr) depending on which AHU is chosen.

Moreover, a multi-active façade solution alone is not sufficient to reach the building code requirements of new building regarding the average heat transfer coefficient and specific energy use. Additional measures have to be implemented to further lower the transmission losses. Further, heat recovery is required of the ventilation air, preferably by an air handling unit although a heat pump solution also showed to be sufficient.

The study showed that implementing a multi-active façade with additional renovation measures on the envelope can be competitive from an economical point of view. It was found that the initial cost for the multi-active façade solution (approximately 2500 SEK/m²) is competitive if compared to previous retrofitting projects in Sweden (1000-5600 SEK/m² for energy saving measures alone). Furthermore, it was found that the investment the multi-active solution implies, results in almost reaching the breakeven point within the end of the life cycle (60 years). Compared with traditional added insulation and an exhaust heat pump this alternative has a breakeven point of approximately 20 years and a somewhat better thermal indoor comfort.

However, in order to proceed with a multi-active façade solution, the co-benefits are highly recommended to be accounted for since the final result is a very improved building with increased level of thermal comfort and most likely significantly improved property value.

Even though building integrated photovoltaics was considered suitable for the Swedish building context, and the energy saving potential is high, the economical aspect limits the application of the technology. The present tax regulations do not contemplate larger systems that overproduce, and the only profitable systems are the ones that do not overproduce and are roof mounted. However, such small PV installations show a low energy saving potential on the building scale. No profitability was found in façade integrated systems, therefore they are not recommended from an economical point of view for façade integration since the electricity output is limited which in turn affects the profitability negatively. However, they could be recommended from an environmental point of view since they reduce the amount of bought electricity from other sources.

8 Summary

In Sweden, between 1964 and 1975, approximately one million dwellings were raised in the so called million programme. Due to their age and often neglected maintenance regarding both building envelope and installations, in many cases, comprehensive retrofitting is now required. Furthermore, such dwellings have a high specific energy use compared to todays standard and therefore have a high energy saving potential which should be addressed in the upcoming retrofittings. The retrofitting of these buildings can be addressed in various ways, one of which is a concept investigated in this study; prefabricated insulating multi-active facade elements, to minimize tenant disturbance and reduce work on site. The multi-active concept allows integration of various active technologies in the façade elements such as ventilation ducts, photovoltaics, solar thermal, decentralized micro heat pumps and micro air handling units etc.

The aim with this study was to theoretically investigate the energy saving potential and cost-effectiveness of integrating active technologies into a prefabricated insulating façade module, when retrofitting a Swedish case-study multi-family building from the "Million Program". Initially, existing active technologies found by means of a literature review were evaluated regarding their potential to be implemented in the Swedish building context. The active technologies that were found most suitable were; centralized supply- and exhaust air ducts with heat recovery where the supply air ducts are routed through the multi-active elements as well as facade integrated photovoltaics. These were further analysed to estimate the energy saving potential and economic feasibility applied on a representative case study building from the million programme.

It was found, in the early stage of the literature review study, that decentralized systems are not to be recommended in the Swedish context due to the expected difficulties for maintaining and repairing as well as the additional costs they result in. Furthermore, the active technology solar thermal was found to have a very high energy saving potential since it can reduce the amount of bought energy from the district heating network. However, the highest energy output from the solar thermal system is obtained during the summer, when the buildings energy demand is the lowest. Moreover, the district heating price in Sweden varies throughout the year, with the lowest price during the summer. This results in that solar thermal is not to recommend from only an economical point of view, therefore they were not further studied.

The energy saving potential of the two technologies found relevant were estimated by carrying out various energy simulations for a case study building and the economic feasibility was addressed by both analysing initial costs and life cycle costs. Furthermore, the multi-active façade solution was compared to traditionally insulating the building envelope with and without an exhaust air heat pump.

It was found that the heat losses as well as the annual energy losses from wall integrated ducts were minor even without high performing insulation materials applied. Furthermore, the decrease in the supply air temperate during the coldest hour in the year was acceptable.

The results showed that by improving the building envelope and reusing the present exhaust air ducts as well as integrating the supply air ducts in the multi-active element the specific energy use can be lowered by 55 %, from 141 to 62.8 kWh/($m^2 \cdot yr$). The combination of heat recovery from the exhaust air as well as the insulating properties of the multi-active elements are the main contributing factors to the energy savings. The multi-active façade solution with complementary energy saving measures (roof insulation, windows and heat recovery) was found to have a higher saving potential compared to traditionally insulate the building with or without a heat pump.

Moreover, the integration of photovoltaic modules in the façade have a restricted potential due to limitations in the Swedish tax regulations. This makes the energy savings of installing photovoltaic modules in the façade roughly covering the investment during the lifetime only when the investment subsidy is awarded.

Therefore, they were not suggested as a technology to integrate in a multi-active façade since the profitability would have been higher if using them on the roof. The breakeven time of the investment, for the roof mounted system was significantly shorter than other energy saving measures. However, the energy saving impact is significantly lower.

Furthermore, the economic analysis showed that improving the building envelope and implementing a multi-active façade solution, resulted in a competitive alternative in comparison to traditionally insulate the building with or without an exhaust air heat pump. Moreover, further research is suggested to investigate the co-benefits, such as the improvement of thermal comfort and increase of property value, and their impact on the economic feasibility.

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Appendix A

Table A1: The total lengths and duct compositions for the façades.

Main path to apartment	Duct size / mm	Floor	Duct composition / pcs								Total duct length / m
			8	**7**	**6**	**5**	**4**	**3**	**2**	**1**	
C, I, G, M	80 x 130	9	0	0	0	0	0	0	0	7	7
C, I, G, M	80 x 130	8	0	3	0	0	0	0	0	8.5	11.5
C, I, G, M	80 x 130	7	0	3	2.6	0	0	0	0	8.5	14.1
C, I, G, M	80 x 130	6	0	3	2.6	2.6	0	0	0	8.5	16.7
C, I, G, M	80 x 130	5	0	3	2.6	2.6	2.6	0	0	8.5	19.3
C, I, G, M	80 x 130	4	0	3	2.6	2.6	2.6	2.6	0	8.5	21.9
C, I, G, M	80 x 130	3	0	3	2.6	2.6	2.6	2.6	2.6	8.5	24.5
C, I, G, M	80 x 130	2	0	3	2.6	2.6	2.6	2.6	2.6	11	27
B, F, J , D, H, L	80 x 110	9	0	0	0	0	0	0	0	7	7
B, F, J , D, H, L	80 x 110	8	0	3	0	0	0	0	0	8.5	11.5
B, F, J , D, H, L	80 x 110	7	0	3	2.6	0	0	0	0	8.5	14.1
B, F, J , D, H, L	80 x 110	6	0	3	2.6	2.6	0	0	0	8.5	16.7
B, F, J , D, H, L	80 x 110	5	0	3	2.6	2.6	2.6	0	0	8.5	19.3
B, F, J , D, H, L	80 x 110	4	0	3	2.6	2.6	2.6	2.6	0	8.5	21.9
B, F, J , D, H, L	80 x 110	3	0	3	2.6	2.6	2.6	2.6	2.6	8.5	24.5
B, F, J , D, H, L	80 x 110	2	0	3	2.6	2.6	2.6	2.6	2.6	11	27
E1	80 x 110	9	0	0	0	0	0	0	0	4	4
E1	80 x 110	8	0	3	0	0	0	0	0	4.2	7.2
E1	80 x 110	7	0	3	2.6	0	0	0	0	4.2	9.8
E1	80 x 110	6	0	3	2.6	2.6	0	0	0	4.2	12.4
E1	80 x 110	5	0	3	2.6	2.6	2.6	0	0	4.2	15
E1	80 x 110	4	0	3	2.6	2.6	2.6	2.6	0	4.2	17.6
E1	80 x 110	3	0	3	2.6	2.6	2.6	2.6	2.6	4.2	20.2
E1	80 x 110	2	0	3	2.6	2.6	2.6	2.6	2.6	6.8	22.8
A	80 x 130	9	0.3	0	0	0	0	0	0	5.5	5.8
A	80 x 130	8	0.3	2.6	0	0	0	0	0	5.5	8.4
A	80 x 130	7	0.3	2.6	2.6	0	0	0	0	5.5	11
A	80 x 130	6	0.3	2.6	2.6	2.6	0	0	0	5.5	13.6
A	80 x 130	5	0.3	2.6	2.6	2.6	2.6	0	0	5.5	16.2
A	80 x 130	4	0.3	2.6	2.6	2.6	2.6	2.6	0	5.5	18.8
A	80 x 130	3	0.3	2.6	2.6	2.6	2.6	2.6	2.6	5.5	21.4

A	80 x 130	2	0.3	2.6	2.6	2.6	2.6	2.6	2.6	8.1	24
E2	80 x 110	9	0.3	0	0	0	0	0	0	1.4	1.7
E2	80 x 110	8	0.3	2.6	0	0	0	0	0	1.4	4.3
E2	80 x 110	7	0.3	2.6	2.6	0	0	0	0	1.4	6.9
E2	80 x 110	6	0.3	2.6	2.6	2.6	0	0	0	1.4	9.5
E2	80 x 110	5	0.3	2.6	2.6	2.6	2.6	0	0	1.4	12.1
E2	80 x 110	4	0.3	2.6	2.6	2.6	2.6	2.6	0	1.4	14.7
E2	80 x 110	3	0.3	2.6	2.6	2.6	2.6	2.6	2.6	1.4	17.3
E2	80 x 110	2	0.3	2.6	2.6	2.6	2.6	2.6	2.6	4	19.9
K1, K2	80 x 110	9	0.25	0	0	0	0	0	0	2.1	2.35
K1, K2	80 x 110	8	0.25	2.6	0	0	0	0	0	2.1	4.95
K1, K2	80 x 110	7	0.25	2.6	2.6	0	0	0	0	2.1	7.55
K1, K2	80 x 110	6	0.25	2.6	2.6	2.6	0	0	0	2.1	10.15
K1, K2	80 x 110	5	0.25	2.6	2.6	2.6	2.6	0	0	2.1	12.75
K1, K2	80 x 110	4	0.25	2.6	2.6	2.6	2.6	2.6	0	2.1	15.35
K1, K2	80 x 110	3	0.25	2.6	2.6	2.6	2.6	2.6	2.6	2.1	17.95
K1, K2	80 x 110	2	0.25	2.6	2.6	2.6	2.6	2.6	2.6	4.7	20.55

Appendix B

Figure B1: North-west façade, path alternative one.

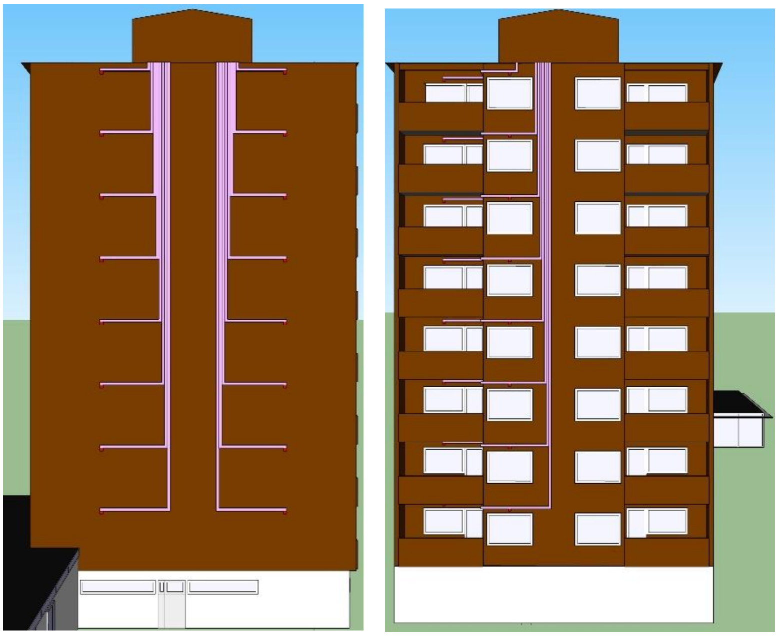

Figure B2: North-east (left) and South-west (right) gable, path alternative one.

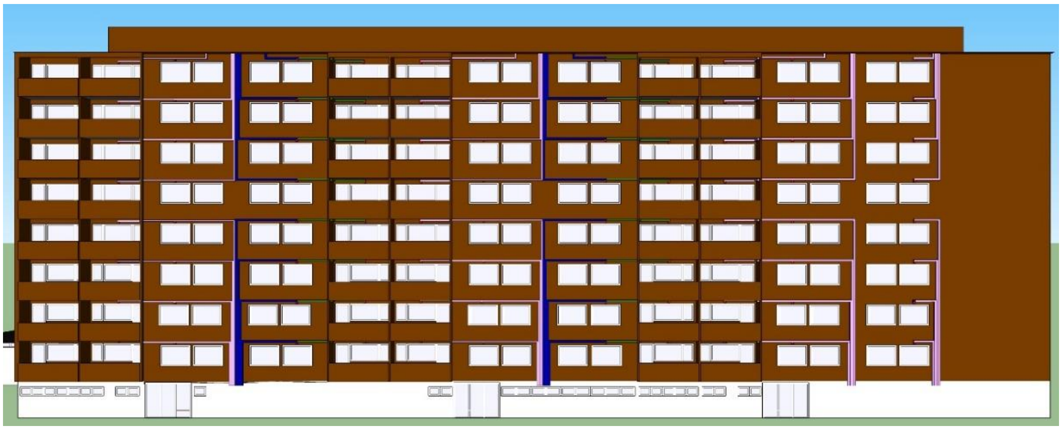

Figure B3: North-west façade, path alternative two.

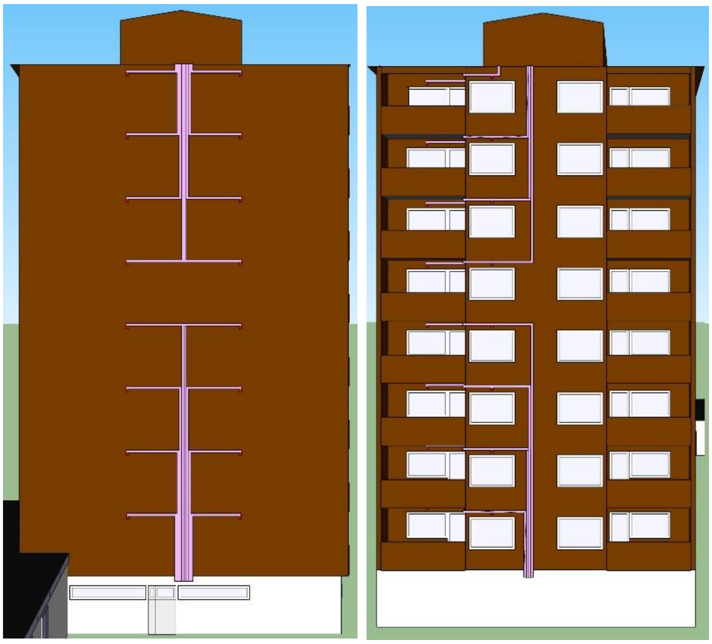

Figure B4: North-east (left) and South-west (right) gable, path alternative two.

Appendix C

Table 34: Pressure drop calculations for apartment type A.

Apartment / floor	Tot. Req. airflow / (l/s)	Path	Length / m	Airflow / (l/s)	Size (W x H) / mm	Velocity / (m/s)	Friction loss duct / (Pa/m)	Pressure loss free duct / Pa	Elbow / pcs	Tee / pcs	Elbow Loss / Pa	Tee Loss / Pa	Fitting losses / Pa	Diffusers / pcs	Diffuser loss / Pa	Tot. Diffuser losses / Pa	Fire damper loss / Pa	Silencer loss / Pa	Total loss / Pa
A		Path																	
9	**23.3**	A9-AB	1	23.31	130 x 80	2.3	1	1	1	1	4.4	0.6	5	0	0	0	12	0	18
		A9-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			27.5
		A9-AB	1	23.31	130 x 80	2.3	1	1	1	1	4.4	0.6	5	0	0	0	12	0	18
		A9-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A9-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			26.2
		Path																	
8	**23.3**	A8-AB	3.9	23.31	130 x 80	2.3	1	3.9	1	1	4.4	0.6	5	0	0	0	12	0	20.9
		A8-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			30.4
		A8-AB	3.9	23.31	130 x 80	2.3	1	3.9	1	1	4.4	0.6	5	0	0	0	12	0	20.9
		A8-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A8-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			29.1
		Path																	
7	**23.3**	A7-AB	6.8	23.31	130 x 80	2.3	1	6.8	1	1	4.4	0.6	5	0	0	0	12	0	23.8
		A7-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			33.3

		A7-AB	6.8	23.31	130 x 80	2.3	1	6.8	1	1	4.4	0.6	5	0	0	0	12	0	23.8
		A7-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A7-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			32.0
		Path																	
6	**23.3**	A6-AB	9.65	23.31	130 x 80	2.3	1	9.65	1	1	4.4	0.6	5	0	0	0	12	0	26.65
		A6-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			36.2
		A6-AB	9.65	23.31	130 x 80	2.3	1	9.65	1	1	4.4	0.6	5	0	0	0	12	0	26.65
		A6-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A6-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			34.8
		Path																	
5	**23.3**	A5-AB	12.5	23.31	130 x 80	2.3	1	12.5	1	1	4.4	0.6	5	0	0	0	12	0	29.5
		A5-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			39.1
		A5-AB	12.5	23.31	130 x 80	2.3	1	12.5	1	1	4.4	0.6	5	0	0	0	12	0	29.5
		A5-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A5-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			37.7
		Path																	
4	**23.3**	A4-AB	15.35	23.31	130 x 80	2.3	1	15.35	1	1	4.4	0.6	5	0	0	0	12	0	32.35
		A4-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			41.9

		A4-AB	15.35	23.31	130 x 80	2.3	1	15.35	1	1	4.4	0.6	5	0	0	0	12	0	32.35
		A4-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A4-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			40.5
		Path																	
3	**23.3**	A3-AB	18.2	23.31	130 x 80	2.3	1	18.2	1	1	4.4	0.6	5	0	0	0	12	0	35.2
		A3-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			44.7
		A3-AB	18.2	23.31	130 x 80	2.3	1	18.2	1	1	4.4	0.6	5	0	0	0	12	0	35.2
		A3-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A3-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			43.42
		Path																	
2	**23.3**	A2-AB	21.1	23.31	130 x 80	2.3	1	21.1	1	1	4.4	0.6	5	0	0	0	12	0	38.1
		A2-BC	0.2	11.65	130 x 80	1.4	0.25	0.05	1	1	1.1	3.3	4.4	1	5.1	5.1	0	0.6	9.55
																			47.6
		A2-AB	21.1	23.31	130 x 80	2.3	1	21.1	1	1	4.4	0.6	5	0	0	0	12	0	38.1
		A2-BD	3.5	11.66	130 x 80	1.2	0.25	0.875	1	0	1.1	0	1.1	0	5.1	0	0	0	1.975
		A2-DE	0.2	11.66	130 x 80	1.2	0.25	0.05	1	0	1.1	0	1.1	1	5.1	5.1	0	0.6	6.25
																			46.3

Table C2: Duct sizes, velocity, pressure drops and airflow for each section.

Section	AB	BC	BD	DE
Flow /(l/s)	23.3	11.65	11.65	11.65
Δp /L (Pa/m)	1	0.25	0.25	0.25
v /(m/s)	2.3	1.2	1.2	1.2
Duct size / mm	130	130	130	130

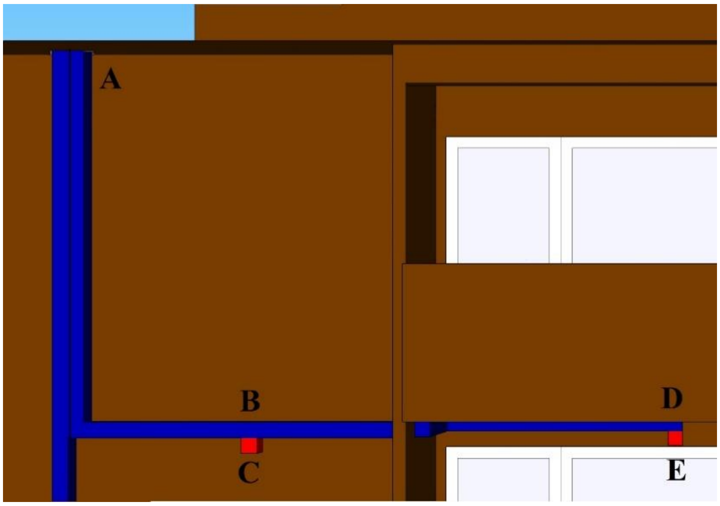

Figure C1: Path naming for the ductwork for each floor.

Table C3: Pressure drop from technical room to facade for apartment A.

Path	Length / m	Airflow / (l/s)	Size (W x H) / mm	Velocity / (m/s)	Friction loss duct / (Pa/m)	Total pressure loss free duct / Pa	Elbow / pcs	Elbow Loss / Pa	Fitting losses / Pa	Total loss / Pa
AHU-Façade	37.5	23.31	130 x 80	2.3	1	37.5	3	0.4	1.2	38.7

Appendix D

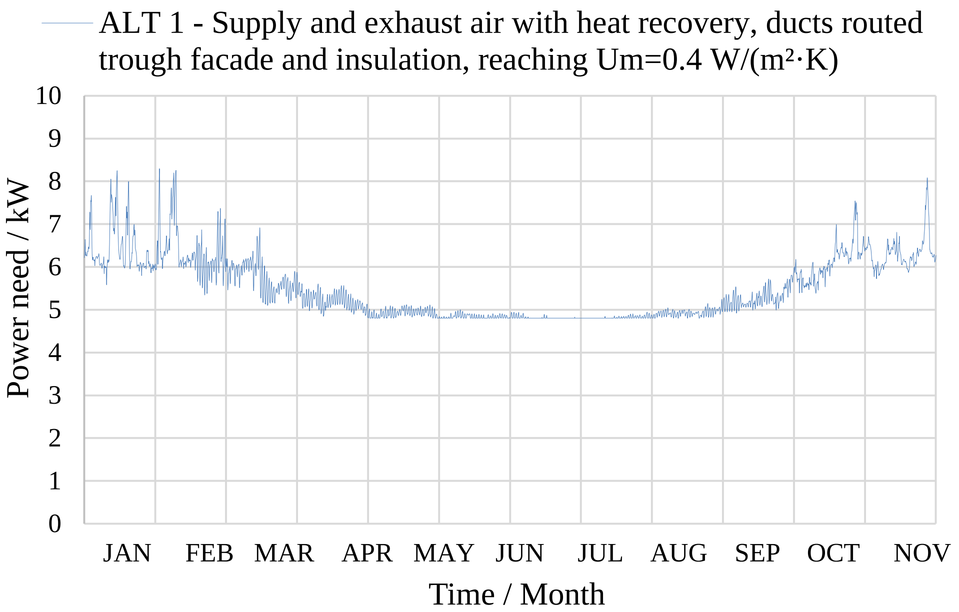

Figure D1: Power need for property used electricity for the first alternative, supply air with heat recovery, ducts routed through façade and insulation, reaching Um=0.4 W/(m²·K).

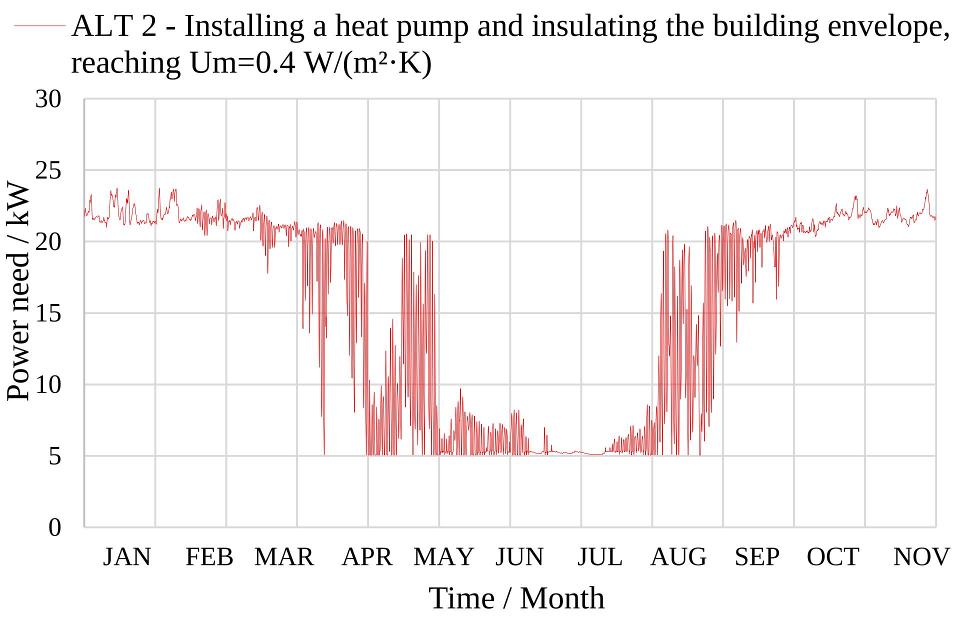

Figure D2: Power need for property used electricity for the second alternative, installing an exhaust air heat pump and insulating the building reaching Um=0.4 W/(m²·K).

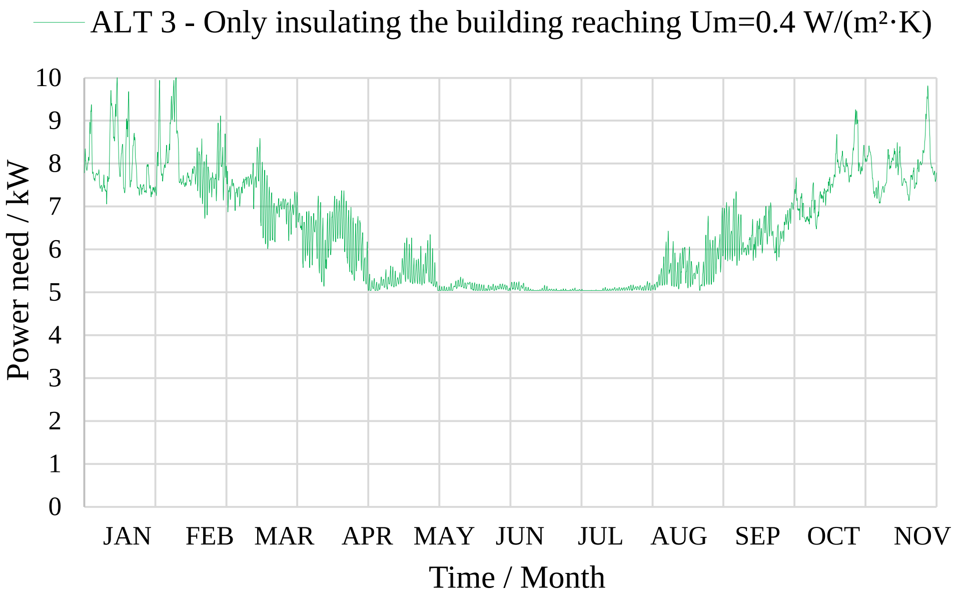

Figure D3: Power need for property used electricity for the third alternative, only insulating the building reaching Um=0.4 W/(m²·K).

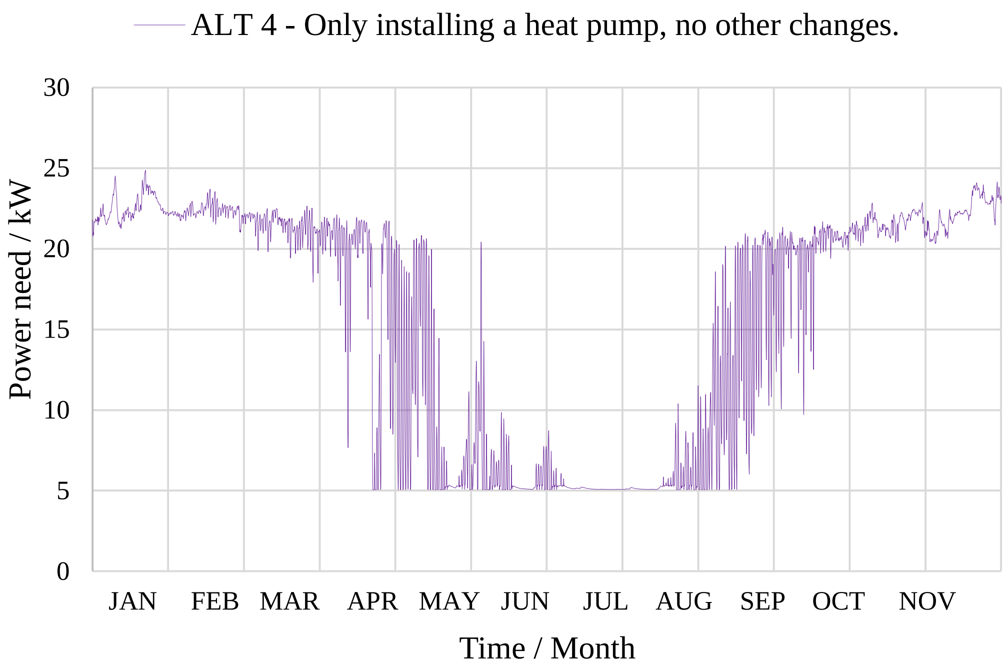

Figure D4: Power need for property used electricity for the third alternative, only installing an exhaust air heat pump.

Appendix E

Table E1: Results of the LCC, LCP and break even time for Alt. 1 with roof mounted PVs.

Alternative	**ALT 1**			
PV placement	**Roof**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	149	36	149	36
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	YES	NO	YES
System size / kWp	57.6	6.8	57.6	6.8
Module area / m²	352	41.6	352	41.6
Initial investment cost / SEK	650 612	82 851	929 445	118 359
LCC / SEK	1 987 652	1 096 099	2 266 485	1 131 606
LCP / SEK	-871 810	19743	- 1 150 644	-15 765
Break even time / years	>life cycle	24	>life cycle	>life cycle

Table E2: Results of the LCC, LCP and break even time for Alt. 2 with roof mounted PVs.

Alternative	**ALT 2**			
PV placement	**Roof**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	149	103	149	103
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	NO	NO	NO
System size / kWp	57.6	6.8	57.6	6.8
Module area / m²	352	41.6	352	41.6
Initial investment cost / SEK	650 612	82 851	929 445	118 359
LCC / SEK	3 513 757	3 069 063	3 792 591	3 104 570
LCP / SEK	- 424 913	19781	-703 747	-15 726
Break even time / years	>life cycle	24	>life cycle	>life cycle

Table E3: Results of the LCC, LCP and break even time for Alt. 3 with roof mounted PVs.

Alternative	**ALT 3**			
PV placement	**Roof**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	149	44	149	44
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	YES	NO	YES
System size / kWp	57.6	6.8	57.6	6.8
Module area / m²	352	41.6	352	41.6
Initial investment cost / SEK	650 612	82 851	929 445	118 359
LCC / SEK	2 126 338	1 260 885	2 405 172	1 296 392
LCP / SEK	-845 673	19 781	-1 124 506	-15 727
Break even time / years	>life cycle	24	>life cycle	>life cycle

Table E4: Results of the LCC, LCP and break even time for Alt. 4 with roof mounted PVs.

Alternative	**ALT 4**			
PV placement	**Roof**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	149	110	149	110
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	NO	NO	NO
System size / kWp	57.6	6.8	57.6	6.8
Module area / m²	352	41.6	352	41.6
Initial investment cost / SEK	650 612	82 851	929 445	118 359
LCC / SEK	3 633 242	3 197 701	3 912 075	3 233 209
LCP / SEK	-415 760	19 781	-694 593	-15 726
Break even time / years	>life cycle	24	>life cycle	>life cycle

Table E5: Results of the LCC, LCP and break even time for Alt. 1 with facade integr. PVs.

Alternative	**ALT 1**			
PV placement	**Façade**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	214	36	214	36
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	YES	NO	YES
System size / kWp	73.4	7.9	73.4	7.9
Module area / m²	448	48	448	48
Initial investment cost / SEK	651 932	76 478	1 006 811	117 449
LCC / SEK	2 364 188	1 118 286	2 719 067	1 159 257
LCP / SEK	-1 248 346	-2 445	-1 603 225	-43 415
Break even time / years	>life cycle	>life cycle	>life cycle	>life cycle

Table E6: Results of the LCC, LCP and break even time for Alt. 2 with facade integrated PVs.

Alternative	**ALT 2**			
PV placement	**Façade**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	284	103	284	103
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	NO	NO	NO
System size / kWp	154.1	7.9	154.1	7.9
Module area / m²	928	48	928	48
Initial investment cost / SEK	1 374 388	76 478	2 119 634	117 449
LCC / SEK	5 027 607	3 091 232	5 772 853	3 132 203
LCP / SEK	-1 938 763	-2 389	-2 684 009	-43 359
Break even time / years	>life cycle	>life cycle	>life cycle	>life cycle

Table E7: Results of the LCC, LCP and break even time for Alt. 3 with facade integrated PVs.

Alternative	**ALT 3**			
PV placement	**Façade**			
Investment subsidies received (YES/NO)	YES	YES	NO	NO
Tax reduction included → cover electricity demand (YES/NO)	YES, overproduction	NO, no overproduction	Yes, overproduction	NO, no overproduction
Resulting minimum fuse size / A	244	44	244	44
Tax reduction applicable by tax regulations (<100 A) (YES/NO)	NO	YES	NO	YES
System size / kWp	84.4	7.9	84.4	7.9
Module area / m²	515.2	48	515.2	48
Initial investment cost / SEK	749 764	76 478	1 157 875	117 449
LCC / SEK	2 808 984	1 283 054	3 217 095	1 324 024
LCP / SEK	-1 528 319	-2 389	-1 936 430	-43 359
Break even time / years	>life cycle	>life cycle	>life cycle	>life cycle

Appendix F

Table F1: Specific energy use on monthly basis for the base case, totally 142 kWh/(m²·yr).

Month	Property used electricity			Heating		
	Hydronic radiator pumps / kWh	Others / kWh	Ventilation fans / kWh	Heat pump / kWh	Space heating / kWh	Domestic hot water / kWh
1	4372	-	3727	0	195528	15392
2	3961	-	3727	0	166088	15392
3	3210	-	3727	0	135519	15392
4	1740	-	3727	0	78912	15392
5	417	-	3727	0	19361	15392
6	29	-	3727	0	5832	15392
7	10	-	3727	0	3447	15392
8	33	-	3727	0	3806	15392
9	866	-	3727	0	31641	15392
10	2115	-	3727	0	81246	15392
11	3706	-	3727	0	142390	15392
12	4273	-	3727	0	180420	15392
Total / (kWh/yr)	24734	10881	44729	0	1044194	184700
Total / (kWh/(m²·yr))	2.68	1.18	4.84	0	113	20

Table F2: Specific energy use on monthly basis for alternative one, totally 63 kWh/(m²·yr).

Month	Property used electricity			Heating		
	Hydronic radiator pumps / kWh	Others / kWh	Ventilation fans / kWh	Space heating / kWh	Losses in ductwork / kWh	Domestic hot water / kWh
1	1203	-	3571	63247	319	15392
2	1068	-	3226	56369	295	15392
3	735	-	3571	39828	298	15392
4	315	-	3456	18790	119	15392
5	93	-	3571	7758	28	15392
6	25	-	3456	4324	5	15392
7	8	-	3571	3492	0	15392
8	10	-	3571	3594	2	15392
9	86	-	3456	7352	17	15392
10	347	-	3571	20409	97	15392
11	928	-	3456	49428	208	15392
12	1136	-	3571	59979	304	15392
Total / (kWh/yr)	5954	10881	42047	334574	1691	184700
Total / (kWh/(m²·yr))	0.6	1.18	5	36	0.2	20

Table F3: Specific energy use on monthly basis for alternative two, totally 76 kWh/(m²·yr).

Month	**Property used electricity**				**Heating**	
	Hydronic radiator pumps / kWh	Others / kWh	Ventilation fans / kWh	Heat pump / kWh	Space heating / kWh	Domestic hot water / kWh
1	1432	-	3727	11107	74686	15392
2	1325	-	3727	10042	69223	15392
3	894	-	3727	11123	47825	15392
4	298	-	3727	9474	17989	15392
5	11	-	3727	3707	3629	15392
6	0	-	3727	779.5	3078	15392
7	0	-	3727	354.7	3078	15392
8	0	-	3727	388.9	3078	15392
9	22	-	3727	5219	4160	15392
10	272	-	3727	10735	16624	15392
11	1071	-	3727	10799	56556	15392
12	1360	-	3727	11124	71202	15392
Total / (kWh/yr)	6685	10881	44729	84853	371131	184700
Total / (kWh/(m²·yr))	0.72	1.18	4.84	9	40	20

Table F4: Specific energy use on monthly basis for alternative three, totally 99 kWh/(m²·yr).

Month	**Property used electricity**				**Heating**	
	Hydronic radiator pumps / kWh	Others / kWh	Ventilation fans / kWh	Heat pump / kWh	Space heating / kWh	Domestic hot water / kWh
1	2182	-	3727	0	112150	15392
2	2005	-	3727	0	103198	15392
3	1651	-	3727	0	85647	15392
4	941	-	3727	0	50079	15392
5	255	-	3727	0	15860	15392
6	53	-	3727	0	5750	15392
7	20	-	3727	0	4095	15392
8	22	-	3727	0	4185	15392
9	359	-	3727	0	20960	15392
10	1004	-	3727	0	53254	15392
11	1801	-	3727	0	93077	15392
12	2110	-	3727	0	108730	15392
Total / (kWh/yr)	12403	10881	44729	0	656989	184700
Total / (kWh/(m²·yr))	1.34	1.18	5	0	71	20

Table F5: Specific energy use on monthly basis for alternative four, totally 105 kWh/(m²·yr).

Month	Facility electricity				Heating	
	Hydronic radiator pumps / kWh	Others / kWh	Ventilation fans / kWh	Heat pump / kWh	Space heating / kWh	Domestic hot water / kWh
1	3103	-	3727	10379	135143	15392
2	2610	-	3727	9460	113196	15392
3	1972	-	3727	10654	82622	15392
4	970	-	3727	8984	37971	15392
5	110	-	3727	3686	5244	15392
6	10	-	3727	872.1	3170	15392
7	0	-	3727	189.3	3078	15392
8	0	-	3727	291	3078	15392
9	177	-	3727	5534	7570	15392
10	840	-	3727	10271	32839	15392
11	2045	-	3727	10221	87789	15392
12	2789	-	3727	10413	121456	15392
Total / (kWh/yr)	14627	10881	44729	80954	633160	184700
Total / (kWh/(m²·yr))	1.58	1.18	5	9	69	20

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