CHALMERS
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Residential Energy Renovation

Analysis of energy savings and economic profitability in a multifamily building block

Master's thesis in the program Structural Engineering and Building Technology

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Cover: Baron Rogers 24/25

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Abstract

The necessity for renovation of the Swedish Million Homes Programme building stock has been under scrutiny in recent years. Many of these buildings are undergoing deterioration and have an energy performance far below the current standard for new buildings (Högberg et al., 2009). In Sweden, up to 40% of the energy usage originates from the building sector (Liu et al., 2014) and less than 1% of buildings are newly added to the building stock each year (Economidou M et al., 2011). Thus, to reduce this energy use, the energy-efficiency of the existing buildings has to be improved via renovation. This strategy is also part of the European Union's Green deal announced in 2019, the policies of which its member states are expected to comply (European Union, 2019).

This thesis aimed to formulate several renovation packages to achieve an annual specific energy use reduction of at least 30%. Six multi-family buildings from the Million Homes Programme located in Hisings Backa, Gothenburg were investigated as part of the study. One building was selected as the case study building and simulated in IDA ICE to replicate its current energy performance. The proposed renovation measures dealt with improving the building envelope, ventilation system and some minimal baseline measures. These measures were put together into several different packages and simulated to determine the post-renovation energy savings and operational CO_2 reductions. In addition, economic evaluations were conducted using the Equivalent Annual Cost (EAC) method to gauge the most economically sound package. Finally, the results obtained from the case study building were extrapolated to the five other buildings connected to the same substation.

The thesis concluded that savings in specific energy use of more than 50% could be achieved by upgrading the existing F-ventilation to an FTX or FVP system. The thesis also established that it is generally challenging to make a renovation project profitable solely based on operational energy cost reductions. However, a few packages with reasonable savings were found to have a comparatively good EAC, which could potentially mean that they are profitable.

Keywords: energy-efficiency, energy auditing, energy simulations, renovation, economic analysis, EAC, FVP, FTX, CO_2 emissions.

Energirenovering av flerbostadshus
En analys av energibesparingar och ekonomisk lönsamhet hos ett flerbostadsområde
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Sammanfattning

Renoveringsbehovet av svenska bostäder från miljonprogrammet har varit i stort fokus under de senaste åren. Många byggnader är i dåligt skick och har en energiprestanda långt under den nuvarande standarden för nya byggnader (Högberg et al., 2009). I Sverige utgörs upp till 40% av det totala energianvändningen av byggsektorn (Liu et al., 2014) och antalet nya byggnader som färdigställs varje år utgör mindre än 1% av det totala byggnadsbeståndet (Economidou M et al., 2011). För att minska byggsektorns energianvändning är det därför nödvändigt att befintliga bostäders energieffektivitet förbättras genom renovering. Denna strategi är också en del av EU:s gröna giv som tillkännagavs 2019 vars riktlinjer förväntas följas av medlemsländerna (European Union, 2019).

Examensarbetets mål var att formulera ett antal renoveringspaket med syftet att uppnå en årlig minskning av specifik energianvändning på minst 30%. Sex flerbostadshus från miljonprogrammet i Hisings Backa, Göteborg undersöktes som en del av studien. En fallstudie utfördes på en av byggnaderna i området som först simulerades i IDA ICE för att replikera byggnadens nuvarande energiprestanda. De föreslagna åtgärderna för att förbättra energieffektiviteten innefattade förbättring av byggnadens klimatskärm, ventilationssystem och några mindre basåtgärder. Dessa åtgärder sattes ihop till ett antal olika renoveringspaket och ytterligare simuleringar utfördes för att fastställa energibesparingarna och minskningarna av CO_2 emissioner under byggnadens drift efter renoveringarna. Kostnadskalkyler genomfördes med hjälp av annuitetsmetoden för att jämföra lönsamheten hos paketen. Slutligen extrapolerades resultaten från fallstudien till de andra fem byggnaderna anslutna till samma undercentral.

Examensarbetet fastställde att besparingar av specifika energi på mer än 40% kunde uppnås genom att uppgradera det existerande F-ventilationssystemet till ett FTX- eller FVP system. Från arbetet drogs också slutsatsen att det i allmänhet är svårt att genomföra lönsamma renoveringsprojekt enbart baserat på minskningar av driftkostnader. Några av de lättare paketen med rimliga besparingar konstaterades dock ha en jämförelsevis god annuitet, vilket potentiellt kan innebära en god lönsamhet.

Nyckelord: energieffektivisering, energikartläggning, energisimulering, renovering, kostnadskalkyl, EAC, FVP, FTX, CO_2 utsläpp.

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Gothenburg, June 2021
Daniel Arvidsson, Gaurab Lama

Abbreviations

AHU	Air Handling Unit
BBR	Boverket's Building Regulations (*Boverkets Byggreglar*)
BPS	Building Performance Simulation
COP	Coefficient of Performance
DH	District Heating
DHW	Domestic Hot Water
EAC	Equivalent Annual Cost
EPC	Energy Performance Certificate
EPS	Expanded Polystyrene
F	Exhaust ventilation (*Frånluftsventilation*)
FTX	Mechanical ventilation with Heat Recovery (*Från och tilluftsventilation med värmeåtervinning*)
FVP	Exhaust Air Heat Pump (*Från och tilluftsventilation med värmepump*)
GHGs	Greenhouse gases
HVAC	Heating, Ventilation and Air conditioning
LECA	Lightweight Expanded Clay Aggregate
MHP	Million Homes Programme
NPV	Net Present Value
LCCA	Life Cycle Cost Analysis
SFP	Specific Fan Power [kW/(m^3/s)]
SMHI	Swedish Meteorological and Hydrological Institute

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1 Introduction

1.1 Background

From 1965-1974, one million dwellings were built in Sweden as part of the Million Homes Programme to remedy the post-war housing shortage (Hall and Vidén, 2005). The necessity for renovation of this building stock has been a pressing matter in recent years. Many of the buildings are undergoing deterioration and have an energy performance far below the current standard for new buildings (Högberg et al., 2009). In Sweden, up to 40% of the energy usage is accounted for by the building sector (Liu et al., 2014) and less than 1% of the buildings are newly built each year (Economidou M et al., 2011). Thus, the potential to reduce energy use by improving the energy-efficiency of existing buildings via renovation is huge.

The Swedish government has set up ambitious goals for energy reductions in the building stock, which is to reduce the energy use by 50% by 2050 counting from 1995 (Sveriges Riksdag, 2009). Sveriges Allmännytta (formerly SABO), an organization of more than 300 municipally owned public housing companies in Sweden, started a Climate Initiative (*Klimatinitiativ*) in 2018 with the goal to reduce greenhouse gas emissions in buildings (Sveriges Allmännytta, 2018). Its two overarching strategies for achieving this is for the participating housing companies to: i) decrease the specific energy consumption by 30% (from 2007 values) and ii) be completely fossil free by 2030.

Many challenges, however, must be faced while renovating the existing building stock. Various uncertainties and variables such as climate change, services change and occupant behavior along with the complex interactions between building subsystems can affect the selection and feasibility of renovation measures (Ma et al., 2012). At the same time, property owners can be hesitant to initiate renovations due to the issue of split incentives and long payoff times (Economidou and Bertoldi, 2015, Ma et al., 2012). Therefore, the need for defining the most efficient means of renovation both in terms of cost and building performance cannot be understated.

1.2 Aims and research questions

The following are the aims of this thesis:

- To produce several renovation packages with the aim of achieving an annual specific energy use reduction of at least 30%.
- To determine a range of energy savings that can be attained by implementing various renovation packages.
- To provide an example of how energy savings estimated for one building can be extrapolated to other buildings sharing similar characterstics.
- To conduct economic analyses taking investment costs, and yearly operational energy savings into account.

At the end of the thesis, the following research questions should also be answered:

- Is it possible to formulate both an energy efficient and cost effective renovation strategy that can be applied on a block of similar buildings?
- Can an FTX system (Mechanical ventilation with Heat Recovery) be implemented in the case study building without relocating tenants?

1.3 Methodology

The thesis started with a literature review concerning past renovation studies in Sweden. This was followed with a background study of the present condition of the case buildings and existing project documents, complemented through site visits. Extensive data and information required for a well-informed and realistic Building Performance Simulation (BPS) was collected during this stage.

BPS was carried out in the software IDA ICE 4.7.1 to simulate the current energy performance of the case study building, Baron Rogers 24/25. The simulation results were analyzed, and potential renovation measures formulated into different packages. The original building model was then modified incorporating the proposed packages and the post-renovation performance was studied. Economic evaluations were conducted using the EAC method to compare and select the most economically sound package. The results from the single building were finally extrapolated to other interconnected buildings in the neighborhood.

1.4 Limitations

Only one building out of six was picked and studied in detail. All analysis of the existing drawings and energy data, proposed package solutions and energy simulations was thus based on this building. Due to time constraints, an investigation of the embodied environmental impacts of renovation was not considered. Instead, CO_2 emission factors were used which concerns the building's operational phase only. The building simulation was based on readily available information provided by the housing company. In-situ measurements such as blower-door tests and observations of the apartments could not be performed.

The effect of the glazed balconies on the energy performance of the building was neglected due to its small coverage of the building envelope and difficulties in simulating it. Furthermore, its effect on the energy performance is greatly dependent on user behavior, which is difficult to predict. The hygrothermal and moisture performance of the building components was not considered as it would require the use of specialized software such as WUFI or COMSOL, which is beyond the scope of this thesis. Finally, all the possible cashflows occurring during the building life cycle was not taken into account for the economic analysis. Instead only the initial investment costs and the resulting operational energy savings were considered.

1.5 Outline of thesis

This thesis consists of eleven chapters including an introductory chapter.

Chapter 1 Introduction provides the background and scope of the thesis.

Chapter 2 Method describes the methods and process used to conduct the thesis.

Chapter 3 Theoretical framework describes the findings of the literature review, and how this thesis was influenced by that work.

Chapter 4 Project description and case study building outlines the project and describes the case study building to be simulated.

Chapter 5 IDA ICE modelling and input parameters deals with the simulation of the case study building, and various input parameters used for that purpose.

Chapter 6 Calibration of results details the calibration of the first output in IDA ICE. It also deals with determining the district heating distribution losses.

Chapter 7 Package solutions presents and describes the development of the renovation packages.

Chapter 8 Economic analysis explains the economic analysis of the various packages and the parameters assumed.

Chapter 9 Results summarizes the findings and results obtained.

Chapter 10 Discussion discusses the results and the possibilities of future research.

Chapter 11 Conclusion concludes the findings of the thesis.

2
Method

The following chapter describes the methods used and the process followed to conduct the thesis.

2.1 Literature review

The thesis started with a literature review by perusing research articles, books, reports and other sources concerning past renovation projects in Sweden. The goal was to get an insight into the process of renovation planning, the objectives of renovation and gathering references of multifamily building projects. Input data required for building energy simulation was also collected and documented. The outcome of the Literature review has been discussed in detail in Chapter 3, Theoretical framework.

2.2 Energy auditing

Energy auditing may be described as an inspection and detailed analysis of the energy flows in a building, for the purpose of identifying opportunities for energy savings (Alexandri and Androutsopoulos, 2008). The building owner provided architectural and structural drawings, an Energy Performance Certificate (EPC) from 2018 and a ventilation adjustment protocol (*injusteringsprotokoll ventilation*) from 2017. Meter readings of district heating, electricity and water consumption were also provided and analyzed. To complement this analysis, a site visit was also conducted to inspect the existing condition of the building and its systems.

2.3 Building simulation

The building was simulated in IDA ICE 4.7.1 to replicate its current energy performance, and to investigate the effect of renovation measures on the building's energy use. The software, developed by Swedish company EQUA Simulation AB in 1998, can be used for dynamic analyses of building energy performance, indoor climate and daylight, among others. Results obtained from the software have closely reflected results concerning the actual performance of buildings (Christensen et al., 2015, Cornaro et al., 2016). The software also has a large built-in database of building materials, windows and building services systems that can simplify the work process. This, together with the intuitive interface and controls, were the main reasons for its selection.

2.4 Energy performance metric

Comparing the energy performances of different buildings requires the use of a standardized performance metric. In this thesis, both the Primary Energy Number (EP_{pet}) defined by Boverket and the building's specific energy consumption was used for this purpose. This was done because Boverket has prescribed the use of the EP_{pet} to standardize energy performances starting from 2017, whereas the *Klimatiniativ* works with the specific energy use to quantify energy improvements. The main difference between these metrics is the weighting factor applied to the various energy carriers for determining the EP_{pet} whereas specific energy use is simply the sum of the building's delivered energy. As defined by Boverket, a building's EP_{pet} may be calculated using the formula below (Boverket, 2020):

$$EP_{\text{pet}} = \frac{\sum_{n=1}^{6} \left(\frac{E_{\text{uppv, i}}}{F_{\text{geo}}} + E_{\text{kyl,i}} + E_{\text{tvv,i}} + E_{\text{f,i}}\right) \times VF_{\text{i}})}{A_{\text{temp}}}$$

where,

E_{uppv} = Energy use for space heating, kWh/year

F_{geo} = Geographical adjustment factor, 0.9 for Gothenburg

$E_{kyl,i}$ = Energy for air conditioning, kWh/year

$E_{tvv,i}$ = Energy for tap hot water, kWh/year

$E_{f,i}$ = Property energy, kWh/year

VF_i = Weighting factor for energy carriers; 0.7 for DH and 1.8 for Electricity

A_{temp} = Area enclosed by the inside of the building envelope of all storeys (incl. cellars and attics) for areas heated to greater than 10°C

2.5 Environmental performance metric

The CO_2 emission factor of each energy carrier was used to compare the environmental performance of the renovation packages. These factors are only concerned with the building's operational energy use, and does not account for the embodied emissions of the building materials. The emission factor for electricity is based on the Nordic electricity mix whereas for district heating is based on data provided by the energy supplier of Gothenburg, Göteborgs Energi.

Table 2.1: CO_2 emission factors

Energy carrier	**Emission factor [gCO_2-eq/kWh]**
Electricity	**93** (Sandgren and Nilsson, 2021)
District heating	**65** (Göteborgs energi, 2019)

2.6 Model calibration

The results of the energy simulation were compared against the measured meter values to verify and calibrate them. Furthermore, additional distribution losses were calculated and added to the simulated results to realistically capture the energy use of the case study building.

2.7 Economic analysis

Although the Net Present Value (NPV) is commonly used to assess profitability, it was deemed unsuitable for the evaluation of two or more one-time investments with different investment periods, which is the case when evaluating a renovation package consisting of different measures (Farahani, 2021). The Equivalent Annual Cost (EAC) method is better suited for this purpose and for selecting the best investment alternative among different ones. The EAC method has been described in more detail in Chapter 8 Economic analysis.

Due to the complexity of determining all the costs incurred during the building's lifecycle, a simplified version of the lifecycle cost analysis (LCCA) method was used. Only the initial investment costs of the renovation and the yearly "benefits" resulting from operational energy savings was considered in the cash flow analysis.

In real estate investments, *direktavkastning* is often used to measure and assess profitability. *Direktavkastning* is defined as the ratio between net operating income and the property's market value (Byman and Jernelius, 2012). This has also been described in the Economic analysis chapter.

Parameters required for economic analysis such as investment costs, energy prices, discount rate etc were collected from various sources. These included literature studies, energy supplier websites and statistical values. A description of these has also been provided in Chapter 8.

2.8 Indoor temperatures

The actual indoor temperatures in the apartments could not be determined due to restrictions placed on entering the apartments. However, temperature data was available through Curves, a tool administered by EcoGuard AB (EcoGuard AB, 2021). Curves is used by a large number of housing companies to collect and aggregate building data such as temperatures and energy consumption. The temperature data is measured via meters placed in the apartments. Hourly, monthly or yearly measurements of the indoor and outdoor temperatures can be viewed and extracted according to the requirement.

2.9 Extrapolation

The main goal of this thesis was to evaluate the effect of energy renovation on a group of six buildings. However, due to complications arising from simulating each building individually, a different approach was taken. Resulting energy savings on one building was determined and this was extrapolated to the other buildings using a simple arithmetic method.

First, the total floor area of all 6 buildings was estimated with the help of the provided architectural drawings. The proportion of the case study building area to this total area was then calculated. Using this proportion along with the results derived from the case study building, the effect of renovating the entire area could be estimated.

Based on the similar architecture and technical systems of the target buildings, this was deemed a reasonable approach. The reductions in energy use and CO_2 emissions is expected to scale well from the extrapolation. However, the investment costs are likely to be overestimated as the method does not account for economy of scale or more efficient logistics in larger projects.

3
Theoretical framework

In this chapter, a literature review concerning research and investigations in energy renovation in Sweden has been summarized. In particular, emphasis was placed on how the renovation planning was carried out in multi-family residential buildings. The chapter sets the scene for the research pursued in this thesis, and how it contributes to new knowledge in the area.

3.1 The definition of renovation

A variety of terms including renovation and retrofitting can be used to describe alterations to buildings, as described by Thuvander et al. (2012). The definition of "sustainable renovation" is more generally agreed upon, and may be described as renovation performed on buildings to upgrade them to more environmentally, socially and economically sustainable ones (Jensen et al., 2018, Thuvander et al., 2012). Often, improvement of building energy efficiency forms an important part of it which may be termed as "energy renovation" (Ástmarsson et al., 2013). Energy renovation is also the main focus of this thesis.

A type of renovation gaining traction and encouraged by the European Union (EU) for the achievement of its climate ambitions is "deep renovation". Deep renovation can be defined as a renovation that reduces energy consumption in a building by more than 60% compared to previous levels (Castellazzi et al., 2016, Femenías et al., 2018).

3.2 The challenges facing building renovation

Insufficient information, lack of capital investments and long payback periods are three main reasons for building owners to be hesitant towards investing in renovation projects (Ferreira and Baptista, 2017). Jensen et al. (2018) listed seven features and challenges that differentiate new constructions from renovations. Existing buildings have a fixed design and architectural form to be worked with, which might restrict the implementation of certain measures. Furthermore, the architecture of the structure will be paramount if the building is deemed worthy of having historical and cultural significance. It is also more important to involve and inform the building occupants in a renovation project as they are primarily the ones who could experience disturbances or even relocation as a result (Jensen et al., 2018).

The "split incentive" or the related landlord/tenant dilemma is one of the biggest obstacles facing renovation projects (Jensen et al., 2018, Economidou and Bertoldi, 2015). Split incentives occur when the resulting benefits of the interventions do not accumulate to the investing stakeholder (Castellazzi et al., 2017). Typically, the landlord provides housing, appliances and installations, whereas the tenant pays the energy bills - individually billed or added as a fixed amount on the monthly rent. The landlord would thus not be too keen on investing time and resources in improving energy efficiency as much as the tenant who would directly benefit from lowered energy bills, provided that the energy cost is individually measured and debited. Otherwise, the tenants would have little incentives to save energy as discussed by Gillingham et al. (2012). Furthermore, as renovations are often financed by tenants through future rent increases, they could be reluctant to support and fully finance something that does not benefit them only (Ástmarsson et al., 2013).

Lind et al. (2016) highlight the danger of making tenants more dependent on governmental aids to pay for higher rents. This could put higher strains on public finances and create large losses to society as a whole (Lind et al., 2016). A renovation with prohibitive expenses could result in rent hikes causing gentrification (Lees et al., 2010), preventing lower income households from moving back to their apartments or "renoviction" (Herrero, 2013) and affecting existing social ties (Öresjö, 2012). Thus, when considering a renovation project that improves energy efficiency of the property at the expense of social sustainability, it is necessary to consider the larger implications and the metaphorical "bigger picture".

3.3 Renovation measures in multi-family buildings

Renovation measures can be categorized into "anyway measures" and "energy saving measures", as described by Ferreira and Baptista (2017). "Anyway measures" refer to those measures that have to be carried out anyway with an aim to restore or maintain the building aesthetics and functionality, and are not intended to affect the energy performance of the building. Usually, the implementation of energy renovation measures are appropriate to be carried out together with "anyway measures" or other improvement work (SABO, 2011).

Energy saving measures are those that have a direct effect on the energy performance of the building and its energy-efficiency. Generally, these can be grouped into three types as (Högberg et al., 2009):

1. **Measures aimed at reducing heat leakage from the building envelope.** Examples include improving the airtightness, replacing windows and adding extra insulation to the outer walls, roofs or the basement.
2. **Measures that can recover outgoing energy.** Examples could be installing balanced ventilation with heat recovery or an exhaust air heat pump.
3. **Measures that limit the energy distribution.** Using energy efficient fixtures such as LED lighting and optimizing the use of building services such as

presence controlled lighting are some examples.

Liu et al. (2014) carried out an investigation of energy retrofitting packages in eleven multi-family buildings in Gävleborg to analyze the potential reduction of energy use and CO_2 emissions. A variety of renovation measures were considered which aimed to reduce the heating and domestic hot water demand. Additional facade/roof insulation, new windows/doors, adjustment of heating system, low-flow faucets and heat recovery systems were some of common measures used in all three packages. Lowering of indoor air temperature, individual measuring and debiting and installation of presence controlled lighting were also considered in two of the packages.

Gustafsson et al. (2016) conducted an investigation to study the environmental and economic aspects of heat recovery systems with other measures to reduce the energy demand. The reference case consisted of district heating and exhaust ventilation without heat recovery. This was compared against three systems with district heating in different configurations along with measures including lower U-value windows, flow reducing water taps and additional insulation of roof and facade.

La Fleur et al. (2019) used the optimization tool OPERA-MILP to identify optimal energy saving measures in a Swedish multi-family building. The renovation measures were grouped into "inevitable" (or anyway) and "energy efficiency" measures. The former included new wood-framed windows and facade repainting and cleaning, whereas the latter included additional insulation in the facade, attic, aluminum-framed windows with low U-values and balanced mechanical ventilation with heat recovery.

Svensson (2017) analyzed the implementation of renovation measures in a multi-family apartment building constructed during the 60's in Malmö following the methodology developed by IEA EBC Annex 56, described in Chapter 3.4. The main aim of the study was to analyze different renovation alternatives and evaluate their effects on the energy use of the building, their cost effectiveness and CO_2 emissions. The measures included additional insulation to the external and basement walls, replacement of windows to low U-value ones, upgrading to a balanced ventilation system and implementation of an individual metering and debiting system to reduce domestic hot water use.

Wang and Holmberg (2015) performed a study where a large number of typical Swedish MHP multi-family buildings were studied. Four types of buildings based on age and size were identified and evaluated separately. The assessment of the energy performance was conducted using the Excel based tool Consolis Retro and validated using IDA ICE and EnergyPlus. To accurately evaluate the effectiveness of each individual renovation measure, a sensitivity analysis was formulated and simulations performed in small incremental steps. Based on the analysis, the most effective energy renovation measures for all four types of buildings were determined.

The most relevant ones that could be proposed in this thesis included improving the heat recovery of the HVAC system and reducing transmission losses (Wang and Holmberg, 2015).

Dalenbäck and Mjörnell (2011) summarized a number of renovation projects conducted between 1999 and 2010 in western Sweden. One of them was located in Gårdsten, Gothenburg and was completed in 2005. The energy saving measures considered in this project included installation of thermal solar panels, recycling of outgoing heat, glazing the balconies and individual energy metering. Another project located at Katjas gata, Gothenburg aimed to achieve a newly-built energy performance standard according to BBR (Dalenbäck and Mjörnell, 2011). To achieve this, additional insulation was provided on the attic, foundation and exterior facade, new 3-pane windows, supply air channels and a rotary FTX unit were installed. Finally, the radiator system was upgraded to a 2-pipe system from a 1-pipe system (Mjörnell et al., 2011).

When a number of energy saving measures are defined they are usually followed by an evaluation of their energy saving potential and economic profitability. The methodology and strategy for this step are presented in the following section.

3.4 Renovation planning framework

The evaluation of the theoretical energy savings and resulting effects of a planned renovation project can generally be divided into three steps. The first step is to evaluate the current energy performance of the building and simulate it using a BPS software. The next step is to apply a number of retrofitting measures to the building model and determine the resulting energy savings. Finally, these savings will be used to evaluate for example the economic, environmental or social impacts of the project (Ma et al., 2012).

The International Energy Agency (IEA) runs a Energy in Buildings and Communities Programme (EBC) program which focuses on research related to energy issues in the building sector. The EBC program has various "Annexes", research projects dealing with a variety of topics. The now-concluded Annex 56, entitled **"Cost-Effective Energy and CO_2 Emissions Optimization in Building Renovation"**, formulated a systematic methodology consisting of 5 sequential phases for planning and conducting such renovation projects (Bolliger et al., 2017). These are: i) the calculation of the primary energy need and carbon emissions, ii) a Lifecycle assessment, iii) a Lifecycle cost assessment, iv) identification and integration of non-financial benefits, or co-benefits and v) analyzing the cost effectiveness and reduction of CO_2 emissions. Svensson (2017) provides an example of a renovation planned following this methodology.

3.4.1 Comparison of pre and post renovation performances

Liu et al. (2014) modelled the building in IDA ICE and validated it against real energy use of the buildings determined from energy bills and EPCs. Various scenarios were set up for calculating the CO_2 emissions, with variations on the energy carriers in Sweden and the Nordics. Gustafsson et al. (2016) used TRNSYS 17 to carry out the Building Energy Simulation. Renovation measures were assessed in terms of Primary Energy Consumption, non-renewable energy consumption, European climate and energy goals and CO_2 emissions.

La Fleur et al. (2019) used an IDA ICE model to validate the results obtained from the tool OPERA-MILP. The tool takes various building input parameters and determines the space heating demand through a heat balance calculation. A comparison of results obtained from the two methods showed good compatibility with each other. In an article published by Mata et al. (2013), the expected energy savings, reductions in CO_2 and the costs of a number of energy saving measures was evaluated for the Swedish building stock. This was done using the MATLAB based tool Simulink to simulate the typical behavior of a building. The results of 1400 cases were further post-processed to extrapolate the results to the entire Swedish building stock (Mata et al., 2013).

3.4.2 Economic profitability

An economic analysis can provide the basis for comparison between different renovation measures and whether the measures are energy-efficient and cost-effective (Ma et al., 2012). Lind et al. (2016) defined a certain investment generating a satisfactory rate of return as an economically sustainable renovation project. Public housing companies are also required by law to follow these demands on economical profitability (Sveriges Riksdag, 2010).

The net present value (NPV), internal rate of return (IRR), discounted payback period (DPP) and simple payback period (SPP) are commonly used methods to determine the economic profitability of a single measure. For multiple renovation alternatives, the Lifecycle cost analysis (LCCA) method and the levelized cost of energy can be used to evaluate profitability (Ma et al., 2012). IEA EBC Annex 56 recommends the use of a dynamic LCCA such as the global cost or the annuity/EAC method to determine the profitability of the renovation packages (Bolliger et al., 2017).

Wang and Holmberg (2015), Gustafsson et al. (2016) and Liu et al. (2014) used an LCCA based on the NPV method to determine the profitability of a renovation. The initial investment, annual operational energy and maintenance costs during the chosen lifetime of the renovation was used to determine the NPVs. La Fleur et al. (2019) used OPERA-MILP to determine the lowest LCC in terms of NPV calculated from the input energy tariffs, service lives and investment costs. It was concluded from the study that it was not cost-effective to invest in highly ambitious energy reducing measures such as ventilation heat recovery and facade insulation (La Fleur et al., 2019).

Based on the analysis performed by Wang and Holmberg (2015), some of the most cost effective renovation measures for a building similar to the case study building in this thesis were presented. These measures included installing heat recovery, improving the airtightness of the building and replacing the southern facing windows.

The project at Katjas gata, Gothenburg presented by Dalenbäck and Mjörnell (2011) turned out to be economically unprofitable and required a lot of external investment. The much "lighter" renovation at Gårdsten ended up being profitable in the end, having a simple payback period of less than 20 years (Dalenbäck and Mjörnell, 2011).

3.5 Developments in EU and Sweden concerning building renovation

The European Union has, for the greater part of the last decade, highlighted and emphasized the importance of renovation in buildings to achieve an energy efficient and decarbonized building stock. It introduced the Energy Performance of Buildings Directive (EPBD) in 2010 and Energy Efficiency Directive (EED) in 2012, legislative frameworks to guide its member states towards the achievement of its goals. These were updated in 2018, and further planning is underway to review it in 2021 (European Union, 2021).

The EU Green deal was announced in December 2019 as a new growth strategy to transform the continent into a net zero Greenhouse gases (GHGs) emissions region by 2050. The Commission proposed to increase its initial GHGs emission reduction target from 40% to 55% by 2030 compared to 1990 levels as part of the Green Deal (European Union, 2020a). One of the strategies to achieve this was increased energy efficiency through the transformational policy of "Building and renovation in an energy and resource efficient way" (European Union, 2019). In October 2020, as part of the Green deal, the Renovation Wave was also announced with the objective to double the annual energy renovation rate of buildings by 2030 (to 3%) and to encourage deep renovation in buildings (European Union, 2020b).

In Sweden, a number of national ambitions have been delineated aiming to reduce building energy use and future GHG emissions. In response to EU developments, the Swedish government submitted an integrated national energy and climate plan in 2019 whereby these targets and goals were summarized. (Ministry of the Environment and Energy, 2019). In buildings, the current goal is to reduce the total energy use per floor area by 50% by 2050 counting from 1995 (Boverket, 2007).

In 2016, the Swedish government introduced a new support policy to encourage and incentivize energy renovations of rental apartments in socio-economically troubled areas (SverigesRiksdag, 2016). 800 million SEK was allocated for this initiative and the eligible support was calculated based on the estimated level of energy efficiency after renovation, which should be at least 20 percent (Ministry of the Environment and Energy, 2019). This support scheme ended in 2018.

Boverket introduced the Primary Energy Number, or EP_{pet} as a measure of the building's energy performance from 1 July 2017, starting in BBR 25. BBR specifies EP_{pet} values for new buildings that have to be conformed with. If these values cannot be achieved following a renovation, certain U-values have been prescribed aiming towards an energy-efficient building envelope. These values are summarized in Table 3.1 (Boverket, 2020). BBR also describes general recommendations for building renovations stated as "Requirements for alterations to buildings".

Table 3.1: BBR's recommended U-values

Part of building envelope	U-value (W/m^2K)
Roof	0.13
Wall	0.18
Floor	0.15
Window	1.2
Exterior door	1.2

3.6 Summary and conclusions of literature review

The emphasis placed by the European and Swedish policies on renovating the existing building stock demonstrates the significance of sustainable renovations and the need to develop effective ways to plan them.

One of the key takeaways from the literature study was that most of the existing research either focused on in-depth renovation of a single building/object, or a larger collection of the building stock studying more generalized renovation measures. Examples of the former include studies done by Liu et al. (2014), Svensson (2017), La Fleur et al. (2019), Gustafsson et al. (2016) and Dalenbäck and Mjörnell (2011). These studies are very specific to a particular building and therefore, harder to draw general conclusions from.

On the other hand, there are broader studies dealing with a larger building stock with a higher number of objects/sample sizes, sometimes numbering in the thousands. Examples of these include studies done by Mata et al. (2013), Mangold et al. (2016) and Wang and Holmberg (2015). Consequently, it is difficult to narrow down the findings and conclusions to specific building cases.

There exists a knowledge gap in investigating a group of buildings connected to the same district heating substation, built in the same year and having similar architectural properties. Furthermore, as such buildings are located in the same neighborhood, it would be more pragmatic to plan and execute a single project to renovate all the buildings together. Thus, this thesis aims to understand the implications of planning and executing such a renovation. Extrapolating the results of the energy simulation and economic analysis from a single building to the interconnected ones has also been explored in the thesis.

Another important finding of the literature study was determining which energy saving measures were the most cost effective to perform for the specific set of buildings in this thesis. It is, of course, difficult to know beforehand which measures will be profitable since they are highly dependent on the building's properties, components, location etc. However, attempts to make older buildings reach modern energy use standards seem to be difficult to justify economically. An example is the project at Katjas Gata, Gothenburg where a lot of extensive and costly measures had to be implemented simultaneously to reach the project goal (Dalenbäck and Mjörnell, 2011). These included upgrading the exhaust ventilation system and replacing the windows. La Fleur et al. (2019) also concluded from their study that it was not cost-effective to invest in ambitious energy measures such as ventilation heat recovery and facade insulation.

Finally, according to the conducted literature review on renovation planning framework, the methodology in this thesis will focus on two elements: i) performing energy simulations for the assessment of pre- and post-renovation energy performance and ii) economic analysis to evaluate the cost-effectiveness of renovation measures. These are described in detail in Chapter 5, IDA ICE modelling and input parameters, Chapter 6, Calibration of results and Chapter 8, Economic analysis.

4
Project description and case study building

4.1 The housing company

Poseidon AB is a Swedish municipal housing company forming part of Förvaltnings Framtiden AB owned by Göteborgs Stad (Förvaltnings AB Framtiden, 2021). Poseidon owns around 27,000 apartments in Gothenburg with a total living space of 1.7 million square meters (Poseidon AB, 2021). It is a part of the Swedish public benefit (Sveriges allmännytta) and a signatory of its climate initiative (*Klimatinitiativ*) introduced in 2018. The housing company would thus like to plan for a prototype renovation project of a type of their building stock from the Million Homes Programme (MHP).

4.2 Description of the target buildings

The target buildings encompass the addresses Baron Rogers (BR) Gata 5-12 and 21-28 and are located in Hisings Backa, Gothenburg. They are a typical example of multi-family residential buildings (*flerbostadhus*) built in the 70s as part of the MHP. Buildings of such architecture are often called *lamellhus*. Out of the six buildings, two of them are 4-storied whereas the rest are 3-storied buildings. Only BR 24/25 will be modelled and simulated in IDA ICE and is referred to as the "case study building".

The case study building consists of three floors above the ground and a basement floor below the ground. There are 4 apartments in each above-ground floor i.e. there are 12 apartments in total. The basement of the case study building consists of the district heating substation (*undercentral*). It supplies District Heating (DH) from the energy supplier to five other connected buildings in the area (shown in Figure 4.1). DH is used for space heating and domestic hot water production.

Since the building's commissioning in 1970, it has undergone a few renovations, albeit not a major one. The most recent one was in 2009, when a refurbishment (*upprustning*) was carried out consisting mainly of minor upgrades such as painting the exterior facade and replacing the street and staircase lighting.

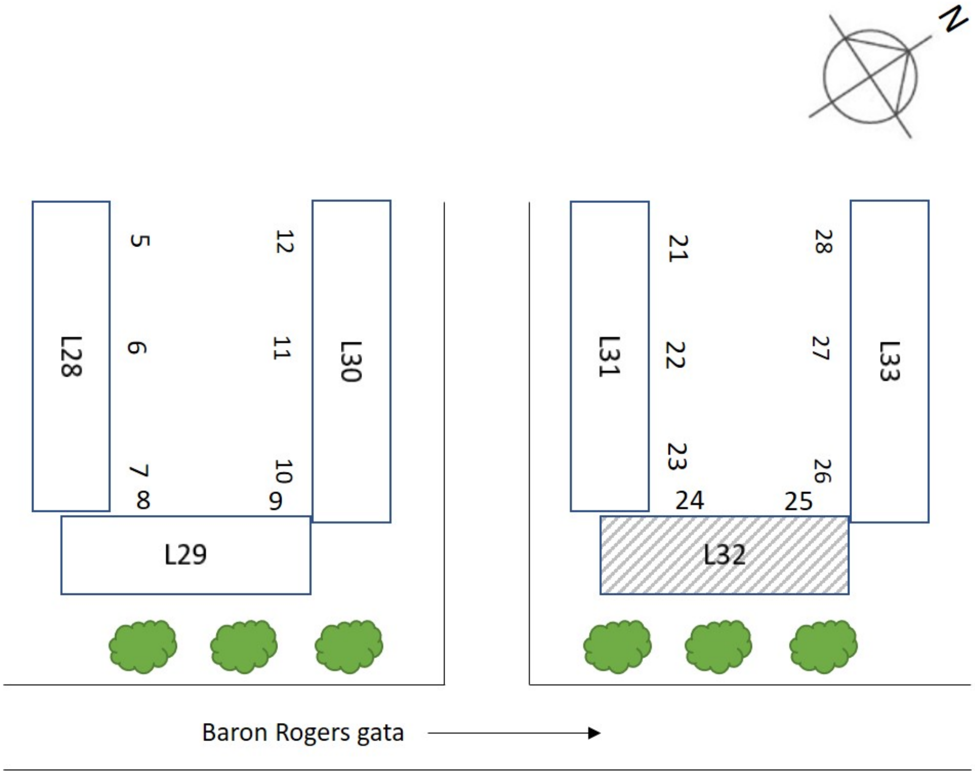

Figure 4.1: The six target buildings with the case study building (shaded)

Figure 4.2: The case study building and the surrounding area. (Source: Google maps)

4.2.1 Building envelope

The exterior walls are made of prefabricated elements consisting of two layers of concrete separated by an insulating material in the middle. Based on structural drawings provided by the housing company, the thickness of the insulation is 100 mm whereas of the two concrete layers is 80 mm each. Buildings with these types of sandwich elements are usually insulated with EPS (Expanded Polystyrene) (Björk et al., 2002). Visual inspections show that the exterior walls are in relatively good condition and show no serious signs of deterioration. Gypsum boards of 13 mm are assumed to be on the inside of the walls. A drawing of the cross section of the exterior wall is shown in Figure 4.3.

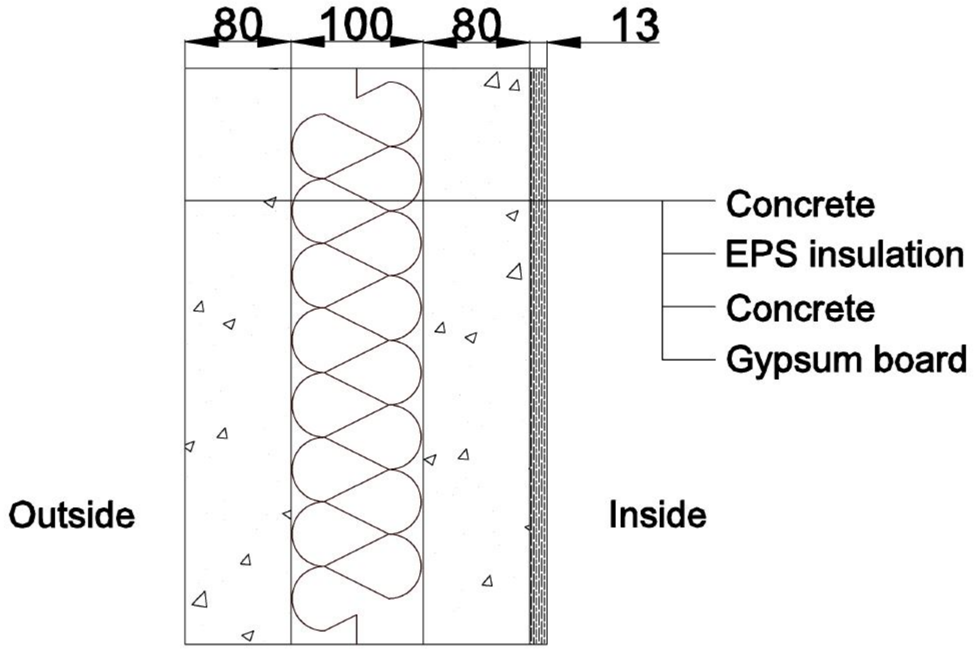

Figure 4.3: External wall section of the case study building

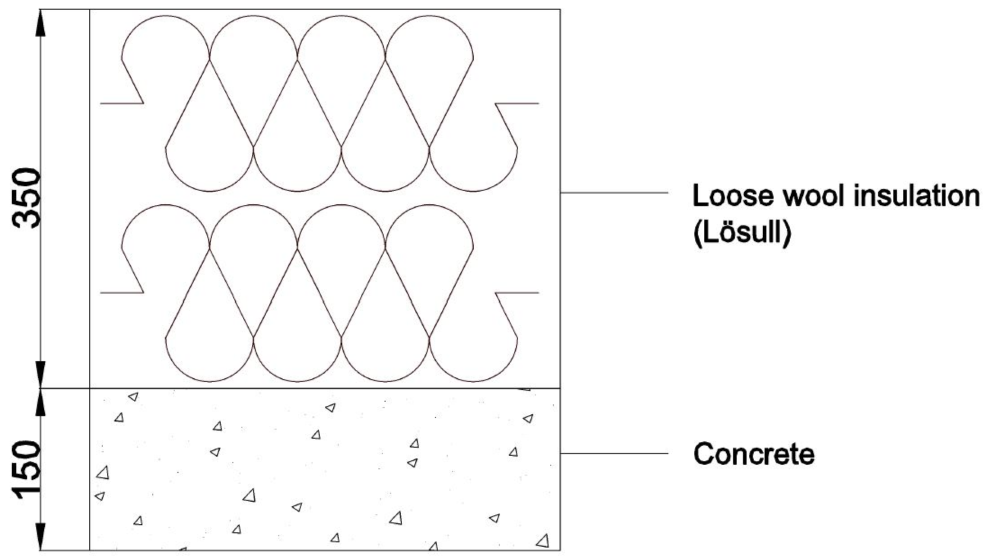

Figure 4.4: Attic floor section of the case study building

During the site visit, the height of the windows was measured to be 1.2 m and found to consist of 2-panes. 2-pane windows (without gas infill) of buildings constructed during the 70s usually have a U-value of around 2.9 W/m^{2}K (Adalberth and Wahlström, 2007).

The attic is insulated with blow-in wool (*lösull*) insulation that is covering most of the attic floor. The thermal conductivity of this insulation is 0.045 W/(mK) (Boverket, 2018). Based on site measurements, the average thickness of the insulation was determined to be 0.35 m. According to the housing company, some additional attic insulation was added during the 90s. A drawing of the cross section of the attic is shown in Figure 4.4.

The basement floor likely consists of a concrete slab with a cement bound LECA layer underneath, both of 150 mm thickness (Björk et al., 2002). The thermal conductivity of LECA is 0.20 W/(mK) (Boverket, 2018).

Due to lack of information required to accurately determine the effect of thermal bridges in the building, an assumption was made regarding such losses. The transmission losses due to thermal bridges was taken as 30% of the total conductive heat losses through the building envelope, based on Miljöbyggnad (Sweden Green Building Council, 2020).

4.2.2 Building services

As with most multi-family apartment buildings of that time (Boverket, 2010), the building ventilation is an exhaust-only (F) system consisting of a single exhaust fan located in the attic. There are exhaust vents installed in the bathroom, kitchen and closet of each apartment, which are connected via a duct system to the fan. There is no supply air coming into the rooms, other than through infiltration from some supply air vents in the walls.

The ventilation adjustment carried out in 2017 shows the different airflow values in each apartment. It indicates that the exhaust airflow in the building meets the minimum target airflow of 0.35 L/(m^{2}s) according to BBR (Boverket, 2020). Through a calibration process described in Chapter 6, the SFP of the fan was determined to be 2 kW/(m^3/s).

The delivered temperature and the main supply temperature of domestic hot water was obtained from the substation operational schematic (*driftbild*). According to it, the main water supply temperature is 1.6°C whereas the delivered temperature of hot water is 59°C. The data from the operational schematics are likely taken during the colder months of the year, thus explaining the low supply temperature of the water.

4.2.3 Ventilation losses

The building has a few supply air diffusers located on the exterior facade that contribute to the intentional ventilation of the building. It should be noted that the building's airtightness has a lower influence on the energy use in an extract-only ventilation system compared to a supply and extract ventilation (Adalberth and Wahlström, 2007). Thus, an airtight building is an important consideration if the ventilation system would be upgraded in future renovation packages.

Due to the unavailability of a blower door test, the airtightness of the building was estimated with the help of literature studies. It was determined that a leakage coefficient of 1.2 $L/(m^2s)$ at 50 Pa was suitable for a building made at that time (Zou, 2010), which includes both the intentional and unintentional ventilation in the building.

4.3 Determination of A_{temp}

Based on Boverket's guidelines, the A_{temp} of the building includes the heated area in the basement. However, it has been excluded in this study to reflect the area used in the EPC for the calculation of energy performance and thus enable comparisons. Furthermore, this is an area that is seldom accessible to the tenants and is only heated to keep the building subsystems from developing frost. Thus, the A_{temp} was taken as **1156 m^2**.

4.4 Available data

4.4.1 Energy performance certificate *(Energideklaration)*

The Energy Performance Certificate (EPC) states that the energy use of the building is **158 kWh/m^2 A_{temp} per year** and falls in the "F" Energy class. This is based on the building's specific energy use with a normal-year correction based on SMHI's Energi-Index. The district heating usage is **147,072 kWh** per year, out of which **29,050 kWh** is used for domestic hot water preparation.

The building's facility electricity (*Fastighetsel*) is **26,600 kWh**, which includes fixed lighting in common areas such as staircases, basements and electricity used for pumps, fans, motors, control and monitoring (Boverket, 2020). This is, in fact, a discrepancy owing to the actual electricity use of the building, which has been discussed in Chapter 4.4.3.

4.4.2 District heating meter

In the basement, there is one meter measuring the total consumption of district heating in six buildings. The corrected (normalized) consumption in 2019 was **1400 MWh**, directly taken from data provided by the housing company. To estimate the consumption of only the case study building, a distribution was made on the assumption that each building consumed a similar amount of heating energy per unit area. This area distribution has been described in Appendix A and the yearly district heating consumption of the case study building was obtained as **168,000 kWh**.

4.4.3 Electricity meter

In the case study building, there are two distribution boxes consisting of two meters measuring the total facility electricity of the building. There are also six meters measuring the electricity consumption of the individual apartments, also referred to as the tenant or household electricity. This is not included in the building's energy use.

Upon analyzing the hourly electricity data from BR 25, a distinct pattern was observed suggesting that the outdoor lighting was also being measured by it. During the shorter days of January, electricity consumption was lower and narrower during the day, whereas higher and wider when it got darker. During the longer daylight hours of July, the opposite held true. This can be observed in Figure 4.5.

On the other hand, meter 24 showed a much more steady and realistic pattern of the building's facility electricity, as seen in Figure 4.6. Therefore, only the consumption of meter 24 in 2019 was chosen as the total electricity consumption of the building. Furthermore, BBR excludes the electricity consumption of outdoor lighting in the building's energy use (Boverket, 2020).

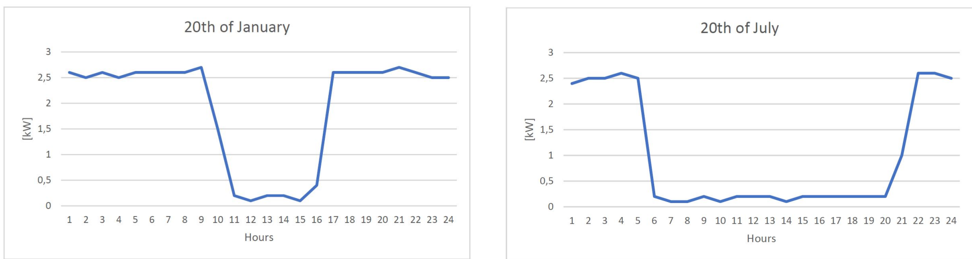

Figure 4.5: Electricity use pattern in BR25 indicating outside lighting measurement

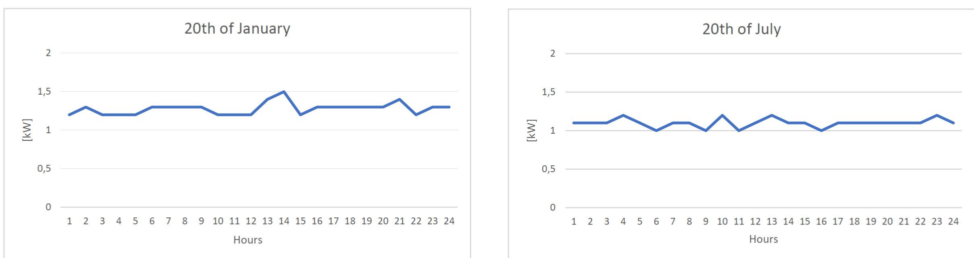

Figure 4.6: Electricity use pattern in BR24

5

IDA ICE modelling and input parameters

This chapter describes the modelling of the case study building in IDA ICE, and the various assumptions and assertions made to determine the required input parameters. The building model can be seen in Appendix B.

5.1 Building envelope

The U-values of various parts of the building envelope were obtained in IDA ICE as shown in Table 5.1.

Table 5.1: U-values obtained in IDA ICE

Building part	**U-value** (W/m^2K)
Exterior wall	0.32
Roof	0.12
Floor slab	1.1
Windows	2.9

The ground slab was modeled with 1 meter of soil under it and follows the methodology described in ISO-13370 for heat transfer into the ground. The assumption of 30% transmission losses due to thermal bridges was modelled directly by using a single factor of **0.202 $W/K/m^2$** for the whole envelope. The envelope area calculated in IDA ICE is **1468.6 m^2** and this resulted in losses of **297 W/K**. A leakage coefficient of **1.2 $L/(m^2s)$ at 50 Pa** was taken which includes both the intentional and unintentional ventilation (holes and cracks) in the building (Zou, 2010).

5.2 Building services

The air handling unit was chosen as **Return air only (no supply side)** and all of the ventilation flows in the zones were chosen as a Constant Air Volume (CAV) system with a return air flow of **0.35 $L/(m^2s)$**.

The average energy use from hot water consumption was set at **25 kWh/(m^2 floor area per year)** for each of the apartment zones (SVEBY, 2012). This can be viewed in Appendix B. Furthermore, distribution system losses of **0.5 W/A_{temp}** was assumed to account for thermal losses from hot water and space heating distribution within the building.

The setpoint temperatures for heating were initially set to 21°C in each apartment based on SVEBY's indoor temperature recommendations (SVEBY, 2012). However, temperature data from Curves indicated that the average temperatures in a few apartments were well above 21°C, even during the coldest months of the year (seen in Figure 5.1). This overheating of the apartments meant that the building would consume more energy compared to when all the spaces were heated evenly. The simplest way to incorporate this was to change the setpoint temperatures in every overheated apartment in the model. The modified apartments and their temperatures can be found in Appendix C.

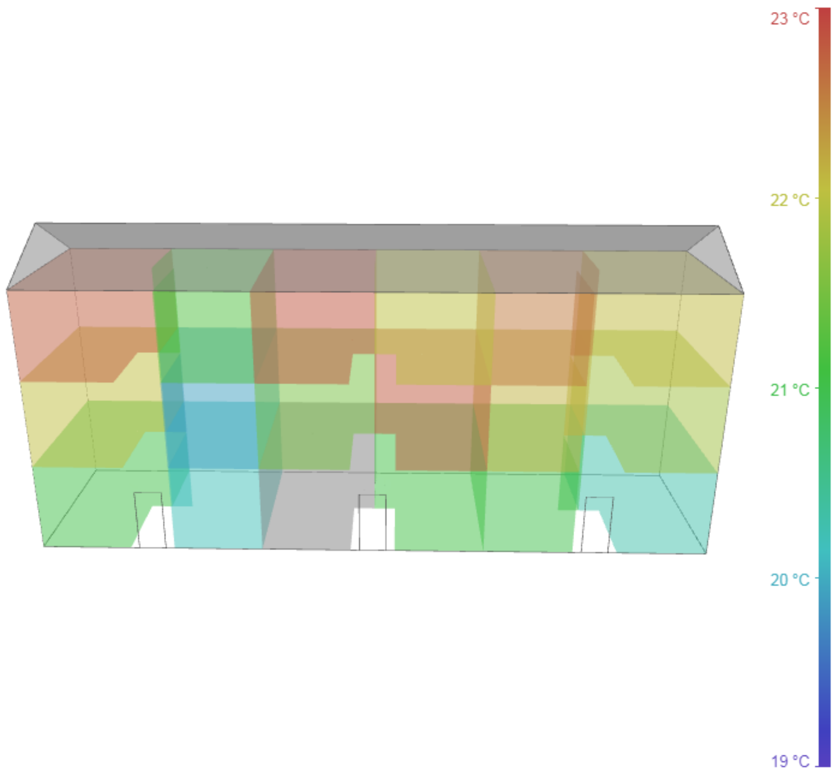

Figure 5.1: Apartment temperatures during December in one of the buildings

5.3 Weather files

To simulate the energy use of the building in a standardized way, climate data representing a normal year was used in IDA ICE. This was obtained from the Swedish Meteorological and Hydrological Institute (SMHI) website which contained one year of hourly weather data in Sweden for the time period 1981-2010 (SMHI, 2021). These climate files represent an average climate from a heating and cooling needs perspective, the so-called "typical years" (SMHI, 2021). This was considered over the default ASHRAE climate files in IDA ICE to obtain results more representative of the Swedish climate. Thus, normal year correction of the energy consumption is not needed in post-processing.

5.4 Internal heat gains

5.4.1 Occupants

The average heat emitted by one tenant was taken as 80 W (SVEBY, 2012). In IDA ICE, this corresponds to a metabolic rate of 0.8 or “reclining rest” activity. Furthermore, the recommended number of tenants in each apartment was chosen depending on the number of rooms (Y. Svensson, 2017).

The presence of occupants in the apartments is expected to vary over a typical day. Therefore, schedules based on the expected occupancy patterns were used in IDA ICE. The schedules were built on the assumption that all the occupants would be present from 8 pm at night to 7 am the next day. Furthermore, the number would be the lowest during the day when the occupants could be expected to be outdoors. During weekends and holidays, the pattern is somewhat similar but slightly narrower as can be seen in Figure 5.2.

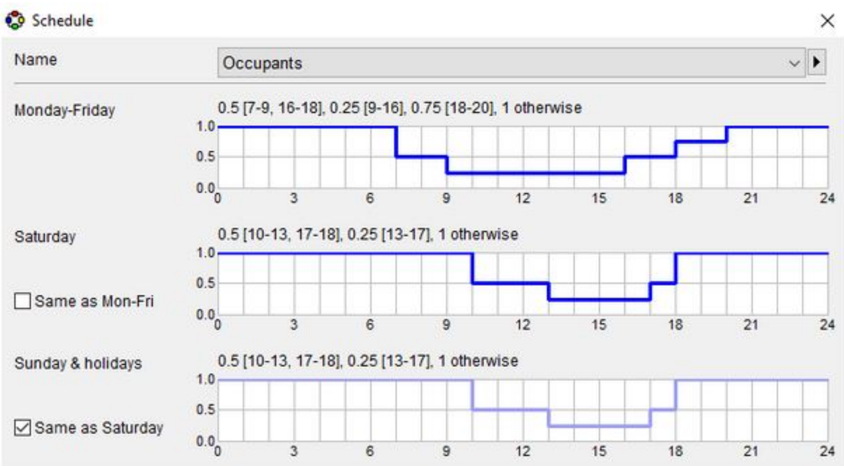

Figure 5.2: Occupant schedules used in IDA ICE

The internal gains from lighting and appliances were determined with the help of a Swedish Energy Agency report presenting measurements of 400 Swedish households authored by Zimmermann (2009).

5.4.2 Lighting

The average number of bulbs in an apartment was assumed as **0.34 bulbs/m²** (Zimmermann, 2009). The number of bulbs in each apartment was then calculated based on this number and the apartment area. The type of bulb was chosen as a

5.2 W, 470 lumen LED bulb from IKEA to reflect today's standards (IKEA, 2021). The daily schedules for the total consumption is shown in Figure 5.3, where the intensities lie between 0 and 1 indicating no usage and full usage, respectively.

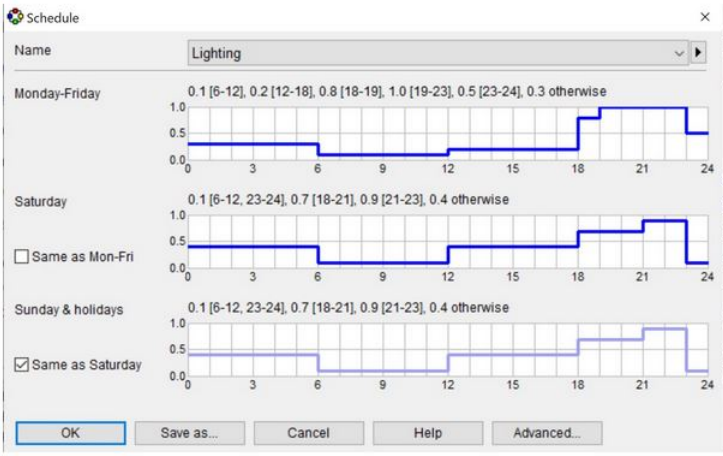

Figure 5.3: Lighting schedules used in IDA ICE

5.4.3 Appliances

When determining the internal gains from appliances, it was assumed that each apartment had the standard appliances such as a TV, refrigerator/freezer, stove, dishwasher and a desktop computer. The larger apartments were however, simulated with two computers to differentiate them from smaller ones. The usage of the appliances at specific hours of the day was determined and added to get the total power usages. Based on this, the relative variations were calculated and converted to schedules in IDA ICE. The detailed calculations can be viewed in Appendix D.

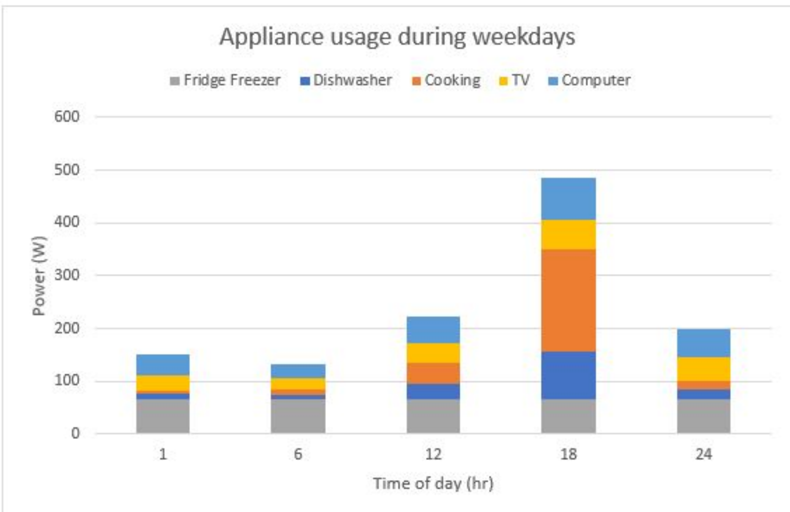

Figure 5.4: Appliance usage in the apartment during weekdays

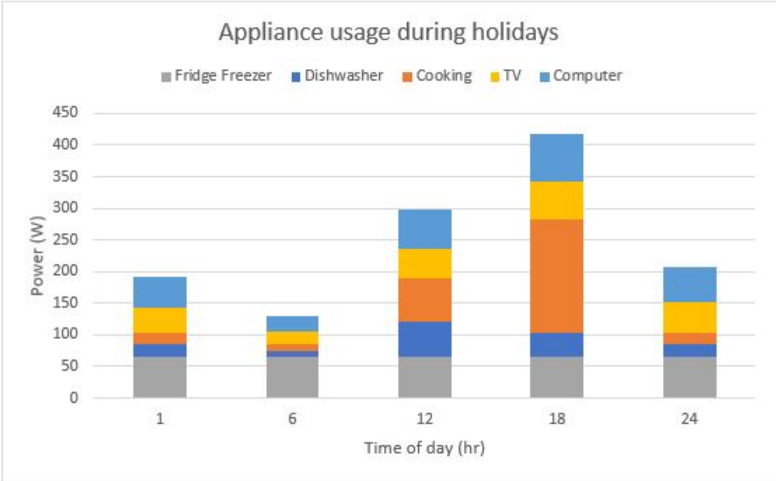

Figure 5.5: Appliance usage in the apartment during holidays

Table 5.2: Internal gains used in IDA ICE

Type of thermal load	Description
Tenants	**Density:** Depending on the number of rooms in each apartment (Y. Svensson, 2017) **Thermal load per person:** 80 W **Metabolic rate:** 0.8 (reclining rest)
Appliances	According to Figure 5.4 and Figure 5.5
Lighting	**Bulb Density:** 0.34 bulbs/m^2 (Zimmermann, 2009) **Bulb Power:** 5.2 W (IKEA, 2021)

5.5 First simulation results

The results from the first energy simulation in IDA ICE is shown in Figure 5.6.

Delivered Energy Overview

	Purchased energy		Peak demand	Primary energy	
	kWh	kWh/m^2	kW	kWh	kWh/m^2
Lighting, facility	152	0.1	0.05		
Electric cooling	0	0.0	0.0		
HVAC aux	5208	4.5	0.64		
Total, Facility electric	5360	4.6		0	0.0
District heating	110931	96.0	45.63	77652	67.2
District heating hot water	30069	26.0	3.43	21048	18.2
Total, Facility district	141000	122.0		98700	85.4
Total	146360	126.6		98700	85.4
Lighting, tenant	5117	4.4	1.55		
Equipment, tenant	12283	10.6	2.68		
Total, Tenant electric	17400	15.1		0	0.0
Grand total	163760	141.7		98700	85.4

Figure 5.6: Initial "Delivered Energy" report in IDA ICE

The facility electricity use of the building was obtained as **4.6 kWh/m^2**. The DH consumption for space heating and domestic hot water preparation was obtained as **96 kWh/m^2** and **26 kWh/m^2**, respectively. As could be expected, the energy use for space heating and domestic hot water form a considerable part of the building's energy use. A comparison of the simulated and measured energy use values is shown in Table 5.3:

Table 5.3: Measured and simulated energy use in BR 24, 25

Energy type	Energy meters (kWh)	IDA ICE reference
District heating	168000	141000
Electricity	10900	5400

Based on these results, it was inferred that some energy losses were being unaccounted for by the model. This presented the need for calibrating the model to reflect the actual energy consumption of the building. This has been described in the next chapter.

6

Calibration of results

This chapter deals with the calibration of results obtained from the first simulation in IDA ICE.

6.1 Electricity use

The SFP of the exhaust fan was calibrated to achieve a realistic electricity consumption from the IDA ICE model. The initial simulation of the case study building generated an electricity consumption half that of the measured consumption, as seen in Table 5.3. This could partly be explained by the fact that the electricity meter at BR 24 was also measuring the consumption of the space heating and hot water distribution pumps utilized by all the six buildings. This presented a challenge as it was necessary to exclude the electricity usage of these pumps when calibrating the fan SFP.

This was done by analyzing the monthly consumption of meter 24 shown in Figure 6.1. There was a drop from **1000 kWh/month** to **800 kWh/month** in the electricity use around April which went back up again in September. This was nearly consistent with the end and beginning of the heating season of the building, as seen in Figure 6.3. The drop could be due to the space heating distribution pump being turned off during the warmer months. This drop of about **200 kWh/month** could therefore be taken as the monthly consumption of the pump.

Assuming that the hot water distribution pump had an equal power demand, the consumption of the fan could be estimated as **600 kWh/month** or **7200 kWh/year**. This value was used to calibrate the fan and motor properties in IDA ICE. When an SFP of 2 kW/(m^3/s) was selected in the model, the consumption of the HVAC system was obtained as **6,878 kWh/year** which was comparable to the expected consumption of **7,200 kWh/year**.

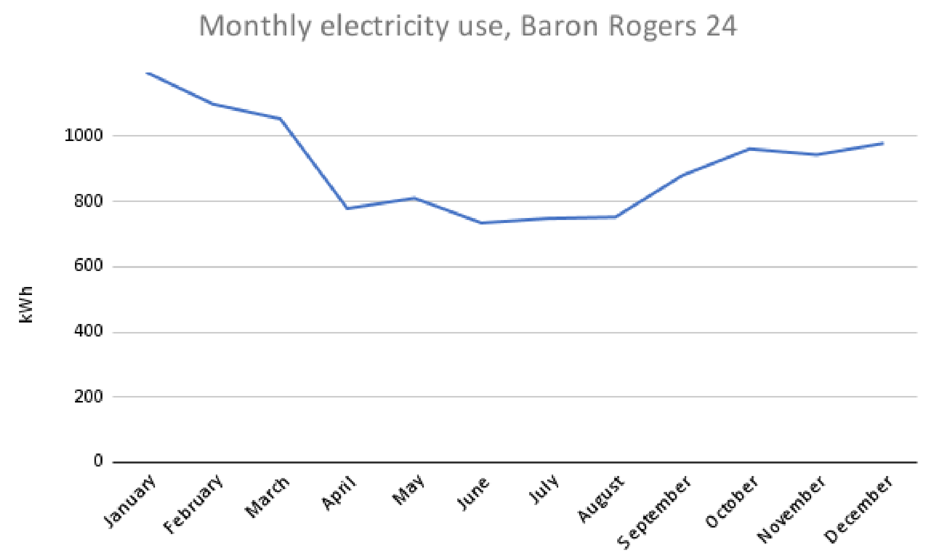

Figure 6.1: Monthly electricity use in 2019 for Baron Rogers 24

6.2 Distribution losses

Determining the distribution heat losses from the DH substation to the rest of the buildings was important to account for the discrepancy between the simulated and measured DH use of the building. These losses were estimated with the help of meter readings of the hourly DH consumption. The pipe characterstics such as the radial dimensions and length, type of insulation were unknown parameters. Thus, a few assumptions had to be made to determine the thermal losses through these pipes which is described in the following subsections.

6.2.1 Hot water distribution

The first step of this process was to determine the heat losses from the hot water distribution system.

To ensure quick delivery of hot water to the tenants, at least a part of the distribution system is circulated with pumps, which can be seen in Figure 6.2. The distribution system consists of a circulating part that is connected to the DH via a heat exchanger. From this main pipe, additional pipes are branching out to the faucets where there is no circulation. This results in a baseline loss from the circulating pipe that will always be present, even when hot water is not being consumed.

During a late summer night, it is reasonable to assume that there is no consumption from space heating (as the heating is turned off) or hot water use. The hot water consumption during these hours could be attributed to this baseline loss, which was determined to be **20 kW** from the hourly consumption of DH. Assuming this as constant over the year, it would result in a total loss of **175.2 MWh**. Considering that this loss is evenly distributed among the six buildings, this equates to a loss of **18 kWh/m²** per year where the considered area is the floor area of all six buildings, i.e 9755 m^2. This value is high but can be considered reasonable when compared to previous studies (BeBo, 2015).

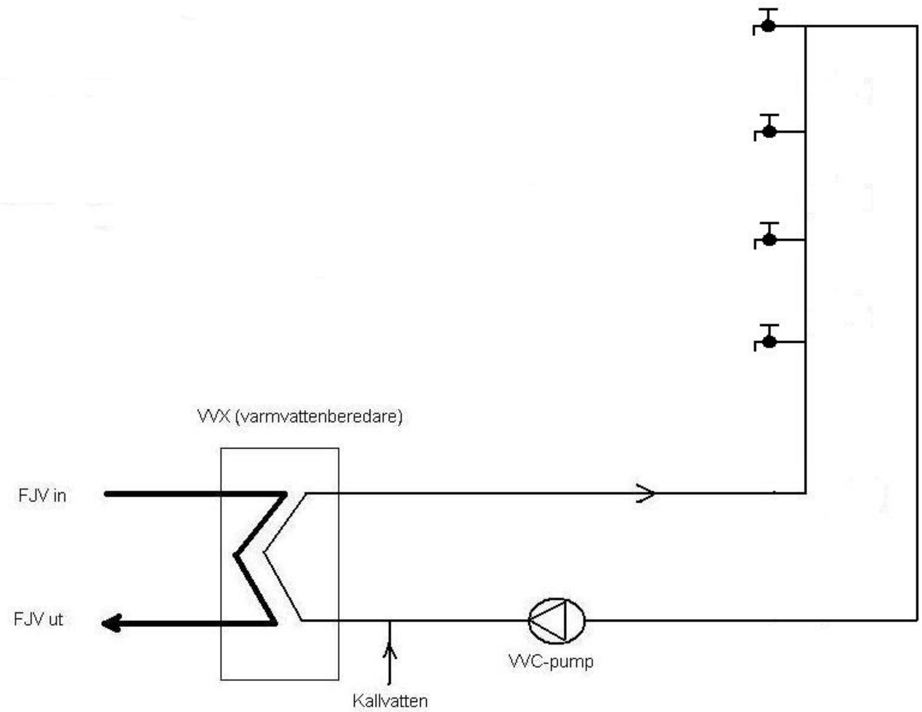

Figure 6.2: A schematic of a hot water circulation system, CC0 1.0 (GreenManXY, 2011)

The drawback of this method is that it only takes the distribution losses in the circulating part of the system into account. There are also additional losses from the pipes that branch off from the circulation system and into the faucets. However, it is expected that a large part of these losses either contribute to the heating of the apartments or are already accounted for in IDA ICE, which can be viewed in Chapter 5.2.

6.2.2 Space heating distribution

The same approach could not be used when determining the losses through the pipes in the space heating system. As the distribution losses and actual usage of the system always occur together unlike hot water, it was difficult to separate these in the data. Additionally, there is a large portion of the year when the heating system is completely turned off. Thus, a baseline loss would need to be reduced to account for this.

The losses from the pipes could be determined using the relationship describing thermal transmission through pipes (Frederiksen and Werner, 2013). It was assumed that both the hot water and space heating distribution system had the same length, diameter and insulation thickness of pipes. This was defined as a constant "S" in calculations, shown in Appendix E. If this was the case, only the temperature of water inside the pipes would make a difference in the thermal losses. This was obtained by assessing the supply and return temperatures in the substation operational schematic. An average temperature of 9°C of the ground could be used for the calculations (Gabrielsson, 1995).

From this method, the thermal losses from the pipes of the distribution system was determined to be **14 kW**, which over a year amounted to **122.6 MWh**. This energy loss needed to be reduced to account for the fact that the heating system was not in operation year-round unlike the hot water system. According to the housing company, the heating was turned off if the outside temperature was above 15°C and turned on if it fell below 14°C, for 3 hours or longer. Using this fact together with the outdoor temperature, the length of the heating period over a year could be approximated.

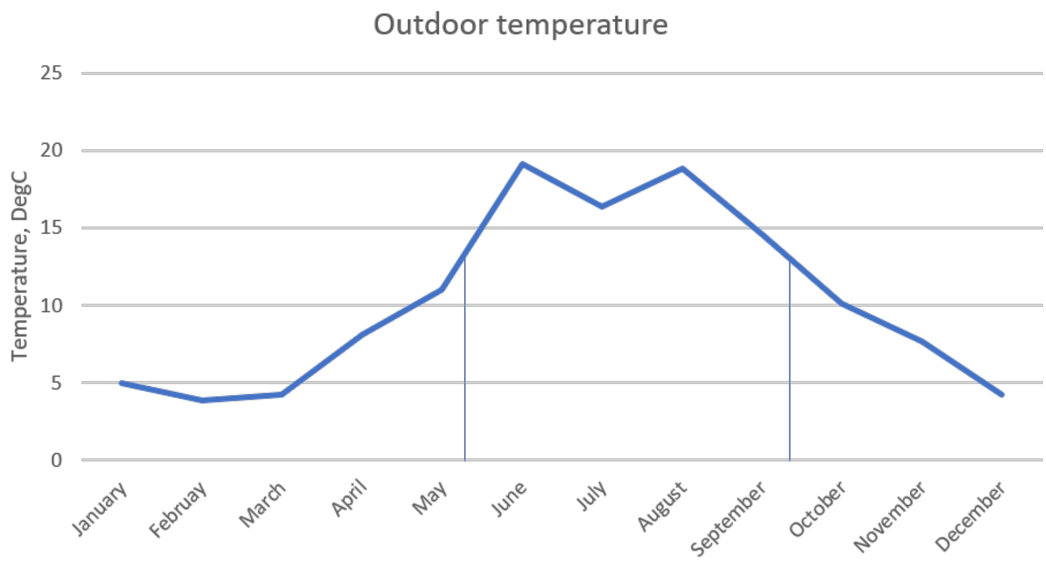

Figure 6.3: Monthly outdoor temperatures from 2020.
The blue lines indicate the end and beginning of the heating season.

The proportional length of the year when the heating system needed to be turned on was **66.7%** according to Figure 6.3. Thus, the correct distribution loss from the heating system is = 66.7% x 14 kW = **9.3 kW**. Following the same assumption made in section 6.2.1 that the distribution losses are spread evenly among the buildings, it would result in a total yearly loss of **81.5 MWh** or **8.3 kWh/m^2** per year. When the hot water and space heating distribution losses are added together, it results in a total loss of **26.3 kWh/m^2** per year which can also be viewed in Appendix A.

One of the biggest shortcomings of this method is that it is disregards the distribution losses from the pipes that branch out from the main pipe. Furthermore, it also assumes that the hot water and the heating pipes share the same characteristics such as the total length, internal diameter and insulation. If any of these parameters would differ in reality, the results would deviate. These characteristics are, however, not expected to differ substantially. Even if they would, they are expected to be within the margins of error for the purpose of this thesis. Additionally, like the domestic hot water system, the majority of the pipes that branch out from the main pipe and into the radiators are expected to be within the building itself and the resulting losses are therefore expected to contribute to space heating or being accounted for in Chapter 5.2.

6.3 Model verification

After running the energy simulation again with the calibration of the fan SFP, the result was obtained as seen in Figure 6.4. The main parameter that has changed is the "HVAC aux" electricity consumption, now **6878 kWh** from the initial **5208 kWh**.

Delivered Energy Overview

	Purchased energy		Peak demand	Primary energy	
	kWh	kWh/m^2	kW	kWh	kWh/m^2
Lighting, facility	152	0.1	0.05		
Electric cooling	0	0.0	0.0		
HVAC aux	6878	6.0	0.83		
Total, Facility electric	7030	6.1		0	0.0
District heating	110931	96.0	45.63	77652	67.2
District heating hot water	30069	26.0	3.43	21048	18.2
Total, Facility district	141000	122.0		98700	85.4
Total	148030	128.1		98700	85.4
Lighting, tenant	5117	4.4	1.55		
Equipment, tenant	12283	10.6	2.68		
Total, Tenant electric	17400	15.1		0	0.0
Grand total	165430	143.1		98700	85.4

Figure 6.4: Calibrated "Delivered Energy" report in IDA ICE

Figure 6.5 shows the comparison between the measured data and the simulation results together with the calculated distribution losses. The distribution losses account for extra losses in district heating. It can be observed that there is a very close correspondence between the measured and the simulated consumption when such losses are accounted for. This gives an energy consumption of **153 kWh/(m^2 year)** and **154 kWh/(m^2 year)** for the measured and calculated data respectively.

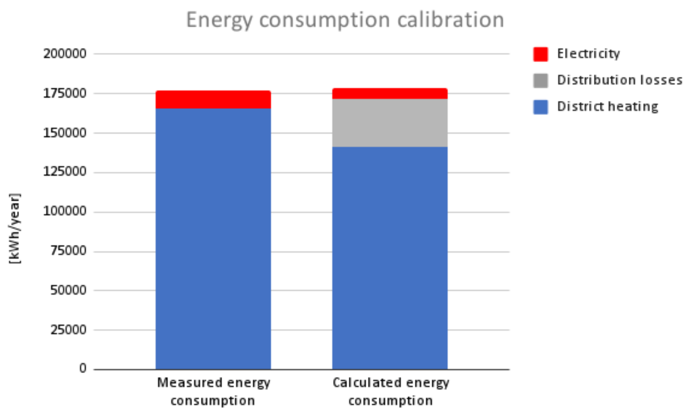

Figure 6.5: Comparison between measured and calculated consumption of the case study building

7 Package solutions

This chapter describes the process of formulation of the renovation packages.

7.1 Summary of the process

1. A variety of possible renovation measures for the case study building was drawn up.
2. A number of simple measures applicable to all renovation packages were grouped together. These were referred to as "baseline measures".
3. Renovation measures considered less relevant for the building were excluded from the list. Thus, adding further insulation to the attic was excluded as its current U-value met the recommended U-value in BBR (Boverket, 2020).
4. Each measure was assigned a level describing the extent of the renovation. For example, additional exterior wall insulation was divided into thicknesses of 50, 100 and 180 mm.
5. Combinations of measures were made and nine packages were picked to be simulated in IDA ICE and thus determine a range of possible savings.

7.2 Renovation measures considered

The following renovation measures were considered to form packages:

1. Baseline measures
   (a) Cleaning of ducts
   (b) Water saving aerators in faucets and showerheads
   (c) Radiator balancing
2. Window measures
   (a) Insulating windows
   (b) Complete replacement
3. Additional exterior insulation
   (a) 50 mm
   (b) 100 mm
   (c) 180 mm (Smartfront method)
4. Ventilation system measures
   (a) Improving the existing F-ventilation
   (b) Installing FVP
   (c) Installing FTX ventilation

7.3 Description of measures

7.3.1 Baseline measures

The baseline measures consist of measures that are easy to plan and carry out. It represents the minimal measures that could be carried out and is included in all the packages.

7.3.1.1 Cleaning of ducts

The cleaning of the existing ducts in the building could improve airflow through the ducts, and therefore put less strain on the exhaust fan. Since the ventilation system only consists of extract air channels, there would be no improvement to the indoor air quality. However, the decreased friction losses in the ducts would mean that the fan can operate at a lower pressure and still deliver the required air flow, reducing the energy use of the HVAC system. However, the amount of possible energy savings has not been accounted for in the analysis.

7.3.1.2 Faucet aerators

Faucet aerators are accessories designed to reduce water consumption by adding air to water flowing from faucets/showers and thus, the energy required for the preparation of hot water (ELLESS, 2021b). Such aerators can be installed manually by the tenants themselves in a very short time. Due to the ease of installation, it also means that it can be easily disassembled by the tenant if they are unsatisfied with the resulting water flow.

The expected savings from installing these aerators in a typical faucet is around 25-50% (ELLESS, 2021c). It is expected that similar savings can be made on the domestic hot water consumption. A saving of 30% was conservatively chosen for the case study building and will be accounted for by reducing the current hot water consumption from **25 kWh/(m^2 floor area per year)** (seen in Chapter 5.2) to **17.5 kWh/(m^2 floor area per year)** in IDA ICE.

7.3.1.3 Changed thermostats and radiator balancing

Radiator balancing means adjusting the valves to direct flow within a heating system such that the desired thermal comfort levels are achieved and maintained in the apartments (Caleffi Hydronic Solutions, 2011). The distribution of apartment temperatures in a building might vary as shown in Figure 7.1. This could be due to incorrect flows hindering the proper operation of the radiator controllers. Controllers can only work efficiently if design flows are being met when operating at design condition. This can be corrected through radiator balancing (Petitjean, 2002).

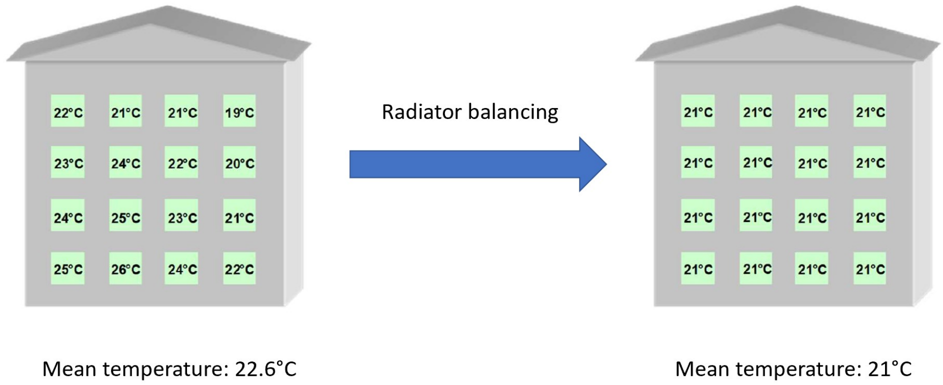

Figure 7.1: Radiator balancing results in a uniform indoor temperature distribution in the apartments

From Curves, it could be observed that there was a difference in the average temperature of the apartments (shown in section 5.2). Thus, radiator balancing was considered a necessary measure to improve and maintain indoor thermal comfort. Radiator balancing is recommended to be performed as a final step at the end of the renovation to make sure that the heating systems reflect and work according to the reduced transmission and ventilation losses due to the other renovation measures (Trüschel, 2020).

7.3.2 Window measures

7.3.2.1 Window replacement

Replacement of the entire windows with better U-value ones can be a cost-effective measure if it is known that the windows are in need of replacement due to poor performance, high leakages and/or deterioration. Both the glass pane and the window frame could be changed to obtain a lower U-value of the window, not to mention, the airtightness and the thermal bridges could be improved considerably. However, it is time consuming as well as expensive to perform. A reduction of window U-values from 2.7 W/m^{2}K to 1.1 and 0.7 W/m^{2}K has been considered in the renovation.

7.3.2.2 Additional window pane with low-e coating

The overall U-value of the existing window can be improved by adding an additional pane with low-emissivity (low-e) coating. These are special types of coatings which can be applied to glass surfaces. Such glasses act by reducing the long-wave heat radiation significantly while the short-wave light transmission and visible transmittance remains largely unaffected. Due to the development of hard coatings, a single pane of glass can also be coated with a low-e layer (Abel and Elmroth, 2007). The U-value of the window can be reduced from 2.7 to 1.3 W/m^{2}K after installing low-e pane on the inside (Glasbranschföreningen, 2008).

This measure could be easily and quickly implemented, in some cases taking just 30 minutes per window to complete with minimal disturbance to the tenants (Grundels Fönstersystem AB, 2021).

Table 7.1: Measures on the windows

Type of window	**New U-value** (W/m^{2}K)
Added low-e pane	1.3
Replace window	1.1
Replace window	0.7

7.3.3 Exterior insulation

Adding an exterior insulation to the facade can help improve the U-value of the building envelope, and address the thermal bridge losses. In this case, an additional exterior insulation of 50, 100 and 180 mm was considered. The 180 mm alternative is only considered for the FTX solution, which is required for placing supply air channels in the insulation. This has been further described in Chapter 7.3.5.2.

Table 7.2: Measures on the external facade

Added insulation (mm)	**New U-value** (W/m^{2}K)
50	0.22
100	0.17
180	0.12

7.3.4 Improving the exhaust ventilation

The existing F-ventilation system can be improved by replacing the existing fan with a lower Specific Fan Power (SFP) one. This means that the new fan will work more efficiently and use less energy for the same amount of airflow. The recommended fan values in case of an exhaust ventilation is 0.6 kW/(m^3/s) (Boverket, 2020).

7.3.5 Ventilation system upgrade

7.3.5.1 FVP system

Upgrading the existing F-system to an FVP-system would involve connecting a heat pump to the existing ventilation system. The heat pump would have one of its heat exchangers placed in the outgoing air channel. This will allow it to extract energy from the outgoing air (at room temperature) and use it to heat water. The heated water could be used to power the radiator system or directly as hot water for tenants. The existing extract ventilation fan and motor in this configuration will also be replaced with one with a lower SFP.

One of the biggest advantages with this approach compared to an FTX system is that no new air channels would have to be installed. The system would still only rely on mechanically driven extract ventilation and the supply air would still enter through infiltration. This usually means that the investment cost for an FVP system is lower than for an FTX system while still achieving good energy savings. Also, because the temperature of the extracted air is relatively high and stable, a high COP of the heat pump could be expected (Warfvinge and Dahlblom, 2010).

On the other hand, the compressor in the heat pump would consume a lot of electricity. Even though the heat pump generates more energy than it consumes (due to a COP greater than 1), it will increase the electricity use compared to an F-system. Additionally, upgrading every building with a separate heat pump in this area would be complicated since they are all connected to a single substation in BR 24. This has been explored in subsection 10.2.2 in the Discussion chapter.

7.3.5.2 FTX system

An FTX system has two separate channels for extract and supply air, which makes it possible to control the amount of fresh air that is supplied to the building more precisely. The extract air goes through a heat exchanger in the airhandling unit (AHU) that recovers heat and uses it to heat the incoming supply air. The heat recovery will lead to large savings in energy and also contribute to good indoor air quality due to the supply channel filters. For an FTX system to work effectively, it is important that the airtightness of the building is also improved. This will be done during the installation of the additional insulation.

On the other hand, installing an FTX system in this group of buildings would require adding extra supply air channels. Due to space constraints and the hard demands placed on tenant relocation, the possibility of an innovative solution patented by Smartfront AB was considered. In this solution, an external facade insulation of 180 mm will be added and the ventilation ducts will be installed there as seen in Figure 7.2 (Smartfront AB, 2021).

The AHU of the FTX will be installed in the attic. Although a rotary heat exchanger is generally more efficient than a plate heat exchanger (Warfvinge and Dahlblom, 2010), a plate heat exchanger was chosen to avoid the risk of odors and smell spreading from one apartment to the other. With modern plate heat exchangers an efficiency of 80% has been claimed to be reached (VERSO, 2013).

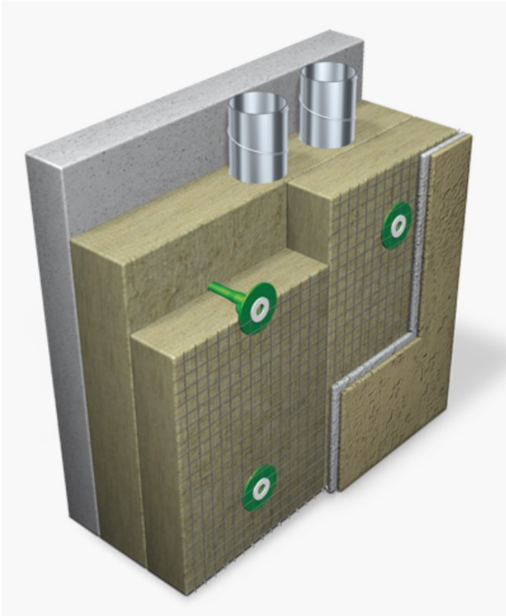

Figure 7.2: External insulation of facade solution by Smartfront AB
(Source: Smartfront AB website)

Table 7.3: Measures on the ventilation system

SN	Type of HVAC system	Technical properties
1	Improved F-system	SFP 0.5 kW/(m^3/s) (for the fan and the motor)
2	FVP-system	Air-to-water heat pump COP 4 Maximum power output: 10 kW
3	FTX-system	Flat plate heat exchanger Efficiency 80%

7.4 Packages considered and simulated

As shown in Figure 7.3, a total of 27 package combinations were made out of the different considered measures. These were designated by using a coding system comprising the type of ventilation, the thickness of insulation and the window U-value. This has also been shown in Figure 7.3. The simulated packages in IDA ICE are shown in Table 7.4.

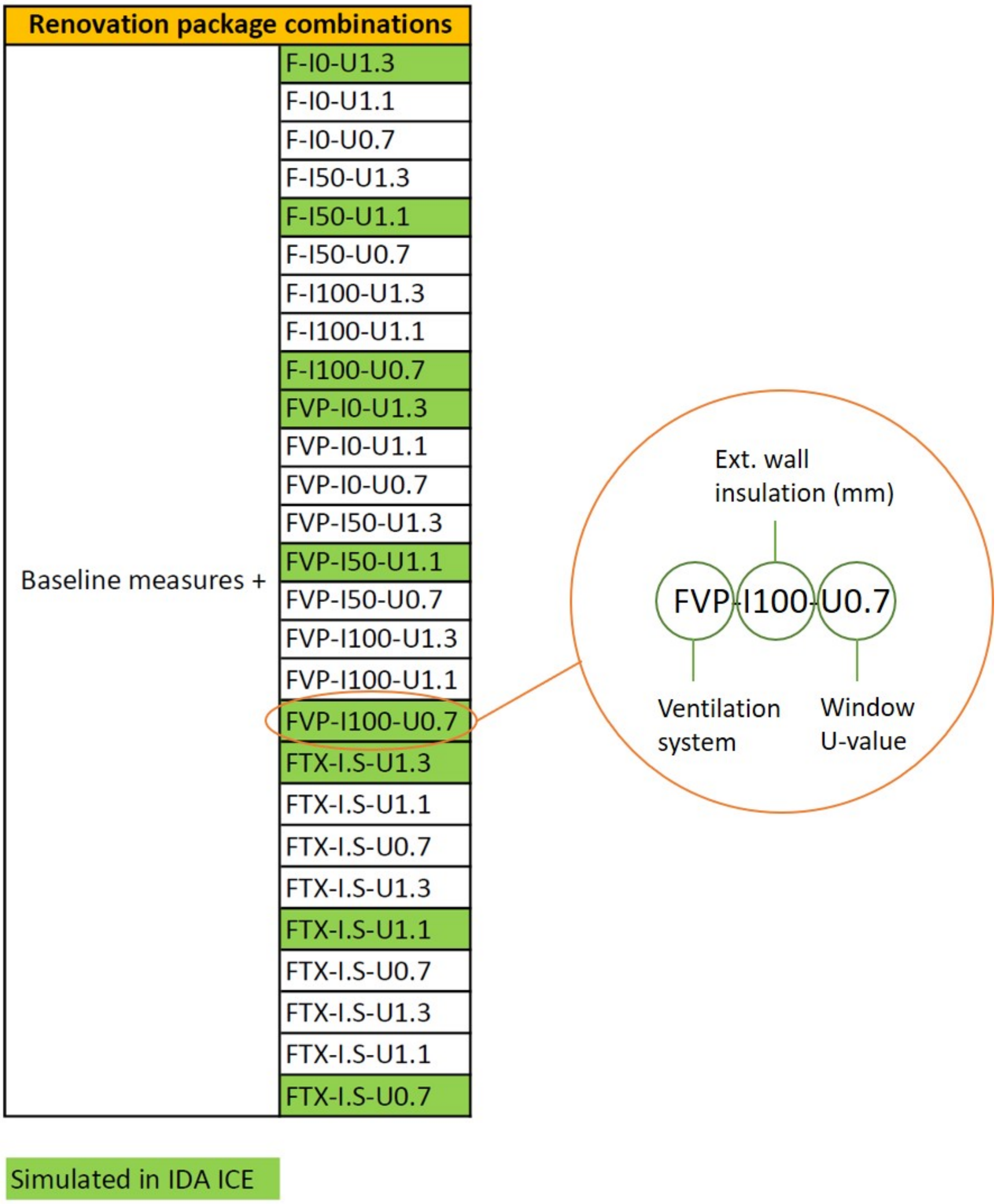

Figure 7.3: Package combinations and designation

Table 7.4: Packages simulated in IDA ICE

SN	Ventilation system	Insulation thickness (mm)	Window measure	Designation
1	Existing F-system	-	-	Baseline (BL)
2	Improved F-system	0	Insulate (U1.3)	BL + F-I0-U1.3
3	Improved F-system	50	Replace (U1.1)	BL + F-I50-U1.1
4	Improved F-system	100	Replace (U0.7)	BL + F-I100-U0.7
5	FVP-system	0	Insulate (U1.3)	BL + FVP-I0-U1.3
6	FVP-system	50	Replace (U1.1)	BL + FVP-I50-U1.1
7	FVP-system	100	Replace (U0.7)	BL + FVP-I100-U0.7
8	FTX-system	180	Insulate (U1.3)	BL + FTX-I.S-U1.3
9	FTX-system	180	Replace (U1.1)	BL + FTX-I.S-U1.1
10	FTX-system	180	Replace (U0.7)	BL + FTX-I.S-U0.7

7.4.1 Changes reflected in IDA ICE model

1. **Baseline measures**:
   (a) Water saving aerators in faucets and showers: Hot water use in each apartment changed to 17.5 kWh/(m^2 year) from 25 kWh/ (m^2 year) (30% savings)
   (b) Radiator balancing: Setpoint temperatures in each apartment changed to 21 °C to reflect a balanced heating system
2. **Window measures**:
   (a) Extra low-e pane in windows: Window U-value changed to 1.3 W/m^{2}K (Glasbranschföreningen, 2008)
   (b) Complete replacement of windows: Replaced with suitable window glazing to obtain total window U-value of 0.7 and 1.1 W/m^{2}K
3. **Additional exterior insulation**: Added insulation of 50, 100 and 180 mm to the exterior along with gypsum for support
4. **Improving the existing F-ventilation**: Changed SFP of the fan to 0.5 kW/(m^3/s) (Boverket, 2020)
5. **Upgrading to FVP/FTX ventilation**:
   (a) FVP: COP 4 of the pump
   (b) FTX: Changed AHU designation to FTX, airtightness reduced to 0.8 L/(m^{2}s), thermal bridges reduced

8
Economic analysis

This chapter describes the economic comparison of the various packages using the Equivalent Annual Costs (EAC) method and the parameters assumed.

8.1 Economic analysis parameters

The main parameters required for performing an economic analysis are the discount rate, the energy price growth rate, the service life of the individual measures and the energy prices.

The discount rate is the interest rate used to discount future cashflows to the present. It was taken as 4% following the guidelines presented by the European Union (European Union, 2012, Gustafsson et al., 2016). Furthermore, the energy price growth rate takes into account the rise in district heating and electricity prices through the years. This was taken as 3%, including an inflation rate of 1% (Gustafsson et al., 2016).

The service life of a measure is the expected number of years that a measure can function for without the need for reinvestments. When a measure reaches the end of its service life, an optimal level of performance cannot be guaranteed. A variety of sources were consulted to arrive at service life values for different measures. This can be viewed in Appendix F.

Apart from material and labor costs, a renovation project also consists of consulting costs and initial planning costs from the contractor during the design phase. These costs vary greatly between projects but an assumption of 12% of the total investment cost was made to account for this (Byggföretagen, 2021). All investment costs were therefore increased by this amount, except for the Smartfront and FVP solution where these costs were already accounted for in the total price.

The district heating cost was taken as **797 SEK/MWh**, an average value from 2020 specific to the city of Gothenburg (Nils Holgersson-gruppen, 2020).

The electricity cost in Sweden from the customer's perspective consists of two parts. One is the fixed part which includes the price of the electricity provider for the transmission of electricity. The variable part depends on the energy taxes, transfer fees, spot prices, certificate fees and VAT (Statistiska centralbyrån, 2016).

An electricity price of 880 SEK/MWh including both variable and fixed prices was considered for the economic analysis, and was taken from the average prices of Swedish electricity in 2016 (Statistiska centralbyrån, 2016, C. Svensson, 2017). To make the electricity price compatible with the district heating price from 2020, the yearly energy price growth rate of 2% was applied to the electricity price for 4 years. Thus, the price of electricity in 2020 was estimated as:
$(1.02)^4$ x 880 SEK/(MWh) = **950 SEK/(MWh)**.

A summary of the considered economic analysis parameters are provided below:

1. **Discount rate**: 4%
2. **Energy price growth rate**: 3% (including inflation)
3. **Electricity cost**: 950 SEK/MWh
4. **District heating cost**: 797 SEK/MWh

8.2 Investment cost of renovation measures

The investment costs for the renovation measures were obtained from a variety of sources, in some cases even from actual vendors and manufacturers. A detailed overview is provided in Appendix F.

8.2.1 Baseline measures

The cost for installing water saving aerators in the case study building was determined by studying the architectural drawings and quantifying the number of showers and faucets. This was used together with the unit price of aerators and shower heads from the company ELLESS to determine the total investment cost (ELLESS, 2021a). This cost does not include the labor cost of installing the aerators in every apartment. However, it is unlikely that including it would have a considerable impact on the total investment cost due to the quick and easy implementation of the measure.

The price for cleaning of the ducts and radiator balancing was obtained from communications with a service provider.

Table 8.1: Investment costs of baseline measures

Type of measure	**Investment costs** (SEK)	**Service life** (years)
Cleaning of ducts	7,000	6
Faucet aerators	4,335	15
Radiator balancing	30,400	10

8.2.2 Envelope measures

The software Bidcon was used to determine costs for envelope improvements. Bidcon contains a large database with prices related to building and renovation components. It was used to extract the material cost for additional exterior insulation and the labor cost of replacing the windows. The cost of exterior insulation was adjusted to account for the actual thicknesses of the insulation, i.e. 50 or 100 mm. As Bidcon did not have investment costs for the specific U-value windows used in the packages, these were taken from Bygghemma's website (Bygghemma, 2021).

The investment cost for adding low-e coated panes to the existing windows was obtained from the company Grundel, which markets its own window solution (Grundels Fönstersystem AB, 2021). The investment cost was obtained as **1,566,700 SEK** for all six buildings and around **266,000 SEK** for the case study building. This information was provided as a direct quotation from a Grundel personnel based on a recent site visit.

Table 8.2: Investment costs of window measures

Type of window	**Investment costs** (SEK)	**Service life** (years)
Added low-e pane	266,000	30
Replace window	1,346,492	30
Replace window	2,396,793	30

Table 8.3: Investment costs of exterior wall measures

Added insulation (mm)	**Investment costs (SEK)**	**Service life (years)**
50	535,000	30
100	551,585	30
180	(included in FTX-system, Table 8.4)	-

8.2.3 Ventilation system measures

The investment cost of a new fan for the extract ventilation was taken from ebm-papst (EBMPAPST, 2021). A fan was picked based on the requirements of airflow and pressure for every building, and a low SFP of 0.5 kW/(m^3/s).

The total cost for implementing an exhaust air heat pump can be estimated to be **580 SEK/A$_{\mathbf{temp}}$** (Wahlström, 2014). This price includes contractor costs and cost for excavation of trenches between the buildings.

Table 8.4: Investment costs of ventilation system measures

Type of HVAC system	**Investment costs** (SEK)	**Service life** (years)
Improved F-system	25,700	15
FVP-system	670,480	20
FTX-system	2,340,000 (including 180 mm external insulation)	35

8.3 Economic analysis

The EAC method was used to compare and select the best investment opportunity among each of the packages. As the energy savings for the whole package was available, as opposed to energy savings of the individual measures, these were separated from the investments. The EAC was calculated from the Net Present Value (NPV) as follows:

$$EAC = \frac{NPV}{EACfactor}$$

The EAC factor is calculated on the basis of the service life of each individual measure of the package. If T is the service life of each individual measure, then the EAC factor of that measure is given by:

$$EACfactor = \frac{1}{r_i}\left[1 - \left(\frac{1}{1 + r_i}\right)^T\right]$$

In summary, the following method was used to determine the total EAC of the package (Farahani, 2021):

1. The EAC of the investment costs for each measure in the package was calculated.
2. The EAC of the energy savings for the entire package was calculated by using the longest service life (among the measures) as the calculation period.
3. The EACs calculated above were added to get the total EAC for the entire package.
4. The package with the highest EAC was considered as the best investment decision.

The *Direktavkastning* was also calculated to study its influence on the investment decision. In terms of renovation measures, it is calculated as:

$$Direktavkastning = \frac{Saving}{Investment}$$

This is a simple, rule-of-thumb method used by the housing company without accounting for variations in energy prices, operating costs, reinvestments etc. over time. According to the housing company, if a *direktavkastning* of more than 5% is achieved, the package can be considered to be profitable.

9

Results

This chapter summarizes the results obtained from the energy simulations and the economic analyses of the renovation packages. A further presentation of these results can be viewed in Appendix H, I and J.

9.1 Energy performance

A detailed overview of the simulation results of renovation packages can be viewed in Appendix G. The savings have been expressed both in terms of the specific energy use (Figure 9.2) and the primary energy number (EP_{pet}) (Figure 9.6). This was because the specific energy use is a measure of the actual delivered energy whereas the EP_{pet} is a measure of the building's energy performance based on the weighting factors, and used by Boverket.

Table 9.1 shows the range of possible savings for each type of ventilation system. Figure 9.1 summarizes the total consumption of specific energy for each renovation package. Further, it can be seen from Figures 9.2 that the FVP and FTX solutions result in the highest savings of specific energy use.

Table 9.1: Range of savings obtained from packages

SN	Package type	Range of savings in kWh/m^2
1	Baseline	10.4
2	F-system	30.0 - 46.6
3	FVP-system	68.2 - 84.2
4	FTX-system	70.1 - 72.5

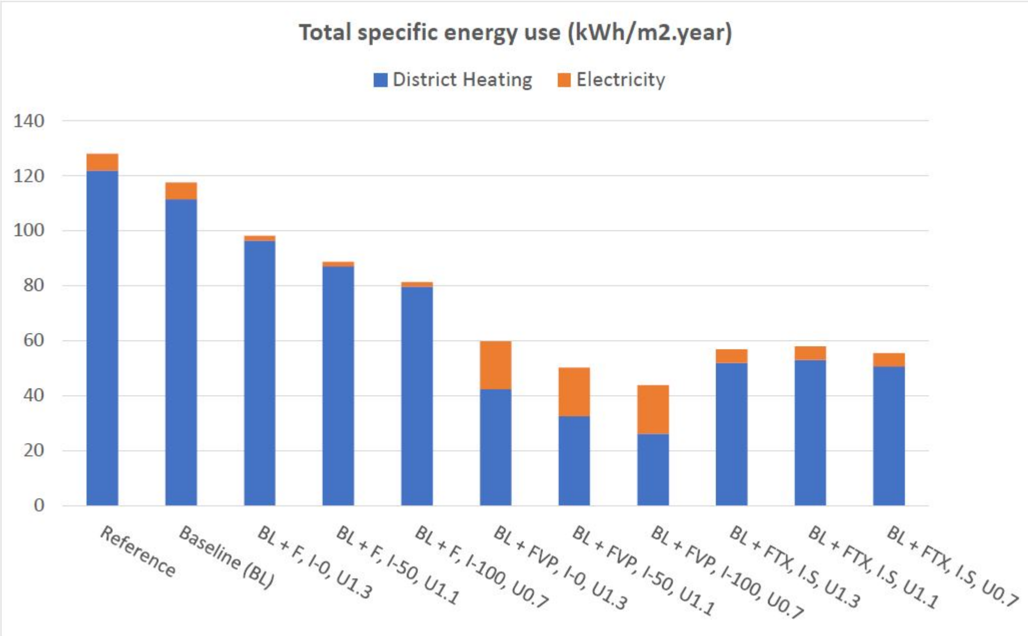

Figure 9.1: Current and post-renovation specific energy use

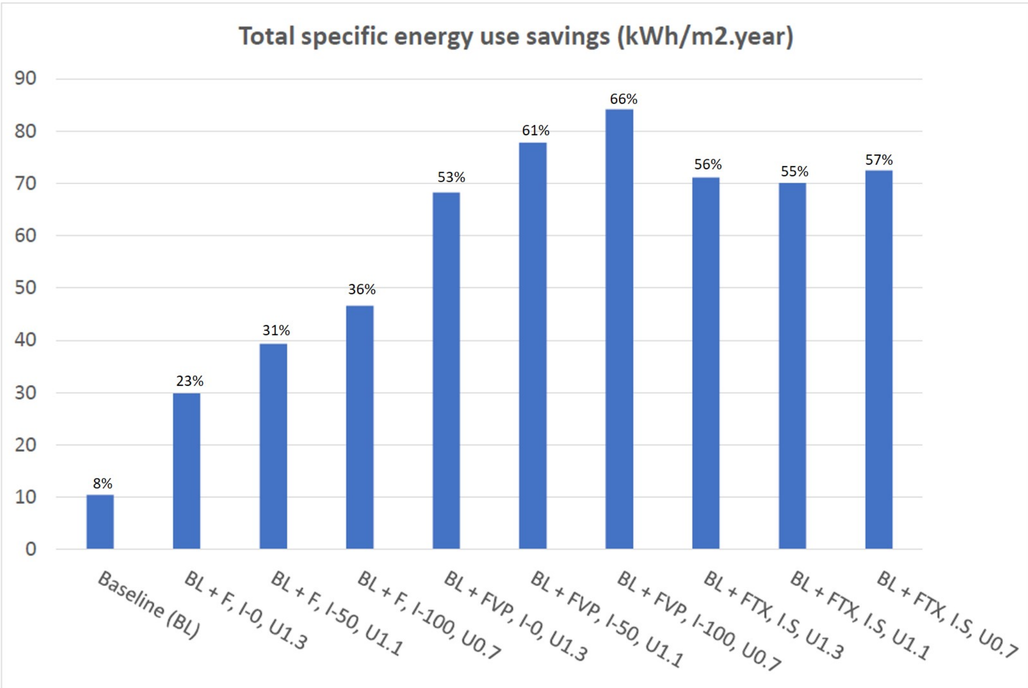

Figure 9.2: Specific energy use savings of packages

The electricity usage is much higher in packages utilizing a heat pump (FVP) because the heat pump needs a significant amount of electricity to operate. One could argue that the much lower use of district heating compensates for the increased use of electricity. The energy use of the FTX solutions are somewhat similar because the only measure that differs between them is the type of window solution.

Figure 9.3 and Figure 9.4, shows the savings in district heating and change in electricity use for every package. It is important to note that the change is negative when there is a decrease in electricity use, and positive when there is an increase.

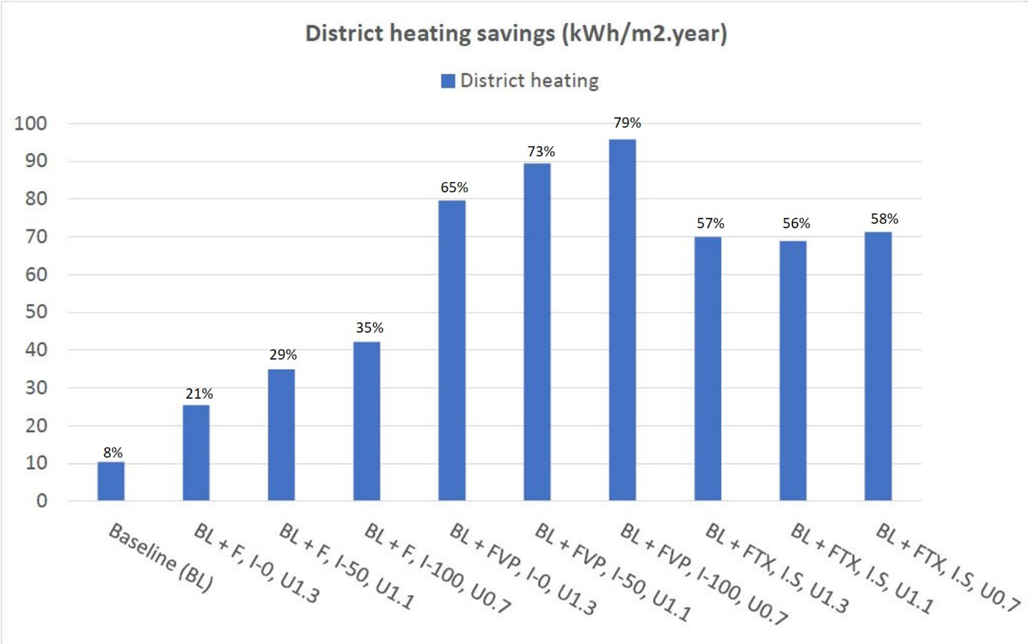

Figure 9.3: District heating savings of packages

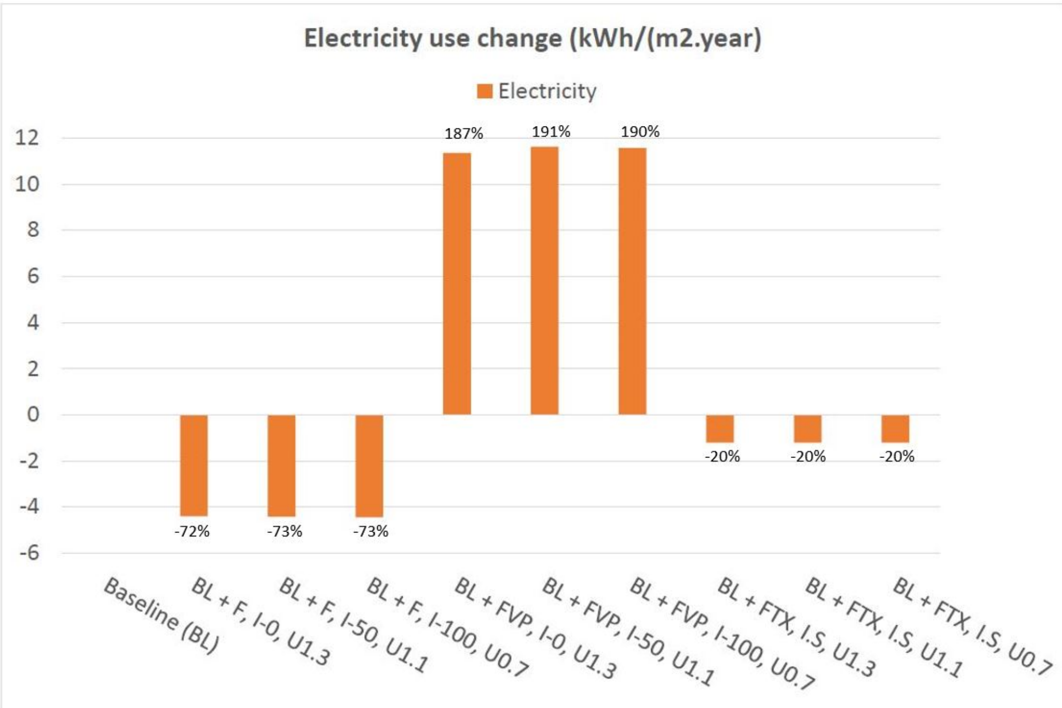

Figure 9.4: Change in electricity of the packages

Figure 9.6 shows the impact of the renovation on the EP_{pet} of the building. Although the reductions in the specific energy use are comparable, or in some cases higher with an FVP instead of an FTX solution, the reductions in EP_{pet} are smaller for FVP than FTX in all the cases. This is due to the higher use of electricity in the FVP packages which has a higher weighting factor compared to district heating in BBR.

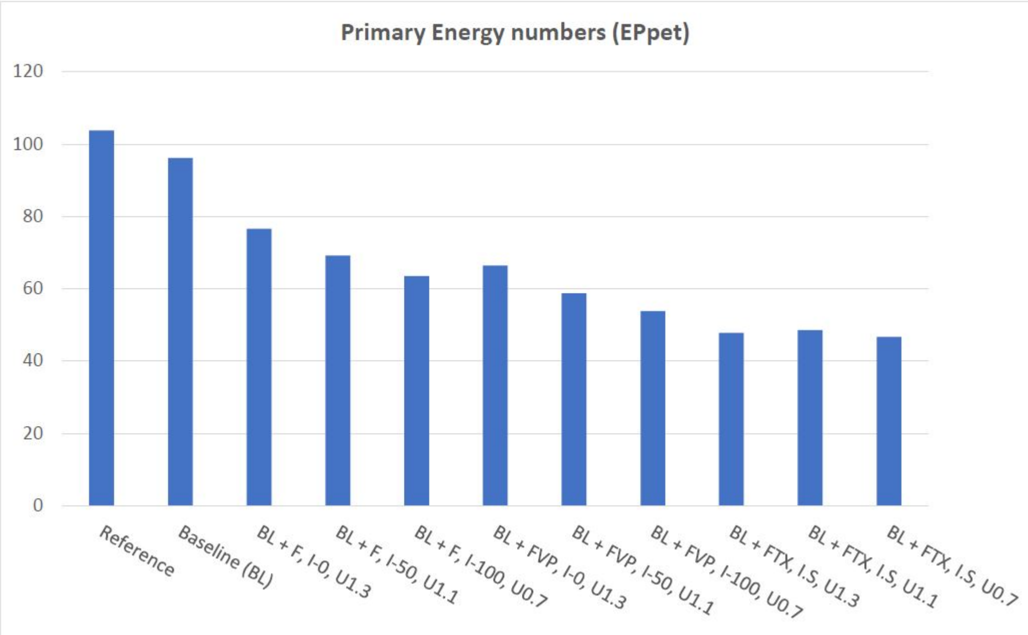

Figure 9.5: Current and post-renovation primary energy numbers

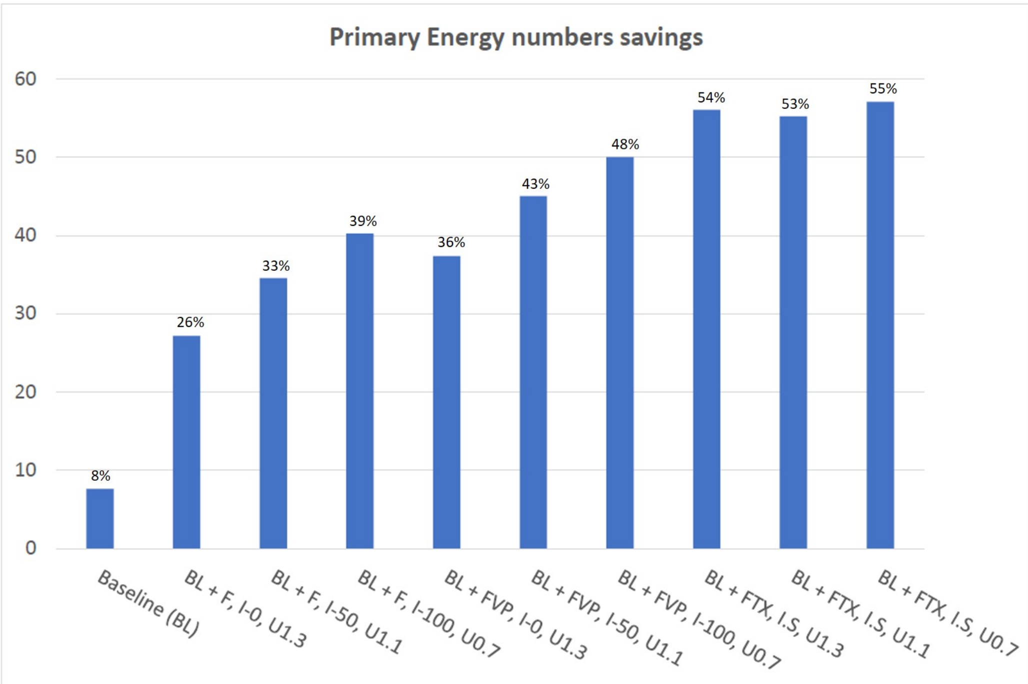

Figure 9.6: Savings in Primary energy numbers

Figure 9.7 shows the relationship between the EP_{pet} values and specific energy use of the packages. It can be observed that the FVP packages result in the lowest specific energy use while the FTX packages result in the lowest EP_{pet} values. Thus, these metrics can result in differing opinions regarding which package performs the best in terms of energy performance.

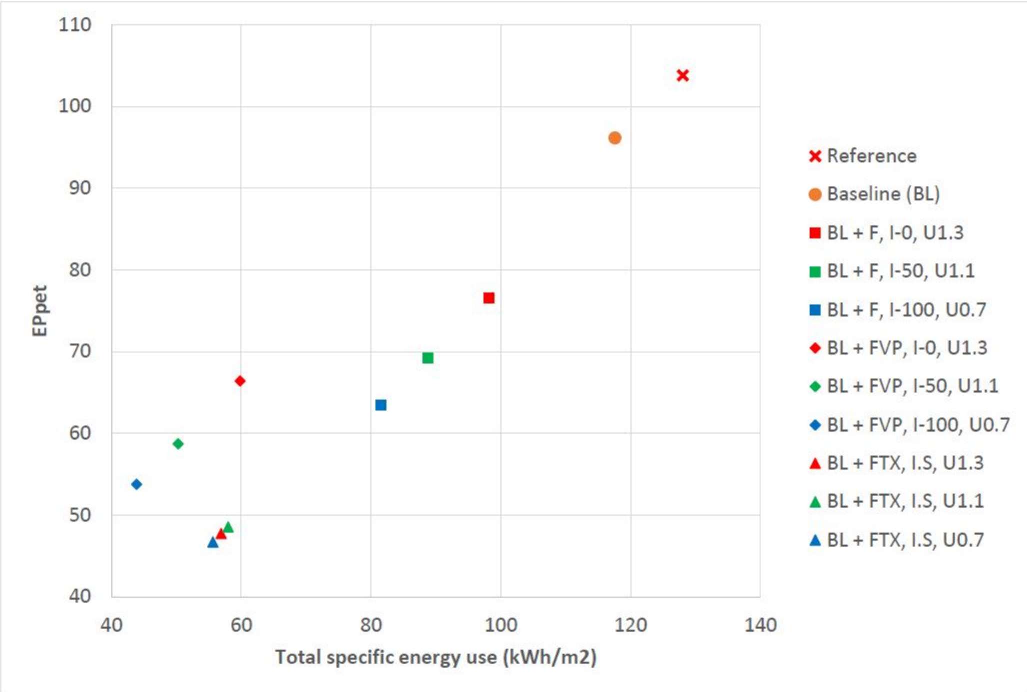

Figure 9.7: Primary energy numbers vs Specific energy use of the packages

9.2 Economic analysis

Figure 9.8 shows the calculated Equivalent Annual Costs (EACs) for each package. It can be seen that the packages with the lowest EACs are the ones involving replacement of windows. The packages with positive EACs are the baseline package and the simplest F and FVP solutions (**F, I-0, U1.3** and **FVP, I-0, U1.3**). It is important to view EAC as a tool to select the best investment opportunity among a variety of different options. It is recommended that this "best" package is further economically analyzed using more input parameters and cash flows to determine if the package is truly profitable or not.

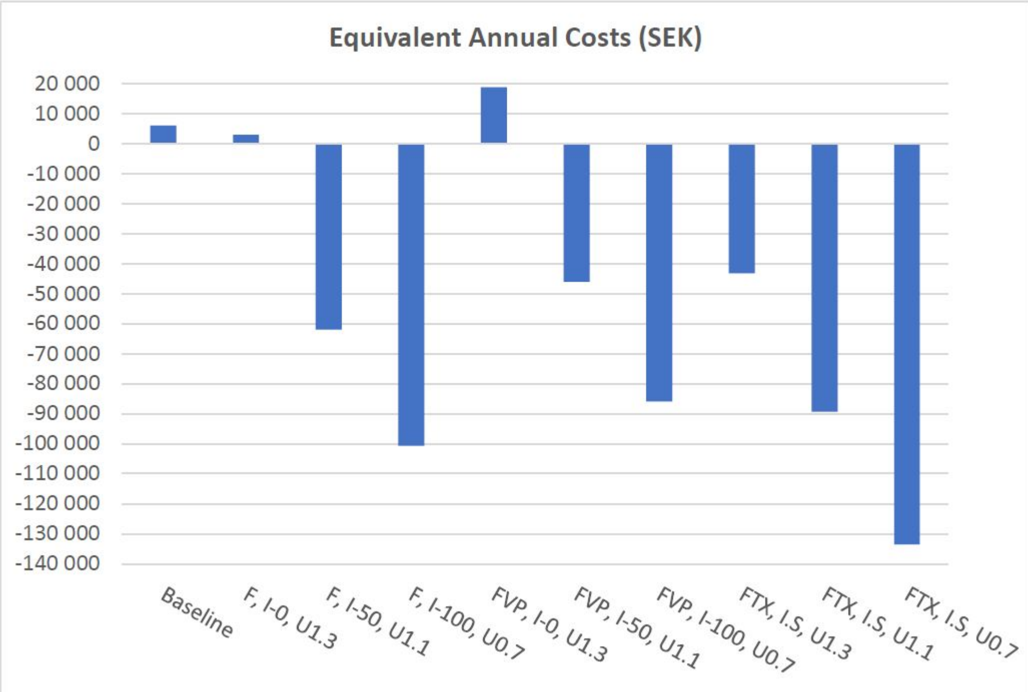

Figure 9.8: Equivalent Annual Costs of packages

The large investment costs entailed by window replacement can be seen in Figure 9.9. The figure shows a comparison of the investment costs between each package.

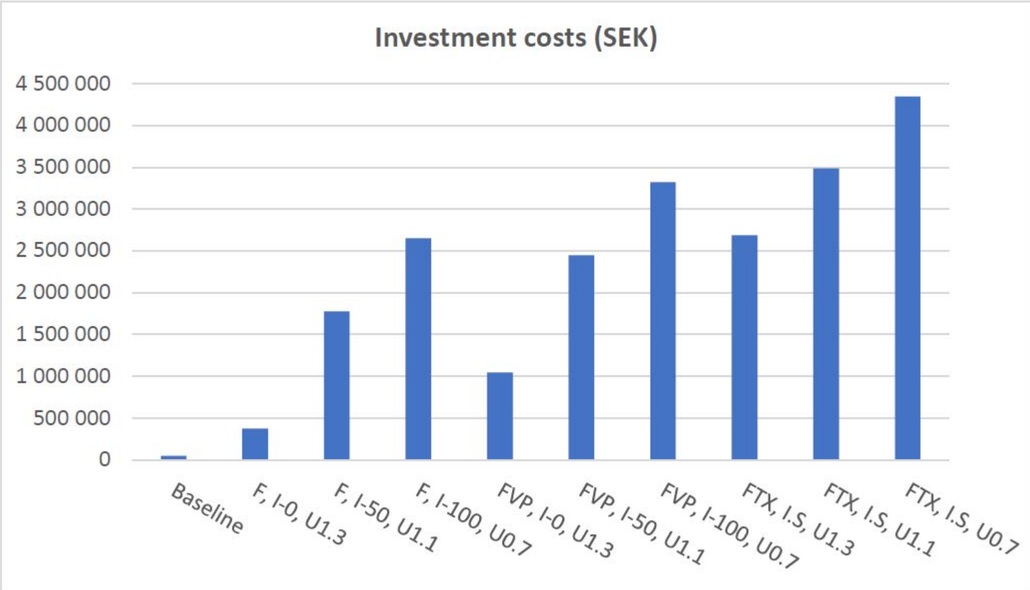

Figure 9.9: Investment costs of packages

Figure 9.10 show the operational energy cost savings for each package after the first year of renovation.

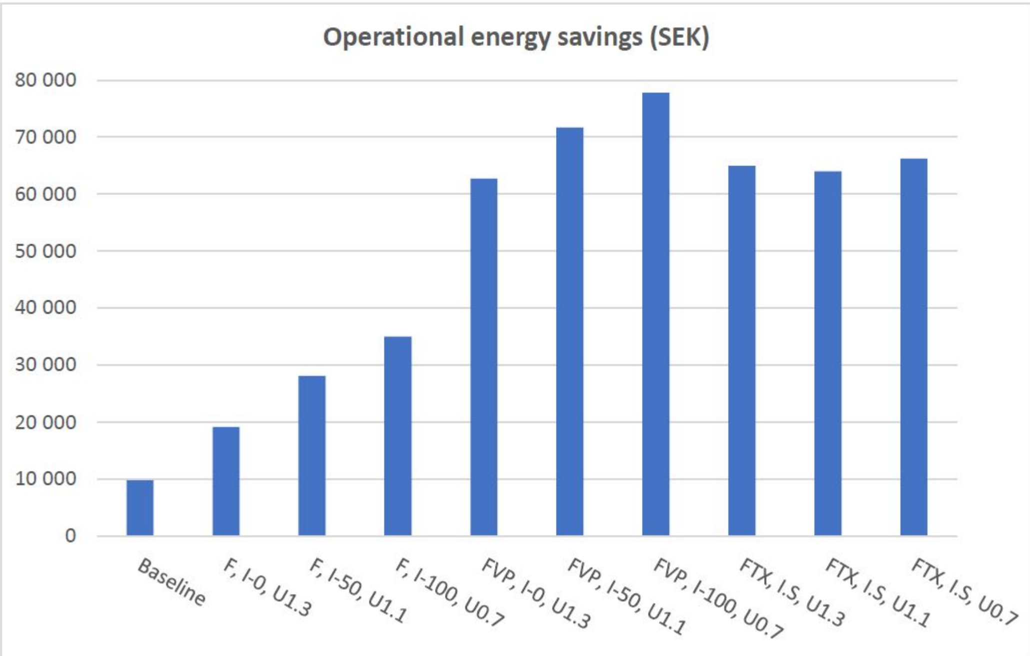

Figure 9.10: Initial operational cost savings of packages

The *direktavkastning* of each package is shown in Figure 9.11. A package exceeding 5% is considered to be profitable by the housing company.

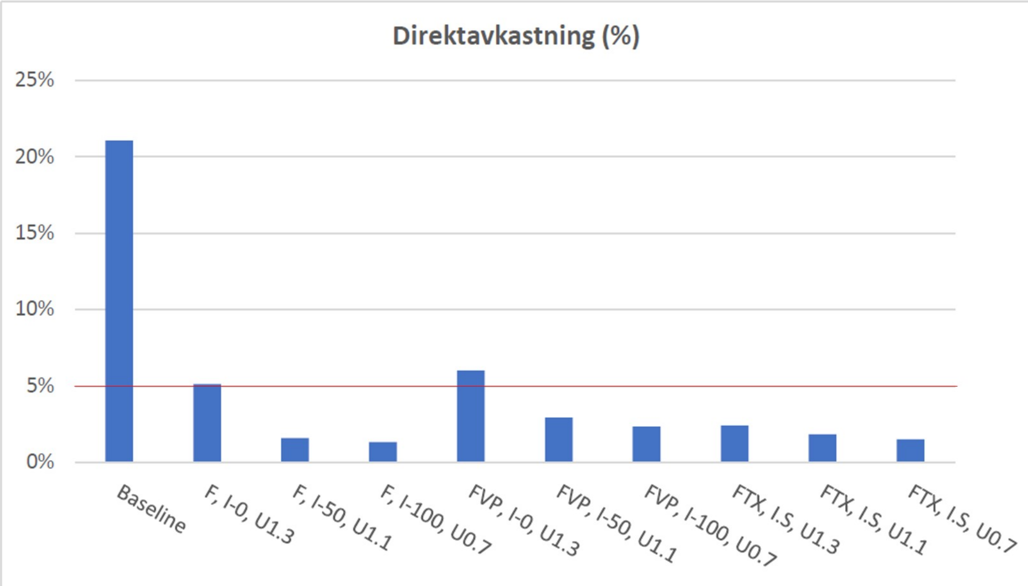

Figure 9.11: Direktavkastning values of packages.
A value greater than 5% indicates a profitable investment decision.

9.2.1 Environmental performance

Figure 9.12 shows the expected reduction of CO_2 emissions during the operational phase of each package. The graph bears a resemblance to the primary energy number savings shown in Figure 9.6. This can be attributed to the fact that the weighing factors for the primary energy number are meant to reflect the environmental impacts of different energy carriers.

However, there are a few noticeable differences between the graphs. It can be seen that two of the FVP packages outperform the FTX packages in terms of CO_2 savings (Figure 9.12) whereas all of the FTX packages outperform the FVP packages in terms of primary energy savings (Figure 9.6). This is because proportionally there is a larger difference between the primary energy weighting factors for electricity and district heating (1.8 and 0.7) compared to their corresponding CO_2 emission factors (93 and 65). Thus, this result is highly dependent on the source mix in electricity generation and the way the primary energy number is calculated, and therefore subject to change.

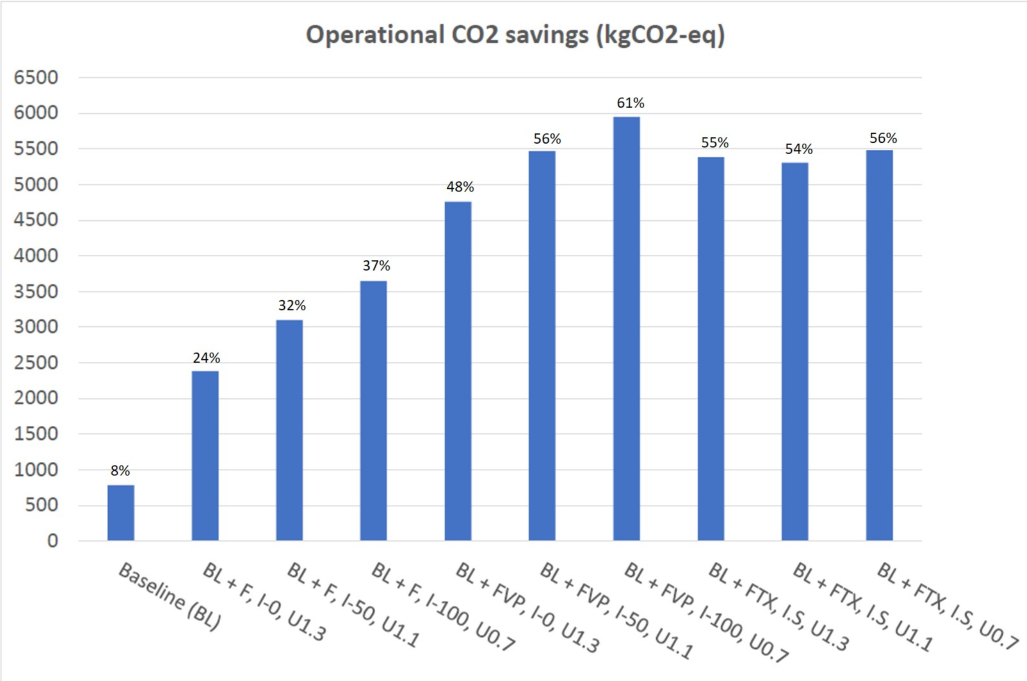

Figure 9.12: kgCO_2-eq savings of packages

9.2.2 Extrapolation

Figure 9.13 shows the investment costs, yearly reduction of CO_2 emissions and operational cost reductions extrapolated to the whole area, i.e. all six buildings. The results provide the housing company an impression of the expected costs and savings of performing such a large-scale renovation. The energy savings are not included because the savings have already been expressed in terms of kWh/m^2, and this remains the same regardless of which building is being considered. The complete extrapolation results can be viewed in Appendix K.

Package designation	Case study building			Whole area		
	Investment Costs (SEK)	Yearly CO2 savings (tons)	Initial savings in operational costs (SEK)	Investment Costs (SEK)	Yearly CO2 savings (tons)	Initial savings in operational costs (SEK)
Baseline (BL)	47 000	0,79	9 800	394 000	6,6	83 000
BL + F, I-0, U1.3	373 000	2,38	19 000	3 149 000	20,1	162 000
BL + F, I-50, U1.1	1 775 000	3,10	28 000	14 960 000	26,1	237 000
BL + F, I-100, U0.7	2 651 000	3,65	35 000	22 350 000	30,7	295 000
BL + FVP, I-0, U1.3	1 044 000	4,76	63 000	8 803 000	40,1	529 000
BL + FVP, I-50, U1.1	2 445 000	5,47	72 000	20 620 000	46,1	605 000
BL + FVP, I-100, U0.7	3 322 000	5,95	78 000	28 010 000	50,2	656 000
BL + FTX, I.S, U1.3	2 685 000	5,38	65 000	22 640 000	45,4	548 000
BL + FTX, I.S, U1.1	3 487 000	5,31	64 000	29 400 000	44,7	540 000
BL + FTX, I.S, U0.7	4 345 000	5,5	66 000	36 630 000	46,2	558 000

Figure 9.13: Extrapolation from
BR 24-25 (one building) to BR 5-12 and BR 21-28 (six buildings)

10
Discussion

This chapter discusses the results obtained, and possibilities of further research.

10.1 Energy performance metric

In some cases, the post-renovation primary energy number or EP_{pet} of the case study building falls well below the requirement for a newly constructed multi-family building, which is 75 kWh/(m^2 A_{temp} year) according to Boverket. From an initial EP_{pet} of 103.8 kWh/(m^2 A_{temp} year), a value as low as 46.7 kWh/(m^2 A_{temp}) was achieved by the FTX solution. While it is reasonable to question if these savings would be reflected in reality, the reason for such a considerable reduction is due to large savings in DH and electricity use by the FTX package. By having a very low U-value of the wall, windows and providing heat recovery, a large amount of DH savings can be achieved.

Furthermore, the EP_{pet} is based on the weighting factors of the energy carriers. As electricity has a higher weighting factor than DH, the EP_{pet} is higher for the packages utilizing more electricity, namely the FVP solution. Thus, although both solutions obtain more than 50% specific energy savings, the EP_{pet} savings are lower for the FVP. Thus, one should be well aware of which metric is being used to compare and judge the energy performance of the building. The specific energy is a direct measure of the building's delivered energy and would probably be more relevant to the layman whereas the EP_{pet} is a more elaborate metric requiring at least a certain level of knowledge on the topic.

10.2 Technical feasibility of the renovation measures

10.2.1 Water aerators

It has been posited that the installation of the water aerators would save 30% on the domestic hot water preparation energy use. However, the efficacy of the measure depends on the extent to which the tenant energy bills are reduced, which can be achieved by implementing an Individual Metering and Debiting (IMD) system. This system measures the hot water energy consumption in each apartment individually and bills them according to the usage. The installation of such a system alone can result in energy savings of 30-40% (Energimyndigheten, 2003, C. Svensson, 2017).

However, it should be noted that the housing companies themselves do not gain financially by implementing the IMD. Currently, the hot water prices are being paid for by the tenants as part of the monthly rent. Implementing the IMD would mean that the housing rent is divided into a fixed and a variable part, with the latter varying based on individual water consumption (C. Svensson, 2017). Thus, as the base rent would be reduced for the housing company, they might not have a good incentive to implement this course of action.

10.2.2 FVP measures

The implementation of the FVP measure can present a significant challenge due to the presence of a substation in only one of the target buildings, i.e. Baron Rogers 24/25. Three possible solutions have been proposed and discussed to overcome this challenge as described below:

1. **Building new separate substations in each building**: This option would only be economically viable if the energy supplier were co-invest in the project. A possible reason for them to be involved would be that the increased number of substations would give them greater control over the delivery of district heating and reduce the distribution losses. However, due to the small number of apartments in each building and the reduced demand for district heating, it is unlikely that such a solution would be economically viable for the energy supplier.

2. **Connecting the heat pump to the inlet of each building via a shunt connection**: This is likely the cheapest and least intrusive option. However, it might present some technical challenges since the energy contribution from the district heating and the heat pump is added in two separate locations. This would make it difficult to control the supply of district heating properly.

3. **Transferring the heated water produced by the heat pump of every building to the substation through the kulvert system**: This method removes the control issue of adding the energy from the heat pump and district heating at different locations. Therefore, this method might be the most viable since it makes sure that both the heat from the heat pumps and district heating are processed at the same location. It is also worth mentioning that the housing company has plans to renovate the current *kulvert* system anyway due to high distribution losses. It would therefore be beneficial to implement this solution at the same time as the *kulvert* renovation.

10.2.3 FTX solution

An important consideration to be made for implementing the FTX solution is the current size of the attic. Boverket and the Swedish Work Environment Authority (*Arbetsmiljöverket*) recommend certain requirements and characteristics of the AHU space for proper installation, operation and future maintenance of the AHU

(Arbetsmiljöverket, 2009, Boverket, 2021, Svenska Byggbranschens Utvecklingsfond, 2009). It is important that these requirements are well complied with. If the size of the attic is inadequate and should be expanded, the roof might have to be dismantled and reconstructed which might incur further costs. Based on the site visit, no such issue has been currently identified in the case study building.

10.3 Recommendation for the housing company

One of the *Klimatinitiativ* goals is a 30% reduction in the specific energy use of the building from 2007. Although the energy use of the building in 2007 is unknown, eight out of ten packages achieve theoretical savings of 30% from 2019 values.

The recommendation for the housing company would be to carry out the "baseline measures" if a short-term energy saving solution is required. These comprise of simple, easy-to-perform measures that can be executed without extensive planning, forethought and minimal expenses. On the other hand, if a higher energy saving but cost-effective solution is sought, the **FVP, I-0, U1.3** package is recommended. With this package, savings of up to 53% can be achieved. In addition, it has a positive EAC of **18,843 SEK** owing to the insulation rather than replacement of windows. This would likely make it a cost-effective measure.

If a thorough and more extensive renovation with higher energy savings is required, then the Smartfront solution is recommended. The company implements its FTX solution from start to finish as a complete package (Smartfront AB, 2021). As they are a single entity hiring and managing required subcontractors and personnel, a large part of the design and project management costs can be saved. These costs accrue to about 12% of the total project cost (Byggföretagen, 2021).

Furthermore, it is recommended to renovate all 6 buildings together as part of a single project. This is because the buildings share similar geometry and architecture, and it would be easier to plan and implement the renovation together. Moreover, building materials such as scaffolding, steel, concrete, insulation etc. could be ordered in bulk and a lot of procurement and transportation costs could be saved.

Tenant relocation would not be a necessity in most of the renovation packages. The FTX solution can also be implemented without the need for tenant relocation as the supply air ducts go through the external facade. A Smartfront project in Stockholm was implemented without this need (Byggastockholm, 2021). The baseline renovation measures will also have minimal impacts on the tenants' housing status.

10.4 Economic feasibility

The economic analysis suggests that replacement of windows is a very unprofitable solution. Even though the windows account for some part of the transmission losses of a building, the energy savings from replacing old windows with new ones are small. These small reductions in energy costs are rarely enough to compensate for the high investment and labor costs of replacing the windows. Window replacement could be a possible solution when it is deemed necessary to replace them because of their bad condition, which is not currently the case. An interesting economic analysis to consider would be when the windows were in fact, in need of replacement. In that case, a comparison could be made between a basic new window with a relatively high U-value (eg. 1.5-2 W/m^2K) and a more expensive window with a lower U-value (<1.5 W/m^2K). The investment cost of the better window solution would be the price difference between them and the cheaper window and is referred to as a "marginal investment cost."

All packages with a *Direktavkastning* of greater than 5% were found to yield positive EAC values. The *Direktavkastning* does not consider the increase in energy prices with time, the discount rate or the service life of the measures. Therefore, it is suggested to use more holistic methods to determine a package's cost-effectiveness. Even after using the EAC method, it is recommended that the package with the highest EAC is further economically analyzed to determine if it is truly profitable or not.

Finally, one aspect disregarded in the economic analysis is the value increase of the whole property after renovation. When a renovation is carried out, the thermal comfort and the building's life expectancy are also expected to be improved. This has not been directly accounted for in the economic analysis as it could not be quantified in terms of operational cost reductions, which was the only "benefit" considered. This could potentially affect the cost-effectiveness of the packages.

10.5 Future outlook

One of the strategies to achieve the EU goals of reducing the GHGs from 40 to 55% by 2030 was by large scale renovation of the existing building stock. Furthermore, the EU proposes that an average annual renovation rate of 3% should be met if the goal to be a climate-neutral region by 2050 is to be met. Considering this rate, close to 100% of the building stock would have to be renovated in the next 30 years. Concerning Sweden's ambitions, the current goal is to reduce the total energy use in buildings by 50% by 2050 counting from 1995 (Boverket, 2007). This is achievable with the help of the FTX or FVP packages, with a reduction of more than 50% on the total energy use and CO_2 emissions. These quantifiable reductions provide a strong case for the renovation plan investigated in this thesis to be implemented on a wider scale.

Currently, the housing company owns and manages around 800 buildings in Gothenburg. This thesis concerns the renovation planning of 6 of these buildings. With a 3% annual rate of renovation, 24 buildings would have to be renovated yearly, assuming every renovation is completed within one year. However, this is a significant undertaking of immense magnitude which could only be realized with substantial external investment, extensive human resources and technological know-how. The same applies for renovating the existing building stock in the whole EU. The *Klimatinitiativ* started by SverigesÄllmannytta to have more housing companies take action and follow up on their climate commitments is definitely a step in the right direction.

10.6 Further research

As this thesis was limited in time and scope, there are still many topics warranting further investigation described below.

Only 10 (including Baseline) out of 27 possible combinations of renovation packages were investigated for their energy savings and cost-effectiveness. This was mainly due to time constraints, resulting in the exclusion of many packages that could be of interest to investigate. For example, no packages combining external insulation with additional low-e window pane have been analyzed. As insulating a window is cheaper than replacing one, doing so could have resulted in more packages with positive EACs. Furthermore, all the simulated packages with window replacements had negative EACs. Thus, it was difficult to determine the cost-effectiveness of adding external insulation as replacement of windows makes almost any package non-profitable. A more holistic analysis including more combinations of packages shown in Figure 7.3 could be a future research topic.

The Smartfront method could be explored further from a research perspective to document how well the actual savings correlate to the theoretical savings. The implications of installing the heat pump in a group of buildings connected to a single substation could also be further analyzed. Finally, the options presented in Chapter 10.2.2 could be studied in greater detail to evaluate the costs and technical challenges associated with each method.

The possibility of future rent increases as a direct result of the renovation could be studied further. A more comprehensive socio-economic analysis could be employed taking into account the entire cashflows that occur during the lifetime of the building.

One drawback of decreasing the U-value of the envelope is that it can lead to overheating of the apartments during summer. This could lead to unacceptable levels of summertime thermal discomfort, for which extra measures such as solar shading would have to be implemented. An improvement of the indoor climate is one of the added benefits of renovation, making the tenants more healthy and adding value to the building. A study incorporating this aspect of renovation could warrant further research.

The extrapolation used in this thesis was an arithmetic method to translate the results from one building to the rest. It is expected that the energy and CO_2 savings scale well whereas the investment costs are likely overestimated. An interesting research topic would be to test this approach in actual renovation projects to see how well the method reflects reality.

11 Conclusion

In this study, 6 multi-family buildings located in Hisings Backa, Gothenburg were investigated as part of a renovation planning study. The process comprised a preliminary study and site visit, energy auditing and simulations of one specific building in IDA ICE. Next, renovation packages were proposed on the building and further simulated to determine a range of savings. The measures dealt with the improvement of the building envelope, the ventilation system and some baseline measures. Economic analyses were also performed using the EAC method to determine the cost-effectiveness of the packages.

It could be concluded from the thesis that it is generally challenging to make a renovation project profitable solely based on the operational energy cost reductions. However, renovations can result in added co-benefits such as improved thermal comfort and property value increases which are of interest to both the property owner and tenants. There were also a few packages that had positive EACs solely through the reduction in operational energy costs. These included the lighter renovation options with limited improvement on the envelope but with emphasis placed on improving the HVAC system. 2 out of 3 packages with positive EACs included insulating rather than replacing the windows.

With respect to energy savings, packages with FTX and FVP ventilation upgrades were very effective at reducing the building energy use, achieving more than 50% savings from the reference case. However, the FVP also results in significantly increased electricity use, which leads to lower reductions on the primary energy number of the building.

Concerning *Klimatinitiativ* goals, 8 out of 10 packages were found to fulfill the annual specific energy use reduction of 30%. It is commendable that the *Klimatinitiativ* is encouraging more housing companies to commit and work towards achieving the Swedish climate goals. However, it is unlikely that housing companies will execute more ambitious renovations on a larger scale without the help of external subsidies from the government. With Sweden's expertise and know-how in FTX and FVP solutions, the technical aspects required for achieving the 50% energy use reduction goal by 2050 are well covered. The economic and social challenges that can hinder this achievement should be further explored to encourage more housing owners to invest in renovation.

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A

Total distribution losses

Measured District Heating Consumption (for 6 buildings)	1 400 000,00	kWh

Case study building	District heating	Electricity	Distribution losses
Measured energy consumption	166 009,74	10 931,00	0
Calculated energy consumption	141 000,00	7 030,00	30372,95

Buildings	Footprint (m^2)	Floors	Floor area (m^2)	Proportion
Baron Rogers 5-7	509	3	1526	16%
Baron Rogers 8-9	386	3	1157	12%
Baron Rogers 10-12	549	4	2195	22%
Baron Rogers 21-23	509	3	1526	16%
Baron Rogers 24-25	386	3	1157	12%
Baron Rogers 26-28	549	4	2195	22%
Total:			9755	m2

Hourly domestic hot water + space heating baseline loss [kW]	Yearly Distribution losses [kWh]	Average consumption from distribution losses [kWh/m^2]	Total District Heating consumption [kWh/m^2]	Actual District heating consumption [kWh/m^2]
29,2	256142,4	26,3	143,5	117,3

B

IDA ICE simulation

Figure B.1: Simulation model in IDA ICE

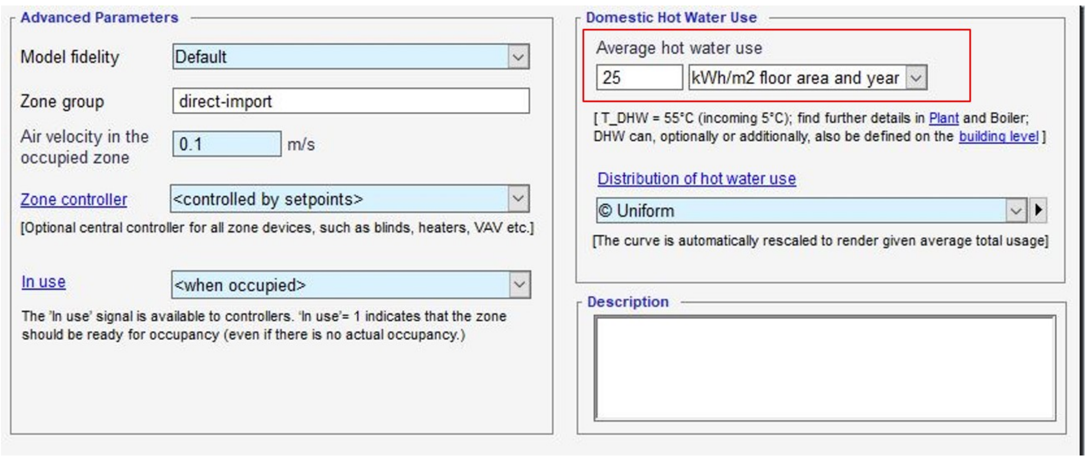

Figure B.2: Apartment hot water consumption in IDA ICE

C

Curves temperature analysis

Apartment numbers	Average indoor temperature (°C)			New setpoint temperature in IDA ICE (°C)
	November	December	January	
BR 25				
301	21,3	21,3	21,3	
302	21	21,5	21,3	
303	21,4	21,5	21,4	21,5
304	22	22,2	22,3	22
305	21,5	21	20,7	
306	21,6	20,9	21,4	21,5
BR 24				
309	22	22,8	23	23
310	20,4	20	21	
311	21,2	21,4	22,1	22
312	20,3	20	21,6	21,5
307	No data	No data	No data	
308	22,6	22,1	22,3	22

D

Internal Gains Calculation

Tenant and lighting heat

Heat from people [W]	Num of bulbs	Bulb Power[W]
80	0,34	5,2

Apt.	Area	Rooms + Kitchens	People	Power (W)	Lamps	Power lighting
301	84	3	2,18	80	28,6	148,5
302	87	4	2,79	80	29,6	153,8
307	73	2	1,63	80	24,8	129,1
308	66	2	1,63	80	22,4	116,7
303	87	4	2,79	80	29,6	153,8
304	87	4	2,79	80	29,6	153,8
309	87	3	2,18	80	29,6	153,8
310	66	2	1,63	80	22,4	116,7
305	98	4	2,79	80	33,3	173,3
306	87	4	2,79	80	29,6	153,8
311	87	4	2,79	80	29,6	153,8

Internal Gains schedules; Appliances: (Zimmermann)

Small apartment, Weekday

Time	Dishwasher	Cooking	Fridge/Freezer	TV	Computer	Total	%
1	12	5	65	30	40	152	31%
6	10	10	65	20	28	133	27%
12	30	40	65	38	50	223	46%
18	90	195	65	55	80	485	100%
24	20	15	65	45	55	200	41%

Small apartment, Holiday

Time	Dishwasher	Cooking	Fridge/Freezer	TV	Computers	Total	%
1	20	18	65	40	48	191	46%
6	10	10	65	20	25	130	31%
12	55	70	65	45	62	297	71%
18	38	180	65	60	75	418	100%
24	20	18	65	48	56	207	50%

Large Apartment, Weekday

Time	Dishwasher	Cooking	Fridge/Freezer	TV	Computer	Total	%
1	12	5	65	30	80	192	34%
6	10	10	65	20	56	161	28%
12	30	40	65	38	100	273	48%
18	90	195	65	55	160	565	100%
24	20	15	65	45	110	255	45%

Large Apartment, Holiday

Time	Dishwasher	Cooking	Fridge/Freezer	TV	Computers	Total	%
1	20	18	65	40	96	239	48%
6	10	10	65	20	50	155	31%
12	55	70	65	45	124	359	73%
18	38	180	65	60	150	493	100%
24	20	18	65	48	112	263	53%

Lighting:

Time	Power consumption Weekday		Power consumption Holiday	
1	50	25%	80	40%
6	25	13%	20	10%
12	60	30%	82	41%
18	150	75%	140	70%
19	200	100%	170	85%
21	200	100%	180	90%
24	100	50%	10	5%

Tenants:

Time	%
1	100%
6	60%
12	30%
18	75%
24	100%

E

Space heating distribution loss calculation

Indata:

$q_{hot.water} := 20kW$

$T_{ground} := 9\,°C$

$T_{hot.water} := 55\,°C$

$T_{space.heating} := 41\,°C$

$$q := \frac{2\cdot\pi\cdot k\cdot L\cdot(T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)}$$

q - Distribution losses [W]
k - Thermal conductivity [W/mK]
L - Pipe length [m]
T.1 - Temperature inside the pipe
T.2 - Temperature outside the pipe
r.1 - Inside radius
r.2 - Outside radius

$$S := \frac{2\cdot\pi\, k\cdot L}{\ln\left(\frac{r_2}{r_1}\right)}$$

Assuming S is a constant

$q_{hot.water.} := S\cdot(T_{hot.water} - T_{ground})$ $\qquad$ $q_{hot..water} := 20kW$

$$S_{.} := \frac{q_{hot.water}}{(T_{hot.water} - T_{ground})} = 434.783\cdot\frac{W}{K}$$

$$q_{space.heating} := S_{.}\cdot(T_{space.heating} - T_{ground}) = 13.913\cdot kW$$

F

Investment costs and service life of measures

SN	Renovation measure	Cost per units or m2	No of units or m2	Investment costs (SEK)	Service life (years)	Remarks
1	**Cleaning of ducts**			**7 000,00**	6	Service life: Sotningstjänst & Kamingruppen STHLM AB Material cost: Radea
2	**Aerators**					
	Shower head LSP 412	203	12	2 436,00	15	Service life: Gustafsson et. al Investment cost: ELLESS
	Bathroom sink LSP 005/6	51	17	867,00		
	Kitchen sink LSP 00024/9	86	12	1 032,00		
				4 335,00		
3	**Radiator balancing**	400	76	**30 400,00**	10	Costs and service life: Indoor energy
4	**Additional low e-coating pane**					
	Window U-value: 1.3 W/m2K	2000	133	**266 000,00**	30	Costs and service life: Grundel
5	**Replacement of window**					
	Window U-value: 1.1 W/m2K	10124	97	**982 028,00**	30	Material cost: Original 3-Glas Aluminium Labor cost: Bidcon; Service life: Gustafsson et. al, Jalilzadehazhari
	Window U-value: 0.7 W/m2K	18021	97	**1 748 037,00**		Material cost: Norrland Passiv 3-Glas Trä/Alu Labor cost: Bidcon; Service life: Gustafsson et. al, Jalilzadehazhari
6	**Additonal exterior wall insulation**					
	50 mm	1000	535	**535 000,00**	30	Investment cost: BIDCON Service life: Gustafsson et. al, Mahapatra et. al
	100 mm	1031	535	**551 585,00**		
7	**F-system**					
	Improvement of fan SFP	1	25700	**25 700,00**	15	Material: Ebmpapst, MXPC35RP-2400 (MXPC II) Service life: Gustafsson et. al
8	**FVP-system installation**					
	Heat pump (including excavation)	580	1156	**670 480,00**	20	Investment cost: BeBo, Teknikupphandling av värmeåtervinning i befintliga flerbostadshus Service life: Gustafsson et. Al
9	**FTX-system installation + 180 mm insulation**			**2 340 000,00**	35	Costs and service life: Smartfront AB
10	**Extra management costs**			12%		Byggkostnader | Byggföretagen (byggforetagen.se)

G

IDA ICE results

IDA ICE summary

Geographical number (F_{geo}) for Gothenburg	0,9
Envelope area (m^2)	1468.6
Floor area (A_{temp}) (m^2)	1156

SN	Type of delivered energy	Calibrated results (SFP = 2)		Baseline measures		F-system (SFP = 0.5)					
						F-I0-U1.3		F-I50-U1		F-I100-U0.6	
		kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
1	Lighting, facility	152,00	0,13	152,00	0,13	152,00	0,13	152,00	0,13	152,00	0,13
2	HVAC aux	6 878,00	5,95	6 841,00	5,92	1 788,00	1,55	1 764,00	1,53	1 749,00	1,51
3	Electric heating										
	Total, facility electric (A)	**7030**	**6,08**	**6993**	**6,05**	**1940**	**1,68**	**1916**	**1,66**	**1901**	**1,64**
4	District heating	110 931,00	95,96	106 492,00	92,12	89 115,00	77,09	78 176,00	67,63	69 755,00	60,34
5	District heating, hot water	30 069,00	26,01	22 479,00	19,45	22 479,00	19,45	22 479,00	19,45	22 480,00	19,45
	Total, facility district (B)	**141 000**	**121,97**	**128 971**	**111,57**	**111 594**	**96,53**	**100 655**	**87,07**	**92 235**	**79,79**
	Total Specific Energy use = C (A + B)	**148 030**	**128,1**	**135 964**	**117,62**	**113 534**	**98,21**	**102 571**	**88,73**	**94 136**	**81,43**
	EPpet		**103,8**		**96,2**		**76,6**		**69,2**		**63,5**
	CO2 emissions (kgCO2-eq)	**9818,79**		**9033,464**		**7434,03**		**6720,763**		**6172,068**	

SN	Type of delivered energy	FVP						FTX					
		FVP-I0-U1.3		FVP-I50-U1		FVP-I100-U0.6		FTX-I.S-U1.3		FTX-I.S-U1		FTX-I.S-U0.6	
		kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
1	Lighting, facility	153,00	0,13	153,00	0,13	153,00	0,13	152,00	0,13	153,00	0,13	153,00	0,13
2	HVAC aux	2 398,00	2,07	2 368,00	2,05	2 348,00	2,03	5 472,00	4,73	5 475,00	4,74	5 472,00	4,73
3	Electric heating	17595	15,22	17931	15,51	17892	15,48						
	Total, facility electric (A)	**20146**	**17,43**	**20452**	**17,69**	**20393**	**17,64**	**5624**	**4,87**	**5628**	**4,87**	**5625**	**4,87**
4	District heating	48 995,00	42,38	37 669,00	32,59	30 318,00	26,23	37 689,00	32,60	38 909,00	33,66	36 176,00	31,29
5	District heating, hot water							22 480,00	19,45	22 480,00	19,45	22 480,00	19,45
	Total, facility district (B)	**48 995**	**42,4**	**37 669**	**32,6**	**30 318**	**26,23**	**60 169**	**52,05**	**61 389**	**53,10**	**58 656**	**50,74**
	Total Specific Energy use = C (A + B)	**69 141**	**59,81**	**58 121**	**50,3**	**50 711**	**43,9**	**65 793**	**56,9**	**67 017**	**58,0**	**64 281**	**55,6**
	EPpet		**66,4**		**58,7**		**53,8**		**47,7**		**48,6**		**46,7**
	CO2 emissions (kgCO2-eq)	**5058,253**		**4350,521**		**3867,219**		**4434,017**		**4513,689**		**4335,765**	

Energy carrier	Weighting factor	CO2 Emission factor (gCO2-eq)
Electricity	1,8	93
District heating	0,7	65

Special calculations for heat pump Package 4

Electric heating = 17595 kWh

From 30,069 kWh which was initially used for DHW, we now have 17595 kWh for electric heating which is used for DHW preparation and space heating instead.
The problem is to find how much of the electric heating is used for DHW and and how much for space heating.

Multiplying the electric heating value by the COP of the heat pump, we can convert the electricity to heating value.
4*17595 = 70380 kWh
The domestic hot water value is reasonably constant, as this depends on user behaviour.
So 22, 479 kWh is the heating required for DHW preparation in the building after applying the baseline measures
Which means the space heating from electricity is = 47 901,00 kWh which is 68% of the total heat.
Thus, 68% of 17368 kWh is used for space heating which is = 11964,6 kWh
And, 32% of 17368 kWh is used for DHW preparation which is = 5630,4 kWh

Special calculations for heat pump Package 5

Electric heating = 17931 kWh

Multiplying the electric heating value by the COP of the heat pump, we can convert the electricity to heating value.
4*17931= 71724 kWh
The domestic hot water value is reasonably constant, as this depends on user behaviour.
So 22, 479 kWh is the heating required for DHW preparation in the building after applying the baseline measures
Which means the space heating from electricity is = 48975 kWh which is 68% of the total heat.
Thus, 68% of 17368 kWh is used for space heating which is = 12193,08 kWh
And, 32% of 17368 kWh is used for DHW preparation which is = 5737,92 kWh

Special calculations for heat pump Package 6

Electric heating = 17892 kWh

Multiplying the electric heating value by the COP of the heat pump, we can convert the electricity to heating value.
4*18144 = 71568 kWh
The domestic hot water value is reasonably constant, as this depends on user behaviour.
So 22, 479 kWh is the heating required for DHW preparation in the building after applying the baseline measures
Which means the space heating from electricity is = 49089 kWh which is 69% of the total heat.
Thus, 69% of 17368 kWh is used for space heating which is 12345,48 kWh
Thus, 31% of 17368 kWh is used for DHW preparation which is 5546,52 kWh

H

Energy savings, EPpet values and CO2 emissions

Energy use						
SN	Packages	District heating [kWh]	District heating [kWh/m^2]	Electricity [kWh]	Electricity [kWh/m^2]	Total specific energy use [kWh/m2]
1	Reference	141 000	121,97	7 030	6,08	128,05
2	Baseline	128 971	111,57	6 993	6,05	117,62
3	F, I-0, U1.3	111 594	96,53	1 940	1,68	98,21
4	F, I-50, U1.1	100 655	87,07	1 916	1,66	88,73
5	F, I-100, U0.7	92 235	79,79	1 901	1,64	81,43
6	FVP, I-0, U1.3	48 995	42,38	20 146	17,43	59,81
7	FVP, I-50, U1.1	37 669	32,59	20 452	17,69	50,28
8	FVP, I-100, U0.7	30 318	26,23	20 393	17,64	43,87
9	FTX, I-180, U1.3	60 169	52,05	5 624	4,87	56,91
10	FTX, I-180, U1.1	61 389	53,10	5 628	4,87	57,97
11	FTX, I-180, U0.7	58 656	50,74	5 625	4,87	55,61

Specific Energy saving									
SN	Packages	District heating savings [kWh]	District heating savings [kWh/m2]	District Heating reduction %	Electricity use change [kWh]	Electricity use change [kWh/m2]	Electricity change %	Total specific energy use savings [kWh/m2]	Total specific energy use savings [%]
1	Reference								
2	Baseline	12 029	10,41	8,53%	-37	-0,03	-0,53%	10,44	8,15%
3	F, I-0, U1.3	29 406	25,44	20,86%	-5 090	-4,40	-72,40%	29,84	23,30%
4	F, I-50, U1.1	40 345	34,90	28,61%	-5 114	-4,42	-72,75%	39,32	30,71%
5	F, I-100, U0.7	48 765	42,18	34,59%	-5 129	-4,44	-72,96%	46,62	36,41%
6	FVP, I-0, U1.3	92 005	79,59	65,25%	13 116	11,35	186,57%	68,24	53,29%
7	FVP, I-50, U1.1	103 331	89,39	73,28%	13 422	11,61	190,92%	77,78	60,74%
8	FVP, I-100, U0.7	110 682	95,75	78,50%	13 363	11,56	190,09%	84,19	65,74%
9	FTX, I-180, U1.3	80 831	69,92	57,33%	-1 406	-1,22	-20,00%	71,14	55,55%
10	FTX, I-180, U1.1	79 611	68,87	56,46%	-1 402	-1,21	-19,94%	70,08	54,73%
11	FTX, I-180, U0.7	82 344	71,23	58,40%	-1 405	-1,22	-19,99%	72,45	56,58%

SN	Packages	EPpet			CO2 emissions		
		EPpet	EPpet reduction	EPpet reduction [%]	CO2 generation (kgCO2-eq)	CO2 savings (kgCO2-eq)	CO2 savings (%)
1	Reference	103,79			9818,79		
2	Baseline	96,15	7,64	7,36%	9033,464	785,326	8,00%
3	F, I-0, U1.3	76,59	27,20	26,21%	7434,03	2384,76	24,29%
4	F, I-50, U1.1	69,19	34,60	33,33%	6720,763	3098,027	31,55%
5	F, I-100, U0.7	63,50	40,29	38,81%	6172,068	3646,722	37,14%
6	FVP, I-0, U1.3	66,07	37,72	36,34%	5058,253	4760,537	48,48%
7	FVP, I-50, U1.1	58,40	45,39	43,73%	4350,521	5468,269	55,69%
8	FVP, I-100, U0.7	53,42	50,37	48,53%	3867,219	5951,571	60,61%
9	FTX, I-180, U1.3	47,73	56,06	54,02%	4434,017	5384,773	54,84%
10	FTX, I-180, U1.1	48,55	55,24	53,22%	4513,689	5305,101	54,03%
11	FTX, I-180, U0.7	46,71	57,08	54,99%	4335,765	5483,025	55,84%

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Economic evaluation using EAC method

BASELINE MEASURES

District heating savings	12 029,00	kWh
Electricity savings	-37,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	**Cleaning of ducts**	**Installation of water saving aerators**	**Radiator balancing**	**Energy savings**
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	9838,52
2	0,00 kr	0,00 kr	0,00 kr	10133,68
3	0,00 kr	0,00 kr	0,00 kr	10437,69
4	0,00 kr	0,00 kr	0,00 kr	10750,82
5	0,00 kr	0,00 kr	0,00 kr	11073,34
6	0,00 kr	0,00 kr	0,00 kr	11405,54
7		0,00 kr	0,00 kr	11747,71
8		0,00 kr	0,00 kr	12100,14
9		0,00 kr	0,00 kr	12463,15
10		0,00 kr	0,00 kr	12837,04
11		0,00 kr		13222,15
12		0,00 kr		13618,82
13		0,00 kr		14027,38
14		0,00 kr		14448,20
15		0,00 kr		14881,65
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	132 737,40 kr
EAC factor	5,24	11,12	8,11	11,12
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	11 938,55 kr
EAC total	**6 044,25 kr**			
Direktavkastning	21,05%			

F-I0-U1.3

District heating savings	29 406,00	kWh
Electricity savings	-5 090,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Additional pane in windows	Improvement of fan	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-297 920,00 kr	-28 784,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	19159,11
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	19733,89
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	20325,90
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	20935,68
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	21563,75
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	22210,66
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	22876,98
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	23563,29
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	24270,19
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	24998,30
11		0,00 kr		0,00 kr	0,00 kr	25748,25
12		0,00 kr		0,00 kr	0,00 kr	26520,70
13		0,00 kr		0,00 kr	0,00 kr	27316,32
14		0,00 kr		0,00 kr	0,00 kr	28135,81
15		0,00 kr		0,00 kr	0,00 kr	28979,88
16				0,00 kr		29849,28
17				0,00 kr		30744,75
18				0,00 kr		31667,10
19				0,00 kr		32617,11
20				0,00 kr		33595,62
21				0,00 kr		34603,49
22				0,00 kr		35641,60
23				0,00 kr		36710,84
24				0,00 kr		37812,17
25				0,00 kr		38946,53
26				0,00 kr		40114,93
27				0,00 kr		41318,38
28				0,00 kr		42557,93
29				0,00 kr		43834,67
30				0,00 kr		45149,71
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-286 461,54 kr	-27 676,92 kr	482 100,16 kr
EAC factor	5,24	11,12	8,11	17,29	11,12	17,29
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-16 566,10 kr	-2 489,29 kr	27 879,90 kr
EAC total	**2 930,21 kr**					
Direktavkastning	5,13%					

F-I50-U1.1

District heating savings	40 345,00	kWh
Electricity savings	-5 114,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Window replacement to U-value of 1.1	Improvement of fan	Additonal Exterior insulation (50 mm)	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-1 099 871,36 kr	-28 784,00 kr	-599 200,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	28115,56
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	28959,03
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	29827,80
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	30722,64
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	31644,32
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	32593,65
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	33571,45
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	34578,60
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	35615,96
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	36684,44
11		0,00 kr		0,00 kr	0,00 kr	0,00 kr	37784,97
12		0,00 kr		0,00 kr	0,00 kr	0,00 kr	38918,52
13		0,00 kr		0,00 kr	0,00 kr	0,00 kr	40086,07
14		0,00 kr		0,00 kr	0,00 kr	0,00 kr	41288,66
15		0,00 kr		0,00 kr	0,00 kr	0,00 kr	42527,31
16				0,00 kr		0,00 kr	43803,13
17				0,00 kr		0,00 kr	45117,23
18				0,00 kr		0,00 kr	46470,74
19				0,00 kr		0,00 kr	47864,87
20				0,00 kr		0,00 kr	49300,81
21				0,00 kr		0,00 kr	50779,84
22				0,00 kr		0,00 kr	52303,23
23				0,00 kr		0,00 kr	53872,33
24				0,00 kr		0,00 kr	55488,50
25				0,00 kr		0,00 kr	57153,15
26				0,00 kr		0,00 kr	58867,75
27				0,00 kr		0,00 kr	60633,78
28				0,00 kr		0,00 kr	62452,80
29				0,00 kr		0,00 kr	64326,38
30				0,00 kr		0,00 kr	66256,17
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-1 057 568,62 kr	-27 676,92 kr	-576 153,85 kr	707 471,03 kr
EAC factor	5,24	11,12	8,11	17,29	11,12	17,29	17,29
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-61 159,30 kr	-2 489,29 kr	-33 319,03 kr	40 913,12 kr
EAC total	**-61 948,80 kr**						
Direktavkastning	1,58%						

F-I100-U0.7

District heating savings	48 765,00	kWh
Electricity savings	-5 129,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	**Cleaning of ducts**	**Installation of water saving aerators**	**Radiator balancing**	**Window replacement to U-value of 0.7**	**Improvement of fan**	**Additonal Exterior insulation (100 mm)**	**Energy savings**
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-1 957 801,44 kr	-28 784,00 kr	-617 775,20 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	35012,95
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	36063,34
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	37145,24
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	38259,60
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	39407,38
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	40589,60
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	41807,29
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	43061,51
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	44353,36
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	45683,96
11		0,00 kr		0,00 kr	0,00 kr	0,00 kr	47054,48
12		0,00 kr		0,00 kr	0,00 kr	0,00 kr	48466,11
13		0,00 kr		0,00 kr	0,00 kr	0,00 kr	49920,09
14		0,00 kr		0,00 kr	0,00 kr	0,00 kr	51417,70
15		0,00 kr		0,00 kr	0,00 kr	0,00 kr	52960,23
16				0,00 kr		0,00 kr	54549,03
17				0,00 kr		0,00 kr	56185,51
18				0,00 kr		0,00 kr	57871,07
19				0,00 kr		0,00 kr	59607,20
20				0,00 kr		0,00 kr	61395,42
21				0,00 kr		0,00 kr	63237,28
22				0,00 kr		0,00 kr	65134,40
23				0,00 kr		0,00 kr	67088,43
24				0,00 kr		0,00 kr	69101,09
25				0,00 kr		0,00 kr	71174,12
26				0,00 kr		0,00 kr	73309,34
27				0,00 kr		0,00 kr	75508,62
28				0,00 kr		0,00 kr	77773,88
29				0,00 kr		0,00 kr	80107,10
30				0,00 kr		0,00 kr	82510,31
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-1 882 501,38 kr	-27 676,92 kr	-594 014,62 kr	881 029,69 kr
EAC factor	5,24	11,12	8,11	17,29	11,12	17,29	17,29
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-108 865,24 kr	-2 489,29 kr	-34 351,92 kr	50 950,03 kr
EAC total	**-100 650,72 kr**						
Direktavkastning	1,32%						

FVP-I0-U1.3

District heating savings	92 005,00	kWh
Electricity savings	-13 116,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Additional pane in windows	Improvement of fan	Installation a heat pump	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-297 920,00 kr	-28 784,00 kr	-670 480,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	62693,82
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	64574,63
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	66511,87
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	68507,23
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	70562,45
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	72679,32
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	74859,70
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	77105,49
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	79418,65
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	81801,21
11		0,00 kr		0,00 kr	0,00 kr	0,00 kr	84255,25
12		0,00 kr		0,00 kr	0,00 kr	0,00 kr	86782,91
13		0,00 kr		0,00 kr	0,00 kr	0,00 kr	89386,39
14		0,00 kr		0,00 kr	0,00 kr	0,00 kr	92067,99
15		0,00 kr		0,00 kr	0,00 kr	0,00 kr	94830,03
16				0,00 kr		0,00 kr	97674,93
17				0,00 kr		0,00 kr	100605,17
18				0,00 kr		0,00 kr	103623,33
19				0,00 kr		0,00 kr	106732,03
20				0,00 kr		0,00 kr	109933,99
21				0,00 kr			113232,01
22				0,00 kr			116628,97
23				0,00 kr			120127,84
24				0,00 kr			123731,67
25				0,00 kr			127443,62
26				0,00 kr			131266,93
27				0,00 kr			135204,94
28				0,00 kr			139261,09
29				0,00 kr			143438,92
30				0,00 kr			147742,09
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-286 461,54 kr	-27 676,92 kr	-644 692,31 kr	1 577 562,48 kr
EAC factor	5,24	11,12	8,11	17,29	11,12	13,59	17,29
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-16 566,10 kr	-2 489,29 kr	-47 437,59 kr	91 230,59 kr
EAC total	**18 843,32 kr**						
Direktavkastning	6,01%						

FVP-I50-U1.1

District heating savings	103 331,00	kWh
Electricity savings	-13 422,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Window replacement to U-value of 1.1	Additonal Exterior insulation (50 mm)	Improvement of fan	Installation a heat pump	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-1 099 871,36 kr	-599 200,00 kr	-28 784,00 kr	###########	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	71692,02
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	73842,78
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	76058,07
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	78339,81
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	80690,00
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	83110,71
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	85604,03
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	88172,15
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	90817,31
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	93541,83
11		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	96348,09
12		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	99238,53
13		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	102215,68
14		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	105282,15
15		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	108440,62
16				0,00 kr	0,00 kr		0,00 kr	111693,84
17				0,00 kr	0,00 kr		0,00 kr	115044,65
18				0,00 kr	0,00 kr		0,00 kr	118495,99
19				0,00 kr	0,00 kr		0,00 kr	122050,87
20				0,00 kr	0,00 kr		0,00 kr	125712,40
21				0,00 kr	0,00 kr			129483,77
22				0,00 kr	0,00 kr			133368,28
23				0,00 kr	0,00 kr			137369,33
24				0,00 kr	0,00 kr			141490,41
25				0,00 kr	0,00 kr			145735,12
26				0,00 kr	0,00 kr			150107,18
27				0,00 kr	0,00 kr			154610,39
28				0,00 kr	0,00 kr			159248,71
29				0,00 kr	0,00 kr			164026,17
30				0,00 kr	0,00 kr			168946,95
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-1 057 568,62 kr	-576 153,85 kr	-27 676,92 kr	###########	1 803 984,03 kr
EAC factor	5,24	11,12	8,11	17,29	17,29	11,12	13,59	17,29
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-61 159,30 kr	-33 319,03 kr	-2 489,29 kr	-47 437,59 kr	104 324,58 kr
EAC total	**-45 974,93 kr**							
Direktavkastning	2,93%							

FVP-I100-U0.7

District heating savings	110 682,00	kWh
Electricity savings	-13 363,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Window replacement to U-value of 0.6	Additonal Exterior insulation (100 mm)	Improvement of fan	Installation a heat pump	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-1 957 801,44 kr	-617 775,20 kr	-28 784,00 kr	-670 480,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	77784,27
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	80117,79
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	82521,33
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	84996,97
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	87546,88
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	90173,28
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	92878,48
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	95664,83
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	98534,78
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	101490,82
11		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	104535,55
12		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	107671,61
13		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	110901,76
14		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	114228,82
15		0,00 kr		0,00 kr	0,00 kr	0,00 kr	0,00 kr	117655,68
16				0,00 kr	0,00 kr		0,00 kr	121185,35
17				0,00 kr	0,00 kr		0,00 kr	124820,91
18				0,00 kr	0,00 kr		0,00 kr	128565,54
19				0,00 kr	0,00 kr		0,00 kr	132422,50
20				0,00 kr	0,00 kr		0,00 kr	136395,18
21				0,00 kr	0,00 kr			140487,04
22				0,00 kr	0,00 kr			144701,65
23				0,00 kr	0,00 kr			149042,70
24				0,00 kr	0,00 kr			153513,98
25				0,00 kr	0,00 kr			158119,40
26				0,00 kr	0,00 kr			162862,98
27				0,00 kr	0,00 kr			167748,87
28				0,00 kr	0,00 kr			172781,33
29				0,00 kr	0,00 kr			177964,77
30				0,00 kr	0,00 kr			183303,72
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-1 882 501,38 kr	-594 014,62 kr	-27 676,92 kr	-644 692,31 kr	1 957 282,88 kr
EAC factor	5,24	11,12	8,11	17,29	17,29	11,12	13,59	17,29
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-108 865,24 kr	-34 351,92 kr	-2 489,29 kr	-47 437,59 kr	113 189,86 kr
EAC total	**-85 848,48 kr**							
Direktavkastning	2,34%							

FTX-I.S-U1.3

District heating savings	80 831,00	kWh
Electricity savings	-1 406,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Additional pane in windows	FTX-System, Walls and AHU	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-297 920,00 kr	-2 340 000,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	64979,21
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	66928,58
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	68936,44
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	71004,53
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	73134,67
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	75328,71
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	77588,57
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	79916,23
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	82313,71
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	84783,12
11		0,00 kr		0,00 kr	0,00 kr	87326,62
12		0,00 kr		0,00 kr	0,00 kr	89946,42
13		0,00 kr		0,00 kr	0,00 kr	92644,81
14		0,00 kr		0,00 kr	0,00 kr	95424,15
15		0,00 kr		0,00 kr	0,00 kr	98286,88
16				0,00 kr	0,00 kr	101235,48
17				0,00 kr	0,00 kr	104272,55
18				0,00 kr	0,00 kr	107400,73
19				0,00 kr	0,00 kr	110622,75
20				0,00 kr	0,00 kr	113941,43
21				0,00 kr	0,00 kr	117359,67
22				0,00 kr	0,00 kr	120880,46
23				0,00 kr	0,00 kr	124506,88
24				0,00 kr	0,00 kr	128242,08
25				0,00 kr	0,00 kr	132089,35
26				0,00 kr	0,00 kr	136052,03
27				0,00 kr	0,00 kr	140133,59
28				0,00 kr	0,00 kr	144337,59
29				0,00 kr	0,00 kr	148667,72
30				0,00 kr	0,00 kr	153127,75
31					0,00 kr	157721,59
32					0,00 kr	162453,23
33					0,00 kr	167326,83
34					0,00 kr	172346,64
35					0,00 kr	177517,03
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-286 461,54 kr	-2 250 000,00 kr	1 864 407,54 kr
EAC factor	5,24	11,12	8,11	17,29	18,66	18,66
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-16 566,10 kr	-120 548,98 kr	99 889,96 kr
EAC total	**-43 119,40 kr**					
Direktavkastning	2,42%					

FTX-I.S-U1.1

District heating savings	79 611,00	kWh
Electricity savings	-1 402,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Window replacement to U-value of 1.1	FTX-System, Walls and AHU	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-1 099 871,36 kr	-2 340 000,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	63981,61
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	65901,06
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	67878,09
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	69914,43
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	72011,86
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	74172,22
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	76397,39
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	78689,31
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	81049,99
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	83481,49
11		0,00 kr		0,00 kr	0,00 kr	85985,93
12		0,00 kr		0,00 kr	0,00 kr	88565,51
13		0,00 kr		0,00 kr	0,00 kr	91222,48
14		0,00 kr		0,00 kr	0,00 kr	93959,15
15		0,00 kr		0,00 kr	0,00 kr	96777,92
16				0,00 kr	0,00 kr	99681,26
17				0,00 kr	0,00 kr	102671,70
18				0,00 kr	0,00 kr	105751,85
19				0,00 kr	0,00 kr	108924,41
20				0,00 kr	0,00 kr	112192,14
21				0,00 kr	0,00 kr	115557,90
22				0,00 kr	0,00 kr	119024,64
23				0,00 kr	0,00 kr	122595,38
24				0,00 kr	0,00 kr	126273,24
25				0,00 kr	0,00 kr	130061,44
26				0,00 kr	0,00 kr	133963,28
27				0,00 kr	0,00 kr	137982,18
28				0,00 kr	0,00 kr	142121,64
29				0,00 kr	0,00 kr	146385,29
30				0,00 kr	0,00 kr	150776,85
31					0,00 kr	155300,16
32					0,00 kr	159959,16
33					0,00 kr	164757,94
34					0,00 kr	169700,68
35					0,00 kr	174791,70
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-1 057 568,62 kr	-2 250 000,00 kr	1 835 784,14 kr
EAC factor	5,24	11,12	8,11	17,29	18,66	18,66
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-61 159,30 kr	-120 548,98 kr	98 356,40 kr
EAC total	**-89 246,17 kr**					
Direktavkastning	1,84%					

FTX-I.S-U0.7

District heating savings	82 344,00	kWh
Electricity savings	-1 405,00	kWh
Discount rate	4%	
Energy price growth rate	3%	
Energy price, district heating	0,797	Kr/kWh
Energy price, Electricity	0,95	Kr/kWh
Management cost	12%	

Year	Cleaning of ducts	Installation of water saving aerators	Radiator balancing	Window replacement to U-value of 0.7	FTX-System, Walls and AHU	Energy savings
0	-7 840,00 kr	-4 855,20 kr	-34 048,00 kr	-1 957 801,44 kr	-2 340 000,00 kr	
1	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	66222,22
2	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	68208,89
3	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	70255,15
4	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	72362,81
5	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	74533,69
6	0,00 kr	0,00 kr	0,00 kr	0,00 kr	0,00 kr	76769,70
7		0,00 kr	0,00 kr	0,00 kr	0,00 kr	79072,79
8		0,00 kr	0,00 kr	0,00 kr	0,00 kr	81444,98
9		0,00 kr	0,00 kr	0,00 kr	0,00 kr	83888,33
10		0,00 kr	0,00 kr	0,00 kr	0,00 kr	86404,98
11		0,00 kr		0,00 kr	0,00 kr	88997,13
12		0,00 kr		0,00 kr	0,00 kr	91667,04
13		0,00 kr		0,00 kr	0,00 kr	94417,05
14		0,00 kr		0,00 kr	0,00 kr	97249,56
15		0,00 kr		0,00 kr	0,00 kr	100167,05
16				0,00 kr	0,00 kr	103172,06
17				0,00 kr	0,00 kr	106267,22
18				0,00 kr	0,00 kr	109455,24
19				0,00 kr	0,00 kr	112738,90
20				0,00 kr	0,00 kr	116121,06
21				0,00 kr	0,00 kr	119604,70
22				0,00 kr	0,00 kr	123192,84
23				0,00 kr	0,00 kr	126888,62
24				0,00 kr	0,00 kr	130695,28
25				0,00 kr	0,00 kr	134616,14
26				0,00 kr	0,00 kr	138654,62
27				0,00 kr	0,00 kr	142814,26
28				0,00 kr	0,00 kr	147098,69
29				0,00 kr	0,00 kr	151511,65
30				0,00 kr	0,00 kr	156057,00
31					0,00 kr	160738,71
32					0,00 kr	165560,87
33					0,00 kr	170527,70
34					0,00 kr	175643,53
35					0,00 kr	180912,83
NPV	-7 538,46 kr	-4 668,46 kr	-32 738,46 kr	-1 882 501,38 kr	-2 250 000,00 kr	1 900 072,60 kr
EAC factor	5,24	11,12	8,11	17,29	18,66	18,66
EAC	-1 438,05 kr	-419,89 kr	-4 036,36 kr	-108 865,24 kr	-120 548,98 kr	101 800,80 kr
EAC total	**-133 507,71 kr**					
Direktavkastning	1,52%					

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Summary of Economic Analysis

Economic analysis					
SN	Packages	EAC (SEK)	Direktavkastning (%)	Investment costs (SEK)	Initial savings in operational cost (SEK)
1	Reference				
2	Baseline	6 044,25	21,05%	46 743,20	9 838,52
3	F, I-0, U1.3	2 930,21	5,13%	373 447,20	19 159,11
4	F, I-50, U1.1	-61 948,80	1,58%	1 774 598,56	28 115,56
5	F, I-100, U0.7	-100 650,72	1,32%	2 651 103,84	35 012,95
6	FVP, I-0, U1.3	18 843,32	6,01%	1 043 927,20	62 693,82
7	FVP, I-50, U1.1	-45 974,93	2,93%	2 445 078,56	71 692,02
8	FVP, I-100, U0.7	-85 848,48	2,34%	3 321 583,84	77 784,27
9	FTX, I.S, U1.3	-43 119,40	2,42%	2 684 663,20	64 979,21
10	FTX, I.S, U1.1	-89 246,17	1,84%	3 486 614,56	63 981,61
11	FTX, I.S, U0.7	-133 507,71	1,52%	4 344 544,64	66 222,22

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Extrapolation

Buildings	Footprint area (m2)	No. Of floors	Floor area (m2)	Proportion of total area
BR 5-7	509	3	1526	16%
BR 8-9	386	3	1157	12%
BR 10-12	549	4	2195	22%
BR 21-23	509	3	1526	16%
BR 24-25 (Case building)	386	3	1157	12%
BR 26-28	549	4	2195	22%
Total:			**9756**	**m2**

Case study building proportional area	12%

Package designation	Case study building			Whole area		
	Investment Costs (SEK)	Yearly CO2 savings (tons)	Initial savings in operational costs (SEK)	Investment Costs (SEK)	Yearly CO2 savings (tons)	Initial savings in operational costs (SEK)
Baseline	46 743,20	0,79	9 838,52	394 145,77	6,6	82 959,91
F, I-0, U1.3	373 447,20	2,38	19 159,11	3 148 963,60	20,1	161 552,57
F, I-50, U1.1	1 774 598,56	3,10	28 115,56	14 963 685,01	26,1	237 074,72
F, I-100, U0.7	2 651 103,84	3,65	35 012,95	22 354 510,86	30,7	295 234,52
FVP, I-0, U1.3	1 043 927,20	4,76	62 693,82	8 802 552,95	40,1	528 643,81
FVP, I-50, U1.1	2 445 078,56	5,47	71 692,02	20 617 274,36	46,1	604 518,05
FVP, I-100, U0.7	3 321 583,84	5,95	77 784,27	28 008 100,21	50,2	655 888,76
FTX, I.S, U1.3	2 684 663,20	5,38	64 979,21	22 637 488,49	45,4	547 914,54
FTX, I.S, U1.1	3 486 614,56	5,31	63 981,61	29 399 664,35	44,7	539 502,66
FTX, I.S, U0.7	4 344 544,64	5,5	66 222,22	36 633 861,29	46,2	558 395,84