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Cost-optimal energy renovation of historic buildings in Arboga, Sweden

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ABSTRACT

In Sweden, 27% of the CO_2 emissions are originated from the residential sector. A third of the building stock has been built before 1945. This implies a high potential of energy use reduction. LCC optimization is a key step in the energetic renovation of historic buildings. In this thesis, optimizations based on different targets have been carried out for four building categories representing the historic building stock in Arboga, Sweden. The other energy targets includes a decrease in energy use by: 10%, 20%, 30%, 40%, 50%, 60% and 70%, as well as LCC optimum. In addition, the environmental effects from energy renovation in terms of CO_2 equivalent is investigated.

The results shows that the groundwater heat pump is the cost-optimal heating system in 27 of 28 cases. Furthermore, it is concluded that weather-stripping, together with floor and roof insulation are cost-effective at LCC optimum. The reduction in LCC at LCC optimum corresponds to a decrease by, 30%, 30%, 46% and 26% for category 1-4, respectively. From this, it can be concluded that the profitability of energy renovation in category 3 is the most profitable one in terms of percentage decrease. Moreover, the results state that energy renovation is profitable for every energy target for the stone building, category 3. This is in contrary with the wood buildings, categories 1, 2 and 4, where the 70% target is not profitable from an economical perspective compared to before energy renovation. After renovation, CO_2 emissions from the buildings have been reduced, obtaining saving higher than 70% of CO_2 equivalent per MWh.

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1. Introduction

This chapter describes the topic of the thesis in general. After the purpose and aim are introduced, the limitations, delimitations and assumptions are presented.

1.1. Background

The climate changes are one of the toughest challenges that the world is facing. The main explanation for the climate change is the severe increase of greenhouse gases (GHG) emissions, where burning fossil fuels is one of the main causes [1]. The local and global emissions have a huge effect not only on global warming and environment, but also on people's health [2].

Of global energy share 33% derives from transportation, 29% from industry, 27% from residential use, 8% from commercial use and 3% from other, as shown in Fig. 1 [3]. In the EU the building sector accounts for 40% of total energy use and 36% of the CO_2 emissions of the EU today [4].

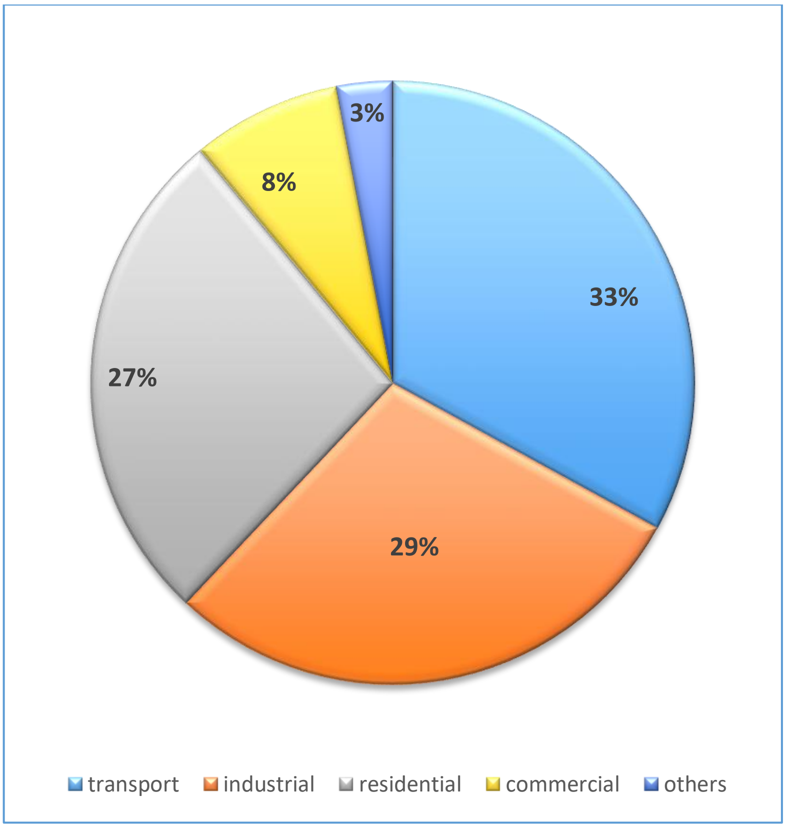

Fig. 1: Sectorial shares of global energy consumption [3]

The European commission suggests that in order to avoid huge environmental problems affected by the climate change, there is a need of reduction of CO_2 emission by 60 % from the levels of today [5]. To face this challenge regarding climate change and energy, European Commission has developed the 2030 strategy with the following targets [6]:

- A 40% cut in greenhouse gas emissions compared to 1990 levels.
- At least a 27% share of renewable energy consumption.

- At least 27% energy savings compared with the business-as-usual scenario.

Following the energy cooperation in the EU, Sweden’s energy policy has fixed the target of not having net emissions of greenhouse gases into the atmosphere by year 2045. By year 2040, the target is to have 100% renewable electricity production [7].

Building construction is associated with a high energy use and waste generation that negatively affects the environment. It can be considered that a building has an energy use throughout its whole life cycle, i.e. from construction, during utilization and for demolition.

It is approximated that about one-third of the buildings in Sweden are built before 1945 [8]. Refurbishment and urban renewal are fundamental instruments for the achievement of a sustainable urban environment [9]. A difficulty that occur when refurbishing a historic building is the eventual impact on the building´s historic values. This is a factor that need to be considered before implementing measures. Anyhow, it is noteworthy that building renovation can enhance the building status and update the performance to the requirements of current regulations, e.g. building stability [10]. Moreover, compared to the construction of a new building, renovation of old buildings allows for reduction of the negative impact on the environment [10]. Firstly, because the production of waste is less than if demolition of the building is selected, as well as the necessity of raw material is reduced compared to construct a new building. Secondly because it reduces the energy use that would be necessary to build a new building.

Life Cycle Cost (LCC) analysis is a common way on investigating buildings during their lifetime. By using optimization, it is possible to obtain the lowest possible LCC. Main parameters studied during LCC optimization in the energy efficiency field for buildings are for example: additional insulation to walls, roof and floor, replacement of windows, cooling and heating set points, efficient electric appliances and lighting, efficient water taps and exhaust air ventilation with heat recovery systems [11, 12, 13]. To evaluate the cost effectiveness financial parameters such as discount rate, energy price, technology price, among other parameters related with LCC optimization effect are used [14]. By doing this it is possible to obtain a better performance of the building efficiency both in terms of economics and energy performance. LCC optimization has previously shown to be a feasible way to decrease the building energy use [15, 16]. OPERA-MILP is an LCC optimization tool for buildings. The software has been used in various contexts investigating cost-effective energy renovation in buildings, i.e. [17, 18, 19, 20, 21].

1.2. Motivation

The development of sustainable housing is a vital step to reduce GHG emissions. One way to achieve this is by historic buildings’ energy renovation, because of their high energy efficiency potential. This thesis studies the relation between minimizing the cost of renovation and the energy use of the building. Additionally, if it is possible to achieve this objective and maintain the historic value of the building is investigated.

This thesis is part of the Swedish research project “Potential and Policies for Energy Efficiency in Swedish Historic Buildings. This project aims to investigate the interdependency between political energy targets and effects on the built heritage.

1.3. Aim

The purpose of the thesis is to study the effects from cost-optimal energy renovation in terms of LCC and renovation strategy depending on different energy targets. This is performed by using LCC optimization. Four buildings, typical of the historic building stock in Arboga, are used as study objects. Furthermore, the environmental performance of the buildings, referring to the CO_2 equivalent emissions, before and after energy renovation, is investigated. To achieve the above-mentioned aim the following energy goals will be performed and analysed compared to the reference case:

- Case 1 - Reference case. No energy efficiency measures (EEMs) applied.
- Case 2 - Decrease by 10% in energy use.
- Case 3 - Decrease by 20% in energy use.
- Case 4 - Decrease by 30% in energy use.
- Case 5 - Decrease by 40% in energy use.
- Case 6 - Decrease by 50% in energy use.
- Case 7. Decrease by 60% in energy use.
- Case 8. Decrease by 70% in energy use.

1.4. Limitations

This thesis is conducted during a specified period and is limited to a historic building district located in Arboga. Four building types are used as case study, which are representing 168 buildings [22].

There are a number of limitations using LCC optimization software OPERA-MILP, which are the following:

- The number of heating systems are limited to district heating, groundwater heat pump, electric radiator and wood boiler.
- The included EEMs are change of windows, weather-stripping, floor insulation, roof insulation and wall insulation.
- The energy calculation for a building is divided into twelve periods during a year, each period representing one month.

1.5. Delimitations

The buildings physical risk are not considered in the boundaries of this thesis. The use of the buildings is considered for housing. The internal area reduction could affect the rental income in case wall insulation on the internal side is selected. This is also not taken into account.

In order to not reduce the heritage value of the building means no changes to exterior appearance (external wall insulation from outside).

1.6. Assumptions

Assumptions about the heating systems and EEMs have been made in order to enable the execution of the thesis.

The assumed efficiencies of the heating systems and their life lengths can be seen in Table 1 [19].

Heating system	Efficiency	Life length in years
District heating	0.95	25
Ground water heat pump	3	25
Wood boiler	0.85	15
Electric Radiator	1	15

Table 1: Assumptions

Other assumptions are:

- The LCC optimization time is set to 50 years.
- The discount rate is set to 5% because it is commercially utilized in real projects.

2. State of the Art

During last years, energy efficiency in historic buildings has become a high-interest topic, as stated by Martínez-Molina et. al [23]. Europe, particularly Italy, is leading the research [23]. This can be evidenced by the many research projects and initiatives that are being carried out. Only about Life Cycle Analysis (LCA), which goes hand by hand with LCC [24], of buildings there has been an extensively studied research area over the past decade because of the high environmental impacts of this sector [25]. This increase is shown in Fig. 2.

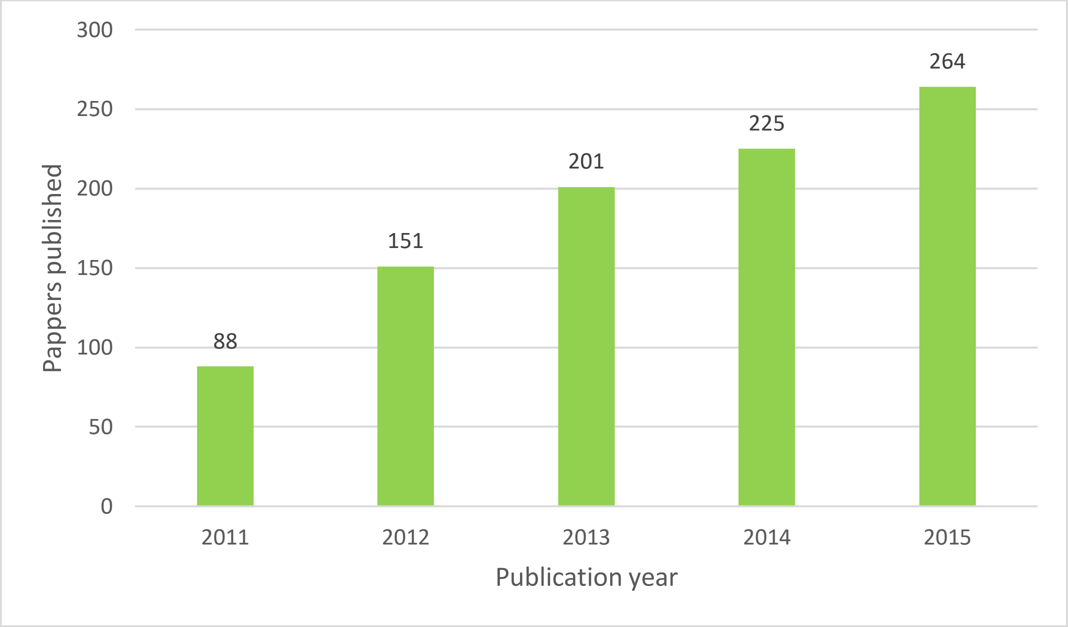

Fig. 2: Buildings LCA related articles published between 2011-2015 [25]

For improving sustainability and energy performance, the refurbishment of buildings is essential. Doing that it is possible to maintain the heritage of historic buildings and thermal comfort standards [23]. Papers trying to identify new methods for studying everyday home energy use and comfort have been written as well [26].

Lucchi et. al [27] studied Nearly Zero Energy Buildings (NZEB) by linking energy and economic benefits and noticed the lack of literature on historic buildings. Even through the fact that NZEB cost optimal methodology is applicable to both, new constructed buildings as well as existing buildings, including historical buildings. Lucchi also conclude that it would be suitable the development of a specific procedure of cost optimization methodology, considering the preservation and the historic patrimonial value, for the monetary valorization of the legacy.

Schmidt and Crawford [28] evaluated the life cycle of the GHG. Not only about operational, but from the building process as well (raw material displacement, construction machinery, etc.). The results showed that these emissions could represent between 10% to 97% of GHG emissions in a building's total life cycle. Fouche and Crawford [29] also remark on their review the importance of evaluating the GHG emissions on all stages of the building life cycle.

Papers regarding the importance of the LCC analysis in the viability study for construction projects have been carried out, e.g. Heralova [30]. Where there are results showing that LCC optimization has to be carried out from the start of the viability studies. Following this it is possible to achieve better economic performance.

In cold climates LCC analysis is for example suitable when comparing the profitability of different heating systems. Ristimäki et. al [31] compared (1) district heating as reference design, (2) district heating with building integrated photovoltaic panels, (3) ground source heat pump, and (4) ground source heat pump with building-integrated photovoltaic panels. From an LCC point of view, option (4) is the most viable even if it represents the highest initial investment.

Niemelä [32] analysed the impact of different energy renovation measures to determine the cost-optimal energy performance renovation measures in an educational building located in Finland. The renovation measures included renovation of the ventilation system, GHP system, new windows and PV-panels for solar-based electricity production. The results showed that the GHP system is the most optimal solution. Furthermore, the study assets that the results can be applied to similar climates and techno-economic environments.

For residential buildings Pal et. al [33] analysed different building in terms of envelope insulation thicknesses, window types, heating systems, heat recovery units, and PV area as design variables for an LCC optimization. Building simulation programs show that the heating system is a strong variable for LCC optimization. Harkouss et. al [11] selected similar EEMs when studying the effect on NZEB during design phases to minimize LCC.

Bull et. al [34] made similar findings as Pal et. al about the heating systems in UK school buildings. Bull et. al [34] also stated the difficulties when predicting the infiltration rate after the application of the EEM. Regarding insulation measures stated that external insulation is slightly similar energy efficient than internal insulation, when used with walls having larger thermal mass. In the simulations floor insulation is shown as the least influential factor regarding operation energy.

Dodoo et. al [35] checked the variables, methods and assumptions implicated in the energy balance of residential buildings in Sweden. That was made by performing an investigation on the effects of energy balance in a multi-storey building from 1970s. After the analysis, the conclusions indicate that in Swedish context the assumptions and input data are very variable. All of that applied to the calculations about energy balance and energy saving. Taking into account that, it is assessed the necessity to start with proper parameters and models for the performance of building energy saving measures. In addition, consumer people behaviour affect the energy-saving potential significantly [36].

Fesanghary et. al [37] developed a multi-objective method to minimize the LCC and carbon dioxide equivalent emissions of the buildings. This is achieved by analysing several building envelope parameters applied to a single-family house case study. In the conclusions it is demonstrated the efficiency of the model proves, and a set of optimal combinations (Pareto optimal solutions) is obtained.

Broström et. al [38] applied, to a stock of historic building an iterative and interactive method to assess potential energy renovation measures and their effect on the energy use of the buildings. The method included the categorisation of the building stock, identification of the energy targets, assessment of measure and LCC optimization. A case study in a typical Swedish building is developed, in order to show the method's performs. After some iterations of the method an optimal solution balancing energy conservation and building conservation is achieved.

Data uncertainty is a well-recognised issue in LCC analysis in the field of building renovation. This data uncertainty is associated with LCC deterministic calculation methods [39]. To avoid or reduce this data uncertainty many different procedures and methodologies have been studied. Giuseppe et. al [39] proposes a probabilistic methodology, Monte Carlo based methodology, combining simulation and LCC analysis. This methodology shows a great potential in the possibility of joining several EEMs and assume the uncertainty calculation with low computational costs and high accurateness of the output.

OPERA MILP is an LCC optimization software for buildings [17, 18, 19, 20, 21], and has been used in various contexts. Liu et. al [18, 20] investigated the potential of cost-optimal renovation of a historic building from the 1900s. It was found that a decrease of 39% in space heating demand is possible, with the consequent reduction in the LCC. In addition, the suggested EEMs were roof insulation, external walls insulation windows replacement and weather-stripping. Milic et. al. [17] obtained similar figures from performing cost-optimal energy renovation. Three historic buildings with varying thermal properties were included in the case study. Moreover, the results stated that the cost-optimal heating system varies depending on building energy use and power. Also, suggested EEMs included floor insulation, roof insulation, wall insulation, weather-stripping and window replacement. Noteworthy is that external wall insulation was suggested for the stone buildings and not for the wood buildings. It was concluded that the reason for this was poor thermal properties of the stone walls.

3. Theory

This chapter describes the theoretical framework of the thesis. Firstly, the energy balance of a building is explained to the reader. Secondly, a description of the heating systems and energy renovation measures considered during the thesis is given. Thereafter, optimization and LCC are introduced. Finally, the principles of the LCC Optimization applied to a building's energy costs during its life cycle are introduced.

3.1. Building Energy Balance

The energy balance in a building is determined by the energy supplied and the energy transferred outside of the building envelope. Building's energy losses can be listed as: transmission, ventilation and infiltration. The energy demand by a building is used mainly for heating or electricity in Northern European climate. Therefore, comfort cooling is not addressed in this thesis. The building has also energy gains in form of free energy, which comes from solar gains and internal heat sources. Fig. 3 shows the total energy balance for a building.

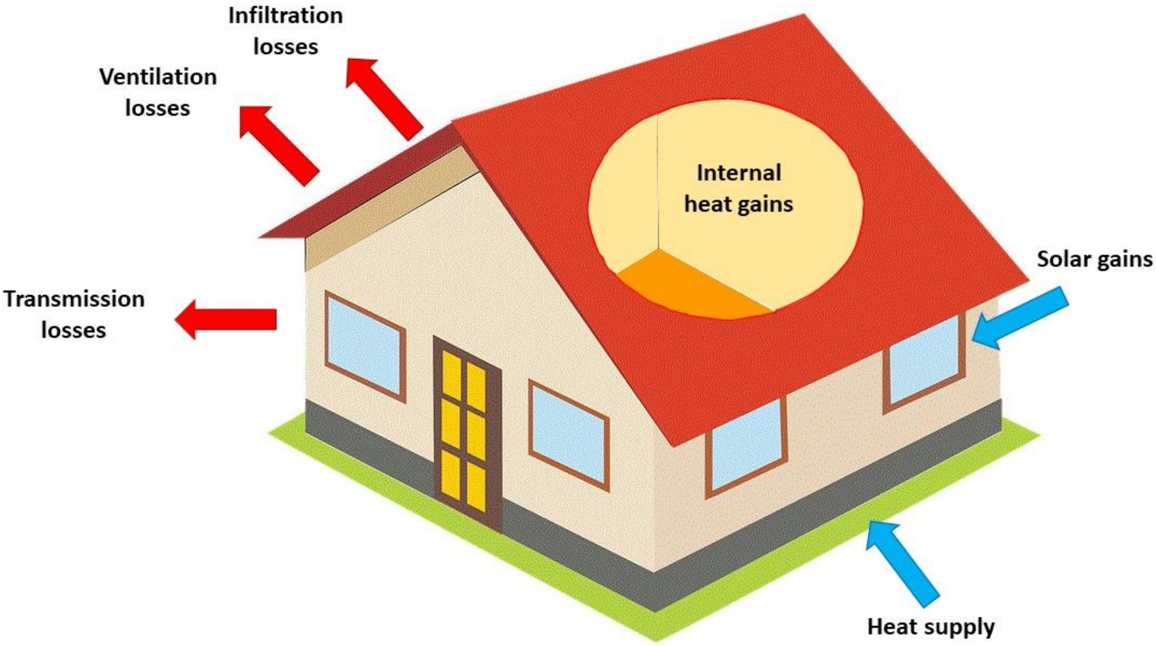

Fig. 3: Building energy balance

Transmission losses are due to the heat transferred between inside and outside of the building, when the temperature is different between indoor and outdoor. These losses are determined by the thermal jump between indoor and outdoor condition as well as for the thermal insulation of the building envelop (walls, roof, floor, windows, junctions…) and the area. This is shown below by (1).

$$Q_{transmission} = U \cdot A \tag{1}$$

$$Q_{transmission} = specific\ heat\ losses\ by\ transmission\ (W/℃)$$

$$U = heat\ transfer\ coeficient\ (W/m^2℃)$$

$$A = area \;\; (m^2)$$

The thermal insulation provides a characteristic transfer coefficient; known as U-value. This coefficient is defined by the inverse of the total heat resistance (2).

$$U = {}^{1}/_{R_T} \tag{2}$$

$$R_T = total\ heat\ resistance\ (m^2 °C/W)$$

The total heat resistance is given by (3):

$$R_T = R_{si} + \sum R_C + R_{se} \tag{3}$$

R_{si}*: Thermal resistance to the heat transmission from the inside of the building component (*$m^2 °C/W$*)*

R_C: *Thermal resistance to the heat transmission by conduction inside the wall layers. (*$m^2 °C/W$*)*

R_{se}*: Thermal resistance to the heat transmission from the outside of the building component (*$m^2 °C/W$*)*

Fig. 4 illustrate the difference in temperature through wall layers. This can be estimated by the effect of R_{si} between the indoor air and the internal layer of the wall. The different resistance of the wall depending on the materials, R_C. As well as the effect of R_{so} between the external layer of the wall and the outdoor air.

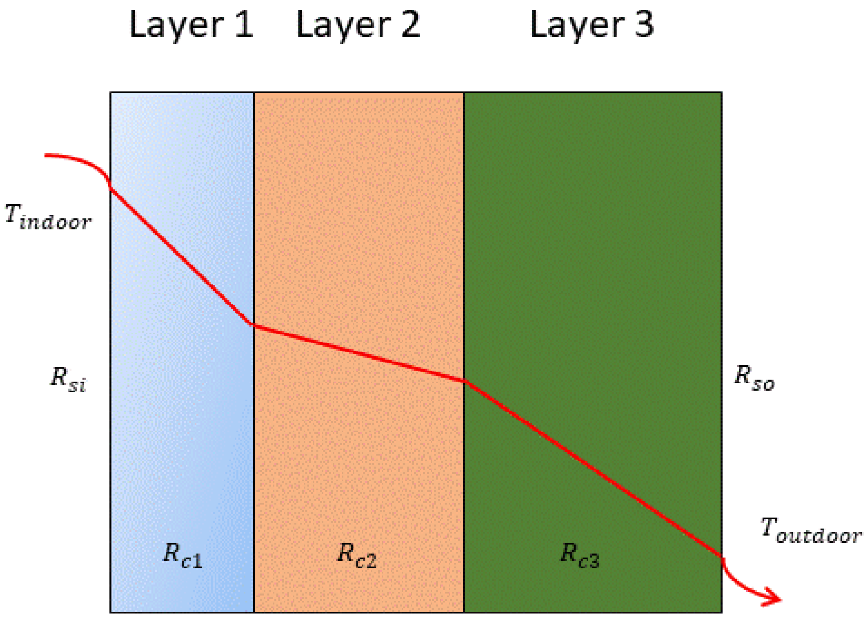

Fig. 4: Difference of temperatures through wall layers

The wall thermal resistance to the heat transmission is proportional to the thickness, b, of the material and inversely proportional to the heat conductivity of the material, λ. This is illustrated in Fig. 5 and (4) [40].

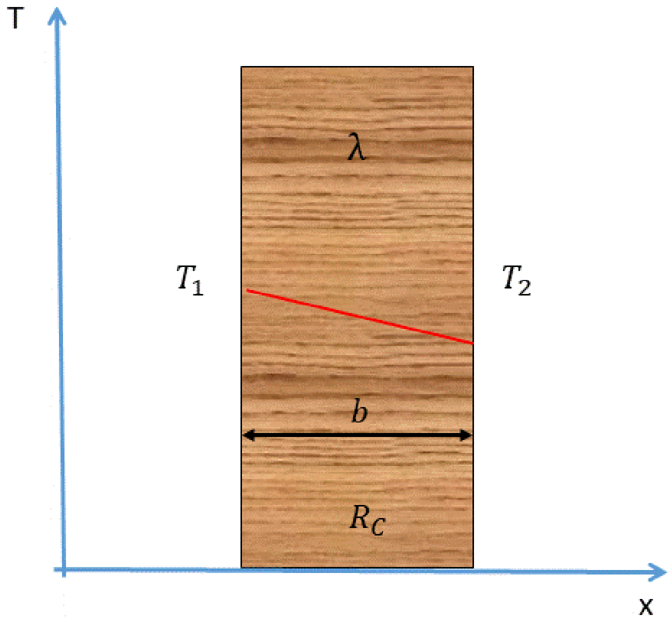

Fig. 5: Heat transfer resistance of wall material

$$R_c = \frac{b}{\lambda} \tag{4}$$

$$b = material\ thickness (m)$$

$$\lambda = heat\ conductivity\ (W/m^2 °C)$$

The Swedish Standards Institute has an ISO standard [41] fixing values for the thermal resistance to the heat transmission depending on the heat flow direction, as it is shown in Table 2.

Table 2: ISO standard surface resistance [41]

Surface resistance m²·K/W	**Direction of the heat flow**		
	Upwards	Horizontal	Downwards
R_{si}	0.10	0.13	0.17
R_{se}	0.04	0.04	0.04

Ventilation losses are presented now. In residential buildings, the ventilation requirement is determined by the outdoor temperature and the volume of external air that needs to be heated, following (5).

$$Q_{vent} = \rho \cdot C_p \cdot \dot{q}_{vent} \cdot (1 - \eta) \tag{5}$$

$$Q_{vent} = specific\ heat\ losses\ by\ ventilation\ (W/°C)$$

$$\rho = density\ (for\ air\ 1.2\ kg/m^3)$$

$$C_p = specific\ heat\ capacity\ (for\ air\ 1000\ J/kgK)$$

$$\dot{q}_{vent} = ventilation\ flow\ (m^3/s)$$

$$\eta = efficiency\ of\ the\ heat\ exchanger$$

Notice that the ventilation losses are decreased by heat recovery in a heat exchanger with a certain efficiency, η, in case the building is provided with heat exchanger or energy recovery system.

Infiltration losses are created by an unnecessary amount of outdoor air leaked inside the building envelop, see (6):

$$Q_{inf} = \rho \cdot C_p \cdot \dot{q}_{inf} \tag{6}$$

$$Q_{inf} = \ specific\ heat\ losses\ by\ infiltration\ (W/°\mathrm{C})$$

$$\dot{q}_{inf} = \ infiltration\ flow\ (m^3/s)$$

A building is supplied with "free energy" in the form of heat. This “free energy” is originated from 2 sources, solar radiation through the windows and internal gains. The first source solar radiation gains are dependent on the incident solar radiation on windows surface, and can be calculated as (7) indicates.

$$Q_{rad} = R \cdot S \cdot f \tag{7}$$

$$Q_{rad} = thermal\ load\ by\ solar\ radiation\ through\ glass\ (W)$$

$$R = solar\ radiation\ that\ crosses\ the\ surface\ (W/m^2)$$

$$S = surface\ of\ the\ windows\ (m^2)$$

$$f = correction\ factor$$

Solar radiation, R, corresponds to the orientation, month and latitude of the place considered. The correction factor is dependent on the type of glass used in the window (which can have particular transmissivity), shadow effects that may exist, etc.

The second source are the internal heat gains, which derive from people, hot water, lighting, appliances, etc… There is user data in Sveby with approximate values for occupants, household appliances and tap water. 8.76 $\mathrm{kWh/m^2}$ year for people heat, 21 $\mathrm{kWh/m^2}$ year for appliances and 4-5 $\mathrm{kWh/m^2}$ year for tap water (depending on if the building is a single-family or multi-family house*)* [22]. Sveby is an industry-wide program that provides tools for energy use agreements, standing for "Standardize and verify energy performance in buildings" [42].

Consequently, the heat demand is calculated using (8).

$$E_{heat} = Q_{tot} \cdot D_h \tag{8}$$

$$E_{heat} = heat\ demand\ (Wh)$$

$$Q_{tot} = Q_{transmission} + Q_{vent} + Q_{\mathrm{inf}}\ (W/°\mathrm{C})$$

$$D_h = degree\ hours\ (°\mathrm{C}h)$$

The number of degree hours are obtained from Appendix I by using the average annual temperature of the location and the balance temperature. The balance temperature is the temperature that should be provided from the heating system, which is lower than the indoor temperature because of free heat gains in the building. It is dependent of the set indoor temperature, the energy loses and the free energy, see (9).

$$T_{balance} = T_{indoor} - {}^{P_{free}}\!/_{Q_{tot}} \tag{9}$$

$$T_{balance} = balance\ temperature\ (℃)$$

$$T_{indoor} = set\ indoor\ temperature\ (℃)$$

$$P_{free} = free\ heat\ power\ (W)$$

Note that free energy is calculated as the sum of the previously mentioned solar radiation and internal heat gains. Fig. 6 shows a duration diagram of degree hours and balance temperature illustrated together with outdoor temperature. The degree hours are dependent of the balance and outdoor temperature, as shown in (10). The red marked area represents the degree hours when the building needs to be provided with heat and the blue marked area represents the degree hours during which the building is supplied with free energy.

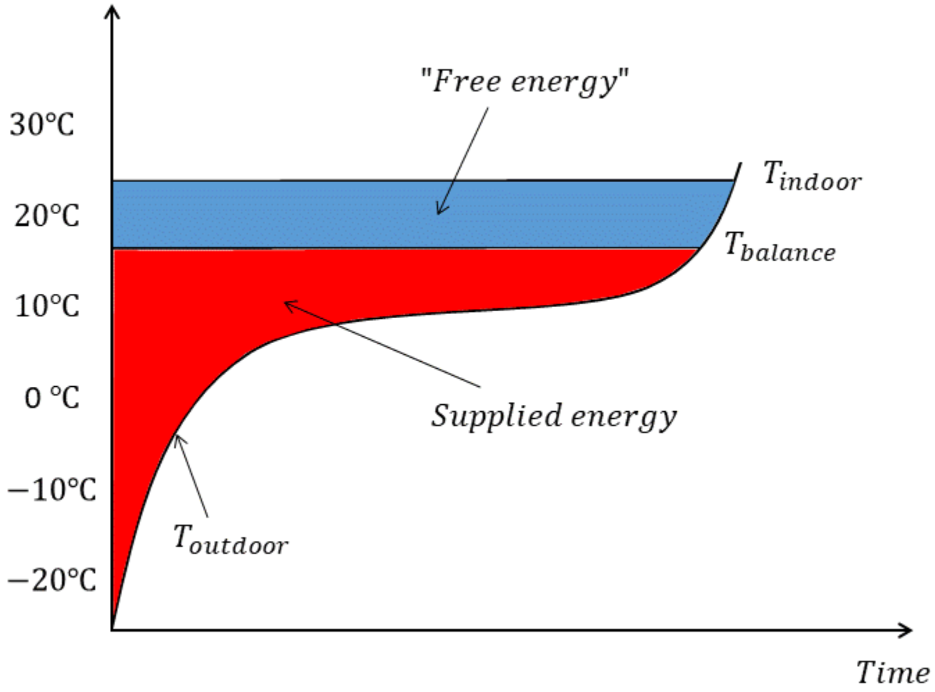

Fig. 6: Duration diagram with temperatures

$$D_h = \sum_{1}^{8760} (T_{balace} - T_{outdoor}) \cdot h_i \tag{10}$$

$$h = hours\ (h)$$

When analysing the energy use of the heating system in a building differentiate the heat energy demand and the heat power demand becomes important. The power demand is the maximum heat flux required during the coldest days of a year. Consequently, the dimension of the supply system is dependent of the power demand. At the same time the power demand dimension depends on the outdoor temperature and building envelope area. Also mention that when calculating the energy demand of the building, the free heat gains are taken into account, but not for the dimensioning of the power demand.

When dimensioning the heating system it is indispensable to consider the average outdoor temperature, ODT. This is towards to install a heating system with an optimal heat power output for the building. ODT considers the time constant, τ, of the building, given in hours. This is dependent on the building's thermal inertia and its heat insulation [43]. It is calculated according to (11).

$$\tau = \frac{\sum C_p \cdot m}{Q_{tot} \cdot 3600} \tag{11}$$

$$\tau = time\ constant\ (h)$$

$$C_p = \ specific\ heat\ capacity\ of\ the\ material\ (J/kgK)$$

$$m = mass\ of\ the\ building\ components\ (kg)$$

$$Q_{tot} = total\ loses\ (W/℃)$$

Note that for the calculations only will be included the mass of the inside insolation. Accordingly, the heat power demand is calculated as in (12).

$$P_{dim} = Q_{tot} \cdot (T_{indoor} - ODT) \tag{12}$$

$$P_{dim} = heat\ power\ demand\ of\ the\ suply\ sistem\ (W)$$

$$T_{indoor} = design\ indoor\ temperature\ (℃)$$

3.2. Heating systems and energy efficiency measures

The choice of heating system of a building is affected by several factors, namely: location of the building, type of construction, environmental aspects and economic factors [44]. The heat source of the different heating systems can be divided as:

- Combustion in a boiler installed in the building: different fuels are burned in a boiler.
- Conversion of electricity into heat inside the building: there are three types of heat generators for this category: electric radiator, electric boiler and heat of work processes.
- Heat produced in a heat generation plant: production is often integrated with the production of electricity simultaneously. The fuels are usually biofuels or fossil fuels. The system can also take advantage of the residual heat of the industries.
- GHP: uses the earth or ground water or both as the sources of heat in the winter, and as the "sink" for heat removed from the home in the summer.
- Air to air heat pump: transfers heat from outside to inside a building, or vice versa.
- Solar panels: in most cases, it is only a complement to the previous categories.

In Table 3, the different heating systems and their characteristics are presented [45].

Table 3: Heating systems

Heating system	Fuel	Efficiency	Advantages	Disadvantages
Boiler	Wood, natural gas, oil	0.7-0.85 [46]	different fuels available	low efficiency compared with other heating systems
Electric radiator	electricity	0.95-1 [47]	high efficiency	extra use of electricity
District heating	biofuels fossil fuels	0.95-1 [46]	possible coproduction of electricity, using waste incineration	less attractive for areas with low population densities
Ground water Heat Pump	electricity	2.5-3.9 [46]	very high efficiency	High installation cost
Air to air heat pump	electricity	2.1-2.8 [46]	very high efficiency	risks related with refrigerant
Solar	-	-*	renewable and free	dependent on sunlight

* This efficiency is very dependent on the solar panel manufacturer as well as the solar radiation and the position of the solar panel.

Common energy renovation measures are described below. In addition, see Table 4 where information in terms of consequences for building physics and impact on heritage values, among others, are presented as well [48].

- Changing windows: windows with better energy efficiency make it possible to reduce energy use considerably.
- Weather-stripping: infiltration losses cause thermal losses, by reducing them a better thermal climate can be achieved, as well as, reducing risk of damage from moisture due to the hot air condensation, noises and smells.
- Change ventilation system: natural ventilation is the most used in old buildings. The rate of ventilation varies depending on the time of year due to changes in temperature. In winter, the high rate of airflow can cause cracks in the wood and during the summer, the humidity is problematic due to insufficient air transport. These problems can be solved by installing an exhaust air blower. To maintain historical value, it is important to use the existing holes in the building for the implementation of a new ventilation system. The changes must be reversible so that the building can be modernized and adjusted to other types of uses in the future.
- Insulation: the additional insulation substantially decreases the use of energy and can be installed as:
  - Interior insulation of the lower floor.
  - External insulation of the lower floor.
  - Inside insulation of external walls.
  - Outside insulation of external walls.
  - Exterior roof insulation.

  - Insulation of the attic floor.
- Control and regulation of temperature and ventilation: can reduce the energy use by reducing the indoor temperature, so the air needs to be heated to a lower temperature, and the renovation per hour, so less volume of air needs to be heated.
- Implementation of solar energy: the building must be able to support the extra weight but it is a support energy source for the building.

Table 4: Energy renovation measures

Energy efficiency measures	**Energy saving potential**	**Heritage impact**	**Investment cost**	**Living area reduction**	**Moisture problems**
windows replacement	HIGH	HIGH	MEDIUM	NO	NO
weather-stripping	MEDIUM	NON	LOW	NO	NO
ventilation system replacement	HIGH	MEDIUM	HIGH	NO	NO
Internal floor insulation	MEDIUM	HIGH	MEDIUM	YES	YES
External floor insulation	MEDIUM	LOW	MEDIUM	NO	YES
Inside external walls insulation	MEDIUM	MEDIUM	MEDIUM	YES	YES
Outside external walls insulation	MEDIUM	HIGH	HIGH	NO	YES
External roof insulation	MEDIUM	HIGH	LOW	NO	YES
Attic floor insulation	MEDIUM	LOW	LOW	YES	YES
Temperature & ventilation control	MEDIUM	LOW	LOW	NO	NO
Solar energy implementation	HIGH	HIGH	HIGH	NO	NO

3.3. Life Cycle Cost

LCC is defined as "*a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs*" (Standardized Method of Life Cycle Costing for Construction Procurement ISO15686, 2008) [30, 31]. Recently several investigation have been carried out trying to establish a LCC methodology for the construction industry [30]. The methodology taken for this thesis is taken from [17] and LCC can be calculated as in (13):

$$LCC_{TOTAL} = LCC_{investment\ cost} + LCC_{energy\ cost} + LCC_{maintenance\ cost} \tag{13}$$

$$LCC_{TOTAL} = total\ LCC\ of\ the\ buiding$$

$$LCC_{investment\ cost} = energy\ renovation\ measures\ and\ heating\ system\ investment\ cost$$

$$LCC_{energy\ cost} = cost\ of\ the\ energy\ during\ the\ optimization\ period$$

$$LCC_{maintenance\ cost} = building\ components\ maintenance\ cost$$

Costs that occur in the future are difficult to estimate, because of the changing value of money with time. It can be managed by using the Net Present Value (NPV) method, converting future costs to a base year. NPV is described by (14) and (15). (14) presents the non-recurring NPV method, wich is used for future punctual investment costs, e.g. weatherstripping replacement each 10 years. (15) presents the recurring NPV method, which is used for annual costs e.g. energy bill.

$$NPV = \frac{C_{fut}}{(1+r)^{T_1}} \tag{14}$$

$$NPV = Net\ Prevent\ Value$$

$$C_{fut} = cost\ of\ the\ future\ investment$$

$$r = discount\ rate$$

$$T_1 = number\ of\ years\ between\ events\ in\ the\ studied\ period$$

$$NPV = C_{annual}\frac{1-(1+r)^{-T_1}}{r} \tag{15}$$

$$NPV = Net\ Prevent\ Value$$

$$C_t = cost\ of\ the\ future\ investment\ (SEK)$$

$$r = discount\ rate$$

$$T_1 = number\ of\ years\ in\ the\ studied\ period$$

The choice of a compatible discount rate is the largest uncertainty of the method. A high rate makes the investment less profitable and a low rate makes it more profitable.

The LCC_{TOTAL} for an EEM can be described by the investment cost of the measure and the energy cost connected to the measure. Lower energy expenses during the life cycle were consequence of higher initial expenses. In Fig. 7 from [19] this is visualized.

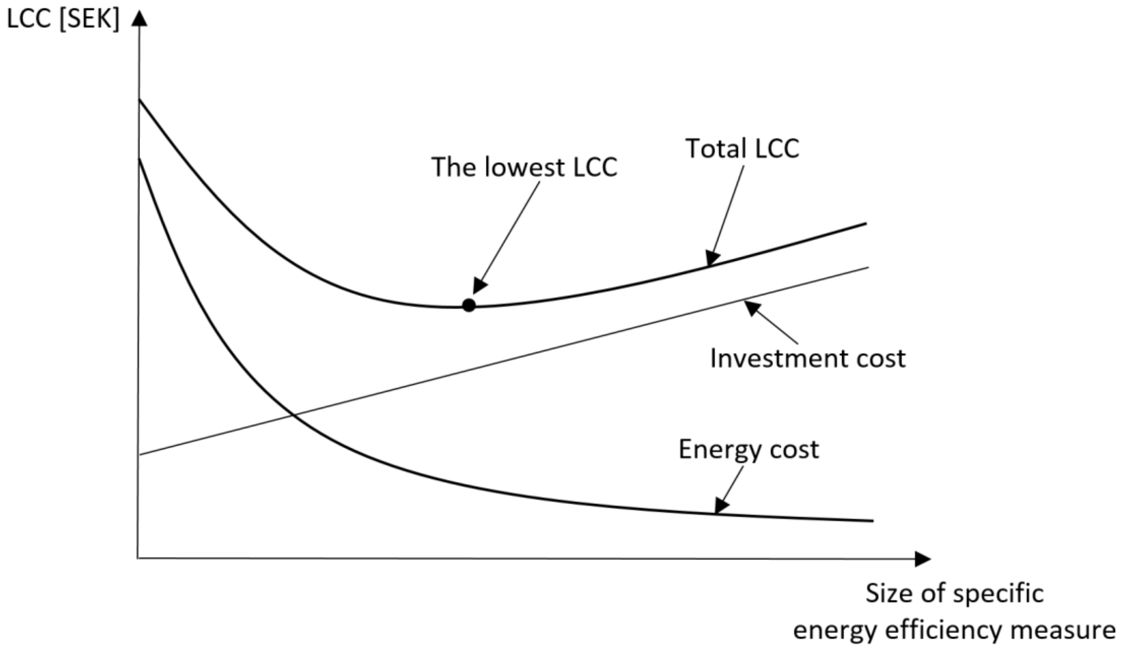

Fig. 7: LCC for an EEM expressed by energy and investment costs

The LCC analysis provides an indication of what strategic options and aspects consider when performing the energy-economic optimization. Taking into account the results of the previous study it is possible to afford which of the different alternative options it is better for the life cycle perspective value [31].

3.4. Optimization

Optimization is simply choosing best design parameters to improve an objective [49], doing the most the most with the least [50]. An example of optimization could be when extracting model parameters from data analysis, keep the error measure minimized. Also, business decisions to maximize profit, is optimization. A general optimization problem is defined by variables, formulation of the objective and constrains. The variables of the problem defines a function. The optimization problem is to minimize or maximize the objective variable of the function. The constrains of the function define the objective variable.

In the engineering discipline, optimization can include many complex mathematical formulas essential for finding optimum solutions to complex engineering problems [51]. An engineering process to be optimized could be staged as:

1. Identifying the need.
2. Defining the problem (specify variables).
3. Search for information.
4. Identify constraints.
5. Specify evaluation criteria (minimization/maximization of objective variable).
6. Generate alternative solutions.
7. Engineering analysis.
8. Optimization.
9. Decision
10. Design specification

It is also important to note that there are many different algorithms and categories to achieve an optimum solution for a problem. Mixed Integer Linear Programming (MILP) is the one used by the software tool OPERA MILP, both the software tool and the optimization process will be presented in the next section.

4. Method

The aim of this chapter is to explain the method used for the LCC optimization as well as the software tool OPERA MILP and the environmental calculations.

4.1. LCC Optimization

OPERA-MILP is an LCC optimization software that is used to obtain the lowest possible LCC for a building.

4.1.1. OPERA-MILP

The main tool to calculate the LCC Optimization during this thesis investigation will be the software OPERA-MILP (OPtimal Energy Retrofits Advisory - Mixed Integer Linear Program). This software is a tool developed in the energy systems department of the Linköping University.

MILP is based on Linear Programming (LP) where both the objective function and all restraints are linear. LP and MILP difference is that some of the variables in MILP are restricted to take on integers' values. Problems that include that kind of restriction can be solved by using binary variables. It is supposed to be taken values of 1 or 0 for these variables, depending on the approval or refutation for the ideal resolution [17]

OPERA-MILP requires basic data about the construction properties of the building, such as U-values, air changes per hour (ACH), window size and direction, etc. Moreover, OPERA-MILP requires climate data and cost of the renovation measures. The software tool uses the C-PLEX optimizer to solve MILP problems. A time-efficient LCC analysis of buildings is achieved on a desktop computer with 2.2 GHz processor, that takes only 1 second of procedure time [17].

Furthermore, it is possible to set a different energy use than the LCC Optimum, depending on different energy targets (this is explained in the next section). In order to obtain lowest LCC, there have been implemented some renovation measures in OPERA-MILP. These measures can be divided into EEMs and heating systems. The eligible heating systems are district heating (DH), electric radiator (ER), groundwater heat pump (GHP) and wood boiler (WB). Regarding EEMs, three new type of windows, weather-stripping, floor insulation, roof insulation and external wall insulation on both inside and outside surfaces are eligible

In order to calculate costs for the different energy renovation measures and heating systems the following cost functions have been developed based on Milic et. al [17]. Labour costs are included in all cost functions.

The cost function for the various insulation measures are given by (16)

$$C_{i.m.} = C_1 \cdot A_{b.c} + C_2 \cdot A_{b.c} + C_3 \cdot A_{b.c} \cdot t \qquad (16)$$

$$C_{i.m.} = total\ cost\ for\ the\ insulation\ measure\ (SEK)$$

$$C_1 = inevitable\ cost\ per\ m^2\ (SEK/m^2)$$

$$A_{b.c} = area\ of\ the\ building\ component\ (m^2)$$

$$C_2 = fixed\ cost\ per\ m^2\ (SEK/m^2)$$

$$C_3 = variable\ cost\ per\ m^2\ (SEK/m^2)$$

$$t = insulation\ thicknes\ (m)$$

The weather-stripping cost function is given by (17).

$$C_{WS} = C_4 \cdot m \tag{17}$$

$$C_{WS} = total\ weatherstripping\ cost\ (SEK)$$

$$C_4 = weatherstripping\ cost\ per\ windows\ (SEK/windows)$$

$$m = number\ of\ windows$$

The windows replacement cost function is given by (18).

$$C_W = C_5 \cdot A_{windows} \tag{18}$$

$$C_W = total\ windows\ replacemenr\ cost\ (SEK)$$

$$C_5 = windows\ replacement\ cost\ per\ m^2\ (SEK/m^2)$$

$$A_{windows} = total\ windows\ area\ (m^2)$$

The heating system installation cost function is given by (19):

$$C_{H.S.} = C_6 + C_7 \cdot P_{H.S.} + C_8 \cdot P_{H.S.} \tag{19}$$

$$C_{H.S.} = total\ heating\ system\ cost\ (SEK)$$

$$C_6 = heating\ system\ base\ cost\ (SEK)$$

$$C_7 = cost\ dependent\ on\ the\ maximum\ power\ of\ the\ heating\ system\ (SEK/W)$$

$$P_{H.S.} = maximum\ power\ of\ the\ heating\ system\ (W)$$

$$C_8 = cost\ of\ pipe\ work\ for\ hydronic\ system\ connection\ (SEK/W)$$

Note that in (19) the cost is conditioned by the heating system base cost or by the heating system size cost dependence (i.e., maximum power). It is also important to note that for the estimation of the maximum power of the heating system is necessary to consider the efficiency, η, of the heating system (or COP in the case of GHP).

OPERA-MILP does not consider comfort cooling due to it is unusual in residential buildings in Northern European climate. To reduce the computational work during the optimization development, the building's energy balance is calculated with a 12 time steps time resolution, each step corresponding to a month of the year.

The annual energy balance of the building is calculated by (20) where the heat losses in the form of transmission, ventilation and infiltration are included in the term Q_{tot}. As well as domestic hot water use and free energy. In the free energy term solar gains and heat from internal sources (electrical appliances, building occupants…) are included. The equation is performed for each time step.

$$E = Q_{tot} \cdot Dh + E_{hot\ water} - E_{free} \tag{20}$$

$$E = energy\ use\ (kWh)$$

$$Q_{tot} = total\ heat\ loses\ (kW/°C)$$

$$Dh = degree\ hours\ (°C/h)$$

$$E_{hot\ water} = domestic\ hot\ water\ use\ (kWh)$$

$$E_{free} = free\ energy\ (kWh)$$

Degree hours is the temperature difference between indoors and outdoors multiplied by the number of hours for each time step.

Free energy represent the energy in form of solar gains and includes transmitted heat and heat absorbed by the window panes. This las heat is estimated by a simplified window model with location-based climate data from ASHRAE IWEC2 [52]. The window model used in OPERA-MILP is implemented in IDA ICE before, and the results obtained is input data for OPERA-MILP.

The maximum building heat power demand P is calculated according to (21).

$$P = Q_{tot} \cdot (T_{indoor} - T_{outdoor}) + P_{hot\ water} \tag{21}$$

$$P = \text{building heat power demand (kW)}$$

$$T_{indoor} = indoor\ temperature\ (°C)$$

$$T_{outdoor} = outdoor\ design\ temperature\ (°C)$$

$$P_{hot\ water} = heat\ power\ demand\ for\ domestic\ hot\ water\ (kW)$$

The performance of OPERA MILP has been compared with dynamic energy building simulation such as IDA ICE, to conclude a good agreement in the calculations of buildings' power demand and energy use, even for different climate zones [17].

4.1.2. Application

When using OPERA-MILP it is possible to obtain 3 different solutions:

1. The first one can be the optimal LCC solution. Where a heating system is indicated as the optimal one and a number of EEMs as well. If there are any indicator that the solution is not appropiated due to the impact on the building, the soution is iterated without the inappropriate measures, leading to a new LCC, with a new heating system and new EEMs. A new energy use, E1, is also obtained for the building.
2. For the second solution the same procedure is followed with the difference that the energy use is set to a lower value than in the first case. This leads the optimization of the LCC to an equal or lower energy use than the set value. A new LCC is obtained and the corresponding energy use, E2.The solution is iterated, as in the previous case, if the measures are considered inappropriate.
3. Based on the idea that the energy use, E3, is set to a specific value, higher than the first case scenario. On this third solution the EEMs are removed depending on cost. The most expensive measure per kWh saved is removed first, etc., until the desired energy use is obtained and a new LCC is calculated.

The above methodology can be seen graphicaly in Fig. 8 below.

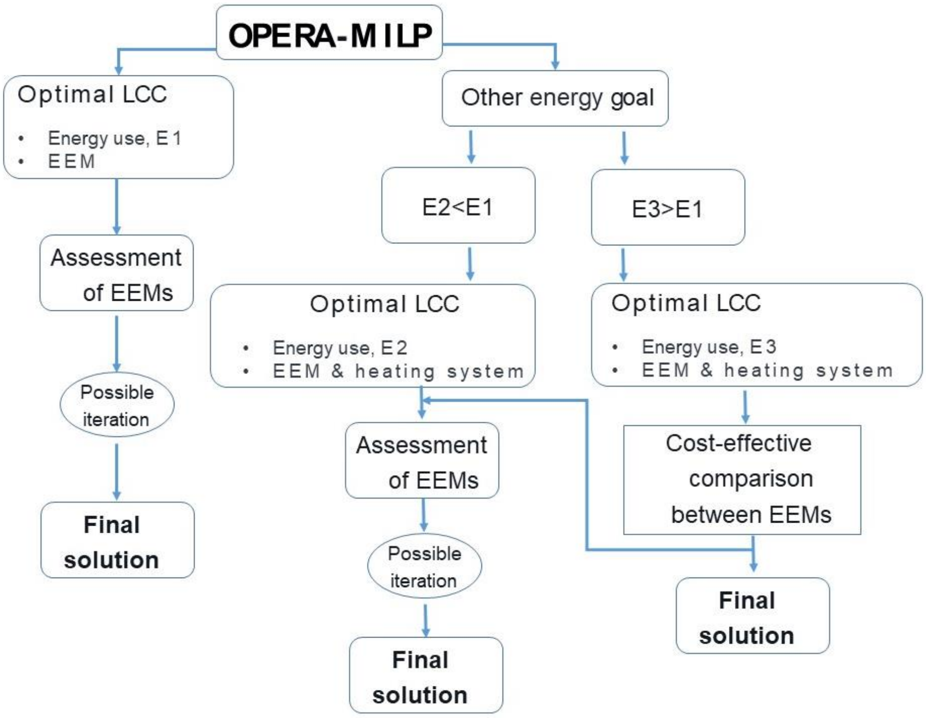

Fig. 8: OPERA-MILP methodology

4.2. Environmental calculations

Within the framework of the thesis, environmental impact in the form of CO_2 emissions are to be investigated. Different values are used for the CO_2 emissions based on different assumptions regarding electricity production and biomass use, resulting in different scenarios. See Table 5 [53] below, where the energy source or fuel for the district heating system in Arboga is presented. It can be seen that 76.6% of the energy comes from recycled energy for the district heating. This is from industrial waste heat, fuel gas condensation and waste. The remaining 23.4%comes from renewable energy, which is pellets, biofuels, bio-oil and renewable electricity.

Recycled energy	**76.6%**
Industrial waste heat	55.3%
Flue gas condensation	3.1%
Waste	18.2%
Renewable	**23.4%**
Pellets, briquettes and powder	6%
Secondary biofuels	14.4%
Bio-oil	1.5%
Renewable electricity	1.5%

Table 5: District heating energy source

The average emissions in Sweden for electricity production is 11 kg/MWh and for wood pellets 4 kg/MWh [54]. It is important to be aware of that different system boundaries are not investigated considering electricity production, as well as different assumptions considering the use of biomass. For instance, as can be seen by the rather low emissions for electricity, marginal electricity production from carbon power plants is not considered. Moreover, wood pellets is seen as an unlimited resource. With the coefficients provided, along with building energy use and efficiency, or COP, of the heating systems it is possible to calculate the CO_2 equivalent emissions.

5. Study object

In this chapter, the case study is described by the geography and history of the localization, and the grouping of the building that will be treated during the project. Also, the input data for the optimization is presented.

5.1. Arboga's history

Arboga is a medieval town next to the Arboga River in Västmanland County with the geographic coordinates:

- Longitude: 15.8381747
- Latitude: 59.3936883

The city is in Swedish climate zone III. Arboga's average annual temperature is 6.3 ° C. The Fig. 9 shows a climograph with basic information of Arboga's climate [55]. The blue bars show the monthly average amount of precipitations in mm. The red curve shows the monthly average temperature, both in °F and °C.

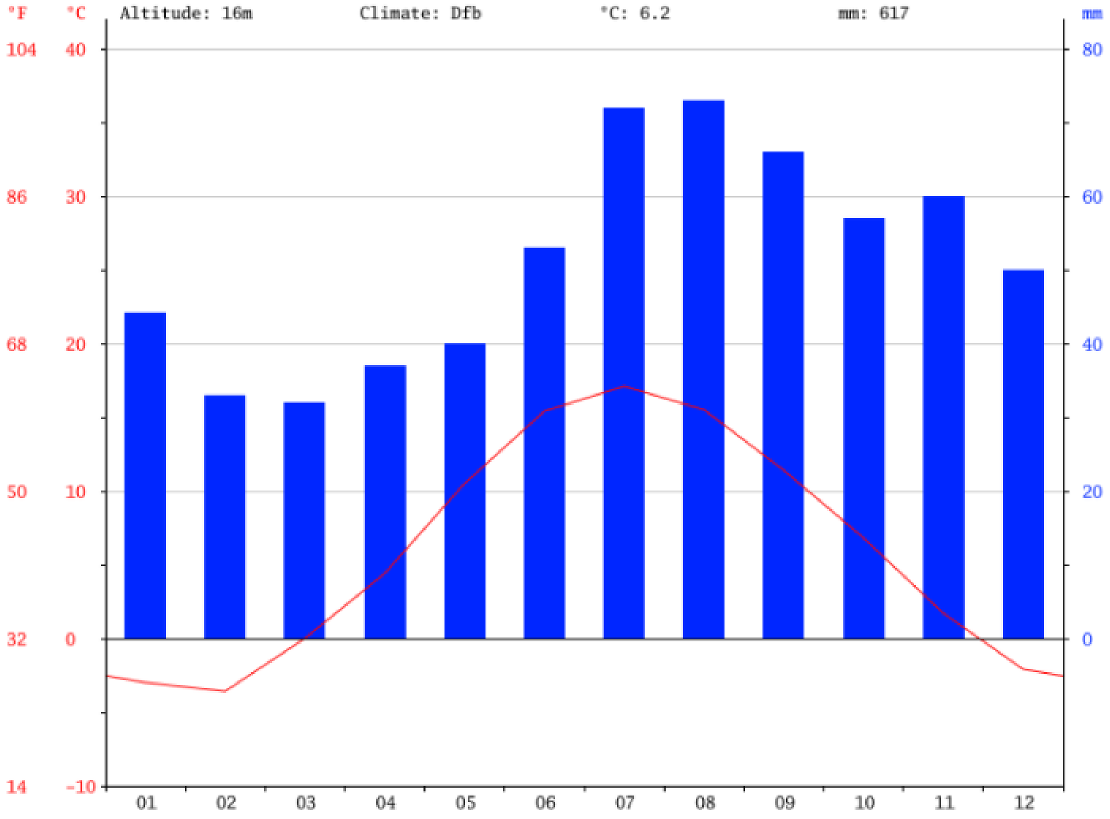

Fig. 9: Arboga's climograma [55]

The city is one of the country's oldest city centres. It has a population of around 14350 (2016), [56, 57, 58]. The culture-historically valuable wooden house building along Arbogaån is an example of it [58].

The river that runs through the city was used as a transport line for iron. The iron was the reason Arboga developed itself. With the river like the city became a transhipment site of goods and transport port of shipment. During the XVI-XVII centuries the city was relatively large compared to other cities in Sweden. It was a well-planned city with clear streets and a square in the centre. The city's first settlement grew up on north side of the river [59].

5.2. Categorization

A categorization of the building stock was made by Torgén [22], resulting in 4 buildings types. This categorization was made based on properties such as number of floors, location in relation to other nearby buildings and the volume of the building.

Depending on the number of floors, the buildings are divided into one-storey and multi-storey houses. If the buildings are detached, adjacent or intermediate the division consist in six groups where the location of the building in relation to other buildings constitutes condition [22]. According to the volume of the building, the average of the volume of the buildings in each category was calculated and made it more clear which size of building was typical for each category. Table 6Table 6: The average value of the building volume in each category by number floors and location summarizes previous information.

Table 6: The average value of the building volume in each category by number floors and location [22]

	Total building (168)					
Type of house	**storey house**			**multi-storey house**		
Number of buildings	31 (18.5%)			137 (81.5%)		
Position	**detached**	**intermediate**	**adjacent**	**detached**	**intermediate**	**adjacent**
Number of buildings	31 (18.5 %)	0 (0%)	6 (3.6%)	82 (48.8 %)	13 (7.7 %)	36 (21.4 %)
Average volume	450 m3	0 m3	930 m3	1580 m3	1720 m3	1600 m3

In Table 6, it is noted that there are no intermediate one-storey houses in the inventory, consequently this category disappears. There are only 6 adjacent one-storey houses and these buildings often have a decorative windows for what can be included in category two consisting of adjacent multi-storey houses.

After standard deviation based on delimitation, the number of buildings decreased from 168 to 149. The final categorization includes 89% of building stock. Table 8 presents the result of categorization. Categories 1 to 4 are presented in more detail in the following section, together with the buildings types developed for each category.

Table 7: The result of the categorization [22]

Category	Quantity of buildings	Volume range (m3)	Mean volume (m3)
1	77	270 - 3240	1260
2	36	300 - 2890	1173
3	12	220 - 3870	1309
4	24	190 - 670	398

5.2.1. Building category 1

This building is a detached wooden building from the mid 1800's. One multi-storey house with two floors, non-heated attic and pitched roof. The facade consists of wooden panel with locklist. The building body is made up of lying timber. Fig. 10 shows an illustration of category 1 building with dimensions of width and length.

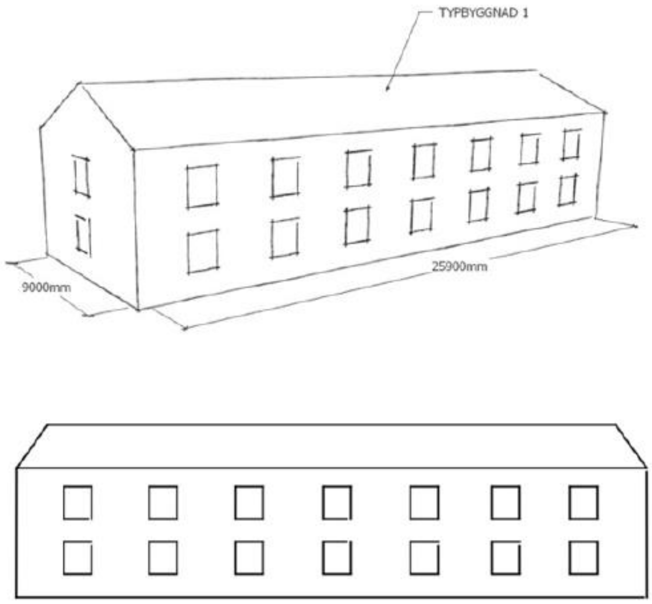

Fig. 10: Illustration of category 1 building [22]

Category 1, which is the largest group, represents 77 buildings. Table 8 below shows the basic geometry information of category 1 buildings. This basic information is composed by roof area, floor area, wall area excluding windows area, windows area, residential area, floor height and volume.

Table 8: Category 1 buildings geometry [22]

Roof area (m2)	262
Floor area (m2)	233
Wall area (m2) (excluding windows)	357
Window area (m2)	38
Residential area (m2)	467
Floor height (m)	2.7
Volume (m3)	1260

Fig. 11 shows architectural examples of category 1 buildings.

Fig. 11: Architectural examples of category 1 buildings. Foto: Johan Torgén [22]

5.2.2. Building category 2

This is an adjacent wooden building from the late 1800's. A multi-storey house with two floors, non-heated attic, and pitched roof. The facade consists of wooden panel with locklist and the body is made up of lying timber. Fig. 12 shows an illustration of category 2 with measures of width and length.

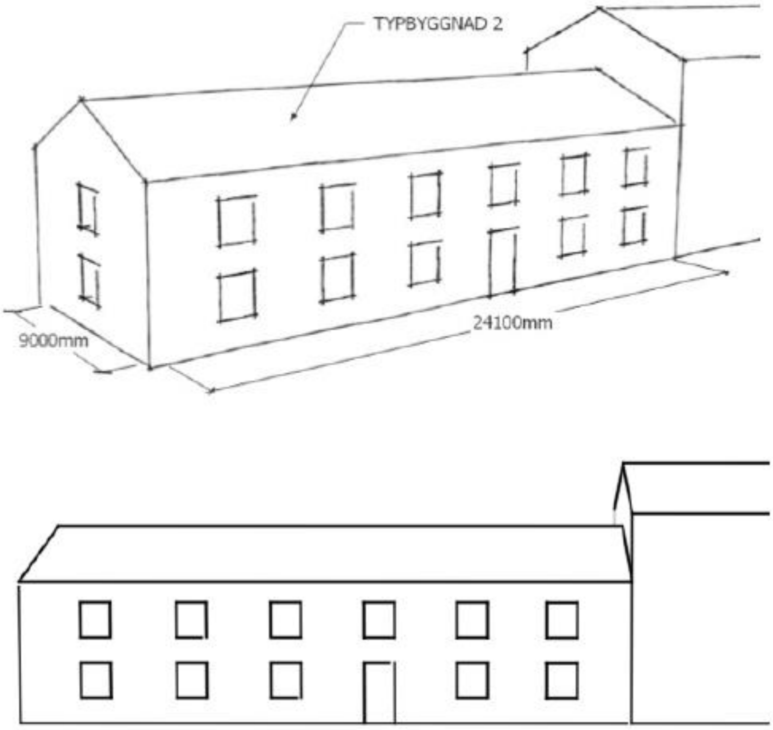

Fig. 12: Illustration of category 2 building [22].

Category 2 represents 36 buildings. Table 9 below shows the basic geometry information of this category.

Table 9: Geometry for category 2 [22]

Roof area (m^2)	244
Floor are (m2)	217
Wall area (m2) (excluding windows)	290
Window area (m^2)	29
Residential area (m^2)	434
Floor height (m)	2.7
Volume (m^3)	1173

Wall area excluding windows is shown in Table 9. This is the wall area that adjoins outside air. When the building is adjacent, the wall area is excluded. This is because it is assumed to have no temperature difference and hence no heat transfer. Fig. 13 shows architectural examples of category 1 buildings.

Fig. 13: Examples of real buildings in Arboga similar to category 2. Photo: Johan Torgén [22]

5.2.3. Building category 3

This is an intermediate brick building from the mid 1800's. A multi-storey house with two floors, non-heated attic and pitched roof. The facade is smooth and the body is brick-colored. Fig. 14 shows an illustration of category 3 building with measures of width and length.

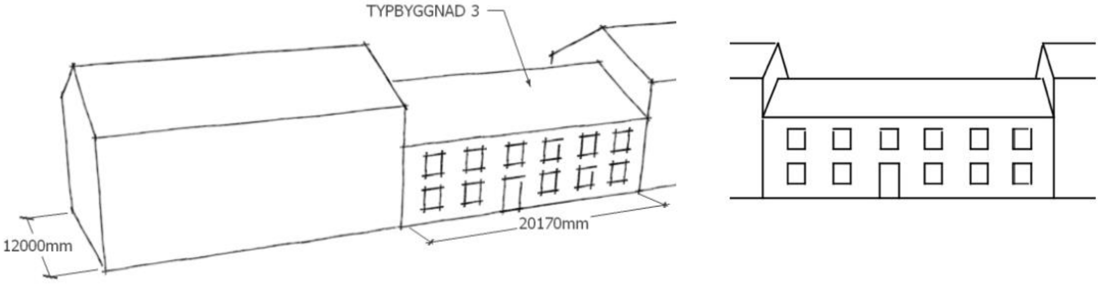

Fig. 14: Illustration of type building 3 [22]

Category 3 represents 12 buildings. Table 10 below shows the basic geometry information of this category.

Table 10: Geometry for category 3 [22]

Roof area (m^2)	272
Floor are (m2)	242
Wall area (m2) (excluding windows)	187
Window area (m^2)	31
Residential area (m^2)	485
Floor height (m)	2.7
Volume (m^3)	1309

Wall area excluding windows is shown in Table 10. This is the wall area that adjoins outside air. Fig. 15 shows architectural examples of this category.

Fig. 15: Examples of real buildings in Arboga similar to category 3. Photo: Johan Torgén [22]

5.2.4. Building category 4

This is a detached wooden building from the late 1800's. A small house with heated attic and pitched roof. The facade consists of wooden panel with locklist and the frames are made of lying timber. Fig. 16 shows an illustration of category 4 building with measures of width and length.

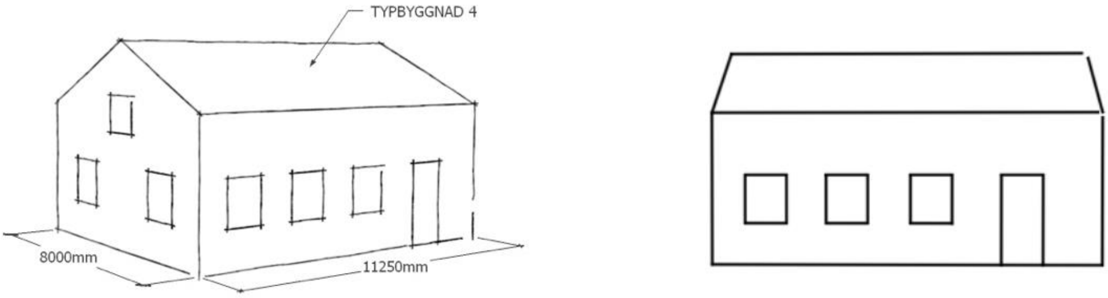

Fig. 16: Illustration of category 4 [22]

Category 4 represents 24 buildings. Table 11 below shows the geometry of category 4.

Table 11: Geometry for category 4 [22]

Roof area (m^2)	102
Floor are (m2)	90
Wall area (m2) (excluding windows)	172
Window area (m^2)	14
Residential area (m^2)	180
Floor height (m)	2.7
Volume (m^3)	389

Fig. 17 shows architectural examples of category 4 buildings.

Fig. 17: Examples of real buildings in Arboga similar to category 4. Photo: Johan Torgén [22]

Table 12 present a summary of the main building category's properties.

Table 12: Summary building categories

	Category 1	**Category 2**	**Category 3**	**Category 4**
Structure material	Wood	Wood	Stone	Wood
Roof/Attic floor	Non-heated attic	Non-heated attic	Non-heated attic	Heated attic
Floor/Basement	Crawl space	Crawl space	Non-heated basement	Crawl space
External walls	Timber and wood chip	Timber and wood chip	Stucco, brick and plaster	Timber and wood chip
Adjoining walls	0	1	2	0

From the categorization and the building components can be extracted an important feature, the U-values. The U-values of the different building components are required to calculate transmission losses. Those values are presented in Table 13 below [22].

Table 13: U-value for building components

U-value (W/m²·°C)	Roof/Attic floor	Floor	Wall	Windows
Category 1	0.53	0.46	0.59	2.9
Category 2	0.53	0.46	0.59	2.9
Category 3	0.79	0.95	1.05	2.9
Category 4	0.35	0.46	0.59	2.9

5.3. Input Data

Besides the building geometry and construction properties, it is necessary to estimate and calculate some more input data for the software tool OPERA-MILP. The climate data and the cost functions developed are both affecting the selection of a cost-optimal energy renovation strategy.

The indoor temperature in the buildings is set to 21°C, as the Public Health Agency of Sweden recommends [60]. The monthly average temperature in Arboga, shown in Table 14, is taken from ASHRAE Standard 140–2004 and presented in °C.

Table 14: Arboga's monthly average temperature and solar irradiation

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
-4.1	-3.1	-0.4	5.8	10.4	15.4	17.9	15.8	11.2	6.7	1.7	-2.5	6.3

A windows model has been developed in IDAICE software for obtaining the solar irradiation data. For the modelling a 1 m^2 windows on each cardinal direction has been implemented and simulated. The irradiation data is used for the calculation of the solar gains. The solar irradiation can be seen in Appendix II.

Table 15 is showing the building time constant and the ODT. The time constant is obtained by following Eq. (11). Data from the materials required to obtain the time constant are obtained from the software CES EDUPACK. The ODT is obtained from Sveriges meteorologiska och hydrologiska institut (SMHI).

Table 15: Time constant and outdoor design temperature

	Category 1	Category 2	Category 3	Category 4
τ (h)	35.6	37.5	35.9	29.0
ODT (°C)	-18.3	-18.2	-18.2	-18.5

Finally, some other remarkable building's properties when facing the software tool OPERA-MILP are presented in Table 16, such as residential area, ventilation and infiltration flow, flow after eventual selection of weather-stripping. For the total airflow, both ventilation and leakage losses are considered. However, in case of using weather-stripping as EEM, leakage is not considered, so after renovation the airflow is only considering ventilation.

Table 16: Other remarkable building properties

	Category 1	**Category 2**	**Category 3**	**Category 4**
A-temp (m^2)	467	434	485	180
Total air flow (REN/h)	0.59	0.58	0.56	0.88
Airflow after weather-stripping (REN/h)	0.47	0.47	0.47	0.68

Moving now to the economical aspect of the input data, the exchange rate is considered to 10.3 SEK ≈ 1 € [61]. The discount rate commercially considered for building projects is 5% set in this thesis. The thermal conductivity of additional insulation is set to 0.037 W/m°C. The step resolution is established to 2cm; the minimal insulation thickness is set to 2 cm, and the maximum to 42 cm.

The values of the cost functions for the different EEM presented in 4.1.1 are presented below. The Swedish database Wikells [62] is used to estimate insulation costs and weather-stripping. All the presented values include labor time and VAT. Table 17 present the cost values of the insulation for roof/attic floor, floor/basement, inside insulation for the external walls and outside insulation for the external walls.

Table 17: C1/C2/C3 values

C1/C2/C3 (SEK/m^2)	**Category 1**	**Category 2**	**Category 3**	**Category 4**
Roof/Attic floor	0/ 33/ 476	0/33/476	0/33/476	0/33/476
Floor/Basement	0/ 230/ 711	0/230/711	0/230/711	0/230/711
External walls (inside insulation)	293 /1438/ 1297	293/ 1438/ 1297	581/ 1856/ 1297	293/ 1438 1297
External walls (outside insulation)	159/ 631/ 1297	159/ 631/ 1297	451/ 1505/ 1296	159/ 631/ 1297

The cost for the weather-stripping is presented in Table 18.

Table 18: Weather-stripping cost

C4 (SEK/window)	**Category 1**	**Category 2**	**Category 3**	**Category 4**
weather-stripping	441	441	562	441

In Table 19 can be seen the cost and new U-values for the new windows models. Those costs come from a study also investigating cost-optimal energy renovation [17].

Table 19: New windows models price and U-values

New windows model	**C5 (SEK/ m^2 windows)**	**New U-value (W/m^2·°C)**
3-panes	1856	1.5
3-panes + low emission glass	8492	1.2
3-panes + low emission glass + gas	12169	0.8

The installation cost for the heating systems presented in Table 20 have been developed by using the Swedish database Wikells [62] and Adalberth and Wahlström [63], taken from [17]. In Table

20 are also given efficiencies values (COP for the GHP), fuel prices, annual cost and lifetime of the heating system units.

Table 20: New heating system values

Heating system	C6 (SEK)	C7 (SEK/MW)	C8 (SEK/MW)	η or COP	Fuel price (SEK/MWh)	Annual Cost (SEK)	Lifetime (years)
District heating	3745	722.50 – 313.75*	447	0.95	959	315	25
Electric radiator	2336	624	0	1	1144	2910	15
Ground heat pump	72395	4778	34956	3	1144	2910	25
Wood boiler	68604	1153	160	0.85	560	0	15

District heating price model for category 4 buildings vary because it is a story house:

- C6 = 5561 SEK
- C7 = 722.5 – 313.75 SEK/MWh*
- C8 = 1156.25 – 313.75 SEK/MWh**

* Periods October – April & **May - September

6. Results and Analysis

This chapter will present each building separately. Starting by showing the reference case. Then the LCC optimal solution will be presented, followed by all the cases studied.

6.1. Reference case

Firstly, the energy balance is presented for all categories in the reference case. Table 21 contains all the energy losses from the different building components. The value between the brackets is the percentage among all the losses. Table 22 contains the energy gains for the buildings with the same structure.

Table 21: Reference case, energy losses

LOSSES MWh (%)	Ventilation losses	Infiltration losses	Roof transmission losses	Wall transmission losses	Windows transmission losses	Floor transmission losses	Heating energy demand
Category 1	25.1 (24%)	6.6 (7%)	15.9 (15%)	13.8 (13%)	27.1 (26%)	14.3 (14%)	102.9 (100%)
Category 2	23.4 (26%)	6 (7%)	14.8 (16%)	12.9 (14%)	22 (25%)	10.8 (12%)	89.9 (100%)
Category 3	25.6 (21%)	5.6 (5%)	24.6 (20%)	29.6 (24%)	25.3 (21%)	11.5 (9%)	134.4 (100%)
Category 4	9.7 (24%)	2.9 (7%)	4.6 (11%)	5.3 (13%)	13.1 (32%)	5.4 (13%)	44.5 (100%)

Table 22: Reference case, energy gains

GAINS MWh (%)	Solar gains	Free energy	Heating system
Category 1	15.9 (15%)	16.2 (16%)	84.9 (69%)
Category 2	11.9 (13%)	15.1 (17%)	75.4 (70%)
Category 3	12.6 (9%)	16.9 (13%)	106 (78%)
Category 4	6.1 (15%)	6.1 (15%)	32.9 (70%)

The largest losses for the wood buildings (category 1, 2 and 4) are the windows' transmission losses and ventilation losses. The transmission losses through the walls, floor and roof are rather similar. The largest losses for the stone building are transmission losses from the external walls. Note that except for the floor, the rest of the building elements have similar amount of losses. Looking at the EEM price models from section 5.3 it can be noted that wall insulation is more expensive than the other two, which would make floor and roof insulation more cost-effective for the first insulation steps. Finally, in Fig. 18 -Fig. 21 a summary of both tables can be seen.

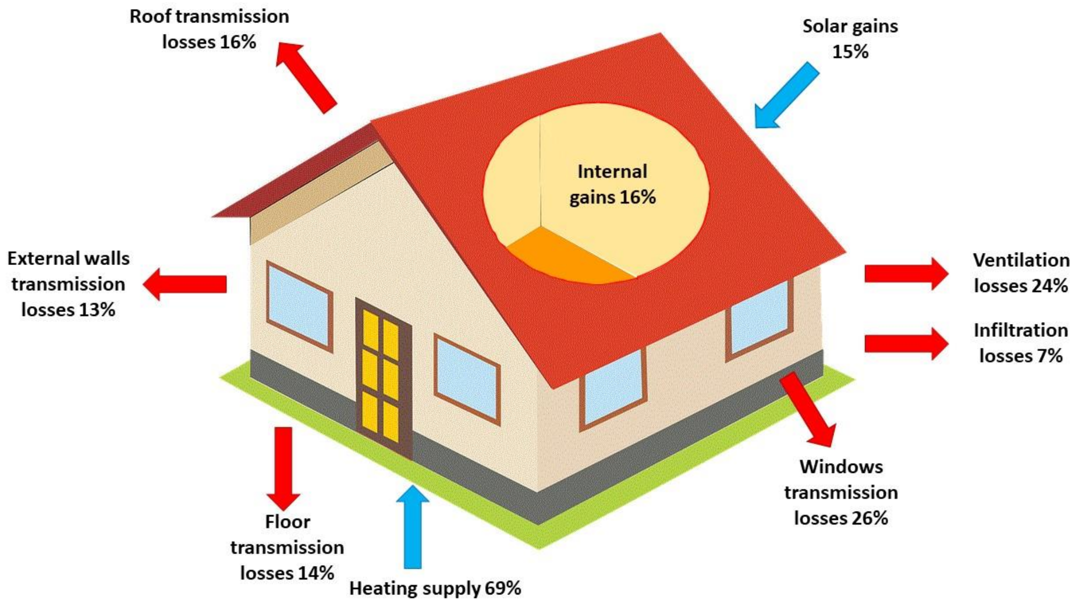

Fig. 18: Category 1 reference case energy balance

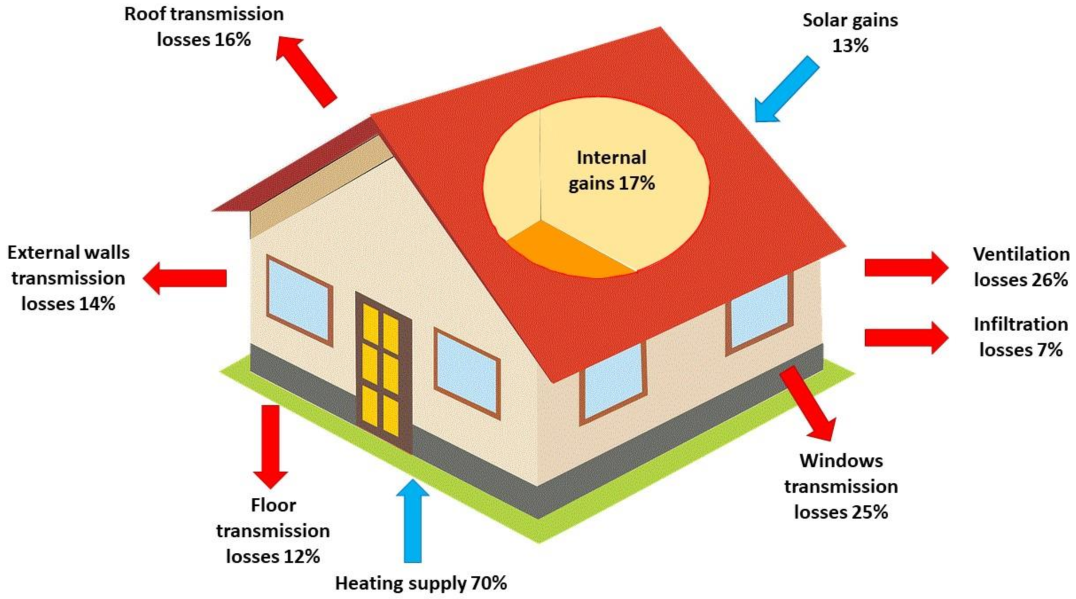

Fig. 19: Category 2 reference case energy balance

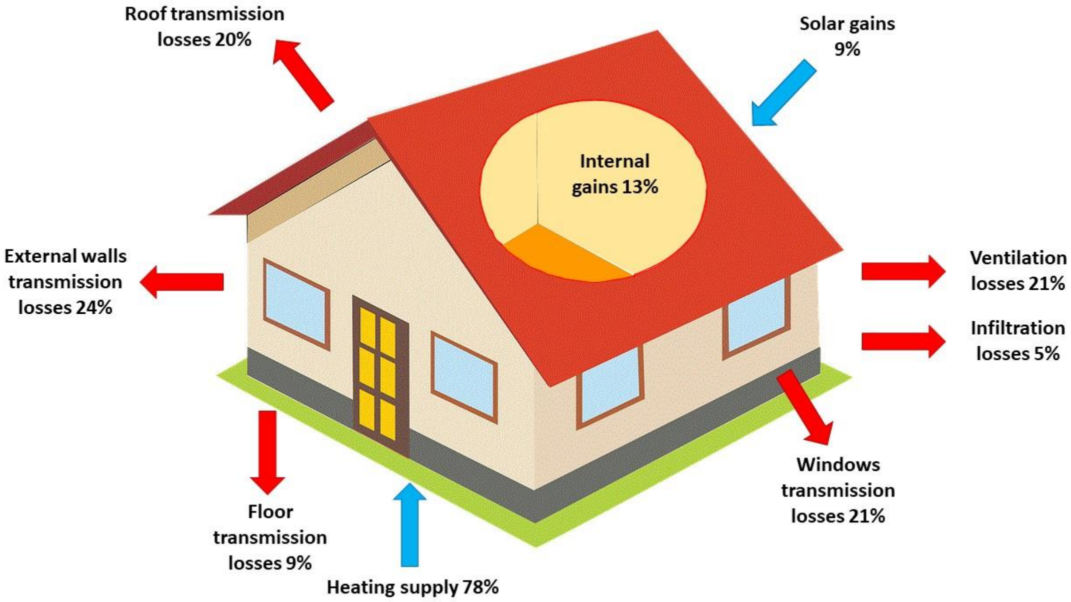

Fig. 20: Category 3 reference case energy balance

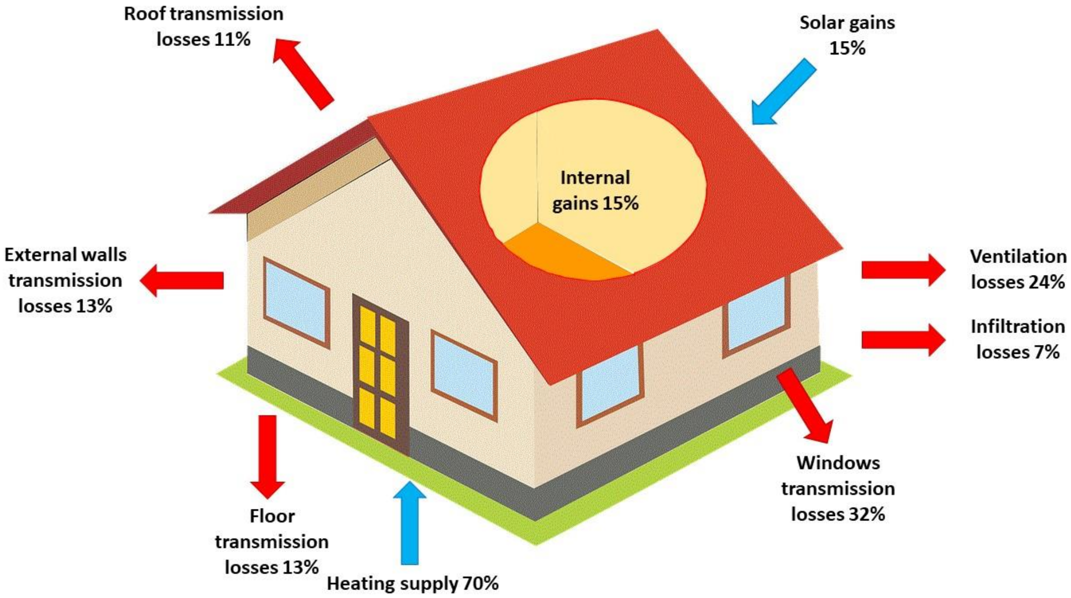

Fig. 21: Category 4 reference case energy balance

6.2. Energy targets

In the optimal LCC solution, ground water heat pump is obtained as heating system, as well as roof insulation, floor insulation and weather-stripping, for all buildings categories.

- The energy use for category 1 optimal solution is 59 MWh/year with an LCC of 917 KSEK.
- The energy use for category 2 optimal solution is 51 MWh/year with an LCC of 814 KSEK.
- The energy use for category 3 optimal solution is 57.324 kWh/year with an LCC of 902 KSEK.

- The energy use for category 4 optimal solution is 24.586 kWh/year with an LCC of 458 KSEK.

Table 23 - Table 26 shows a summary for all the selected EEMs, optimal heating system, LCC and the remaining energy use corresponding to each energy target.

Table 23: Category 1 summary

	EEM	**LCC (KSEK)**	**Energy use (MWh/year)**	**Specific energy use (kWh/m^2)**
Reference	DH	1.500	84	181.7
10%	GWHP, roof ins. 10 cm	941	76	163.2
20%	GWHP, roof ins. 22 cm, weather-strip.	918	67	145.2
30%	**GWHP, roof ins. 22 cm, floor ins. 16 cm, weather-strip.**	**917**	**59**	**127.1**
40%	GWHP, roof ins. 22 cm, floor ins. 16 cm, wall ins. 12 cm, weather-strip.	1.151	53	118.5
50%	GWHP, roof ins. 24 cm, floor ins. 18 cm, wall ins. 12cm, weather-strip.	1.097	42	94.1
60%	GWHP, roof ins. 30 cm, floor ins. 22 cm, wall ins. 18 cm, windows 1 repl., weather-strip.	1.141	33	77
70%	GWHP, roof ins. 42 cm, floor ins. 42 cm, wall ins. 42 cm, windows 3 repl., weather-strip.	1.700	27	66.8

Table 24: Category 2 summary

	EEM	**LCC (KSEK)**	**Energy use (MWh/year)**	**Specific energy use (kWh/m^2)**
Reference	DH	1.336	75	195.6
10%	GWHP, roof ins. 22 cm	853	67	175.7
20%	GWHP, roof ins. 30 cm, weather-strip.	815	59	156.3
30%	**GWHP, roof ins. 30 cm, floor ins. 16 cm, weather-strip.**	**814**	**51**	**136.8**
40%	GWHP, roof ins. 36 cm, floor ins. 26 cm, weather-strip.	844	44	122.8
50%	GWHP, roof ins. 26 cm, floor ins. 18 cm, wall ins. 12cm, weather-strip.	961	37	102.4
60%	GWHP, roof ins. 34 cm, floor ins. 24 cm, wall ins. 16 cm, windows 3 repl., weather-strip.	993	30	83.6
70%	GWHP, roof ins. 42 cm, floor ins. 42 cm, wall ins. 42 cm, windows 3 repl., weather-strip.	1.419	24	70.7

Table 25: Category 3 summary

	EEM	LCC (KSEK)	Energy use (MWh/year)	Specific energy use (kWh/m^2)
Reference	DH	1.813	106	219
10%	GWHP, roof ins. 4 cm	1.113	94	1960
20%	GWHP, roof ins. 26 cm	1.050	85	176.2
30%	GWHP, roof ins. 26 cm, floor ins. 4 cm	980	71	147.6
40%	GWHP, roof ins. 26 cm, floor ins. 20 cm	921	62	129
46%	**GWHP, roof ins. 26 cm, floor ins. 20 cm, weather-strip.**	**902**	**57**	**118.4**
50%	GWHP, roof ins. 36 cm, floor ins. 28 cm, windows 1 repl., weather-strip.	919	52	109.4
60%	GWHP, roof ins. 26 cm, floor ins. 20 cm, wall ins. 14 cm, weather-strip.	1.137	44	9405
70%	GWHP, roof ins. 28 cm, floor ins. 22 cm, wall ins. 18 cm, windows 1 repl., weather-strip.	1.150	32	69.7

Table 26: Category 4 summary

	EEM	LCC (KSEK)	Energy use (MWh/year)	Specific energy use (kWh/m^2)
Reference	DH	573	33	184.9
10%	GWHP, roof ins. 20 cm	471	30	169.5
20%	GWHP, roof ins. 20 cm, floor ins. 4 cm, weather-strip.	466	26	145.7
26%	**GWHP, roof ins. 20 cm, floor ins. 16 cm, weather-strip.**	**458**	**24**	**136.6**
30%	GWHP, roof ins. 24 cm, floor ins. 22 cm, windows 1 repl., weather-strip.	464	22	127.7
40%	GWHP, roof ins. 20 cm, floor ins. 16 cm, wall ins. 4 cm, weather-strip.	558	19	112.4
50%	GWHP, roof ins. 20 cm, floor ins. 16 cm, wall ins. 12cm, weather-strip.	544	16	97.6
60%	GWHP, roof ins. 24 cm, floor ins. 20 cm, wall ins. 16 cm, windows 1 repl., weather-strip.	555	13	83.3
70%	WB, roof ins. 42 cm, floor ins. 42 cm, wall ins. 40 cm, windows 3 repl., weather-strip.	771	9	65.4

Note that for the calculation of the specific energy use, it has been taken into account the residential area after the area reduction due to the external wall inside insulation.

Tables above shows that only weather-stripping and roof insulation is needed for targets with a higher energy use compared to LCC optimum. When investigating the targets with a lower energy use compared to LCC optimum, EEMs such external wall insulation and window replacement are generally needed to reach the set target.

Fig. 22 - Fig. 25 below, presents a summary of the LCC depending on the energy saving achieved.

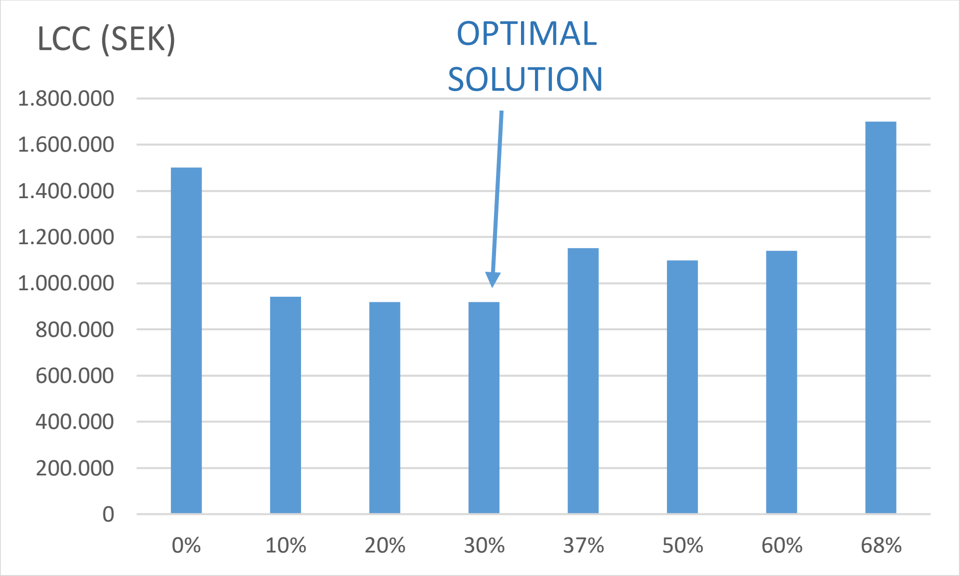

Fig. 22: LCC summary category 1

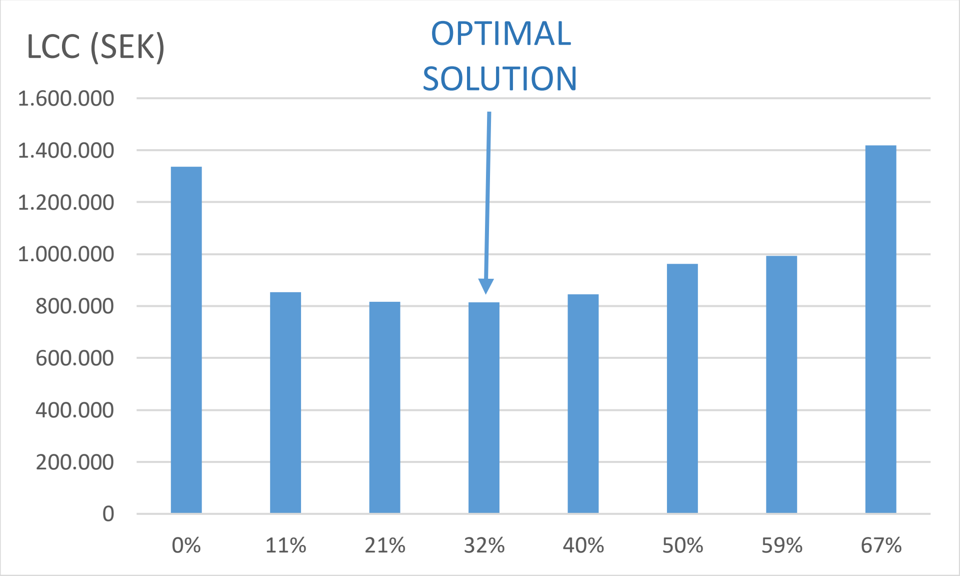

Fig. 23: LCC summary category 2

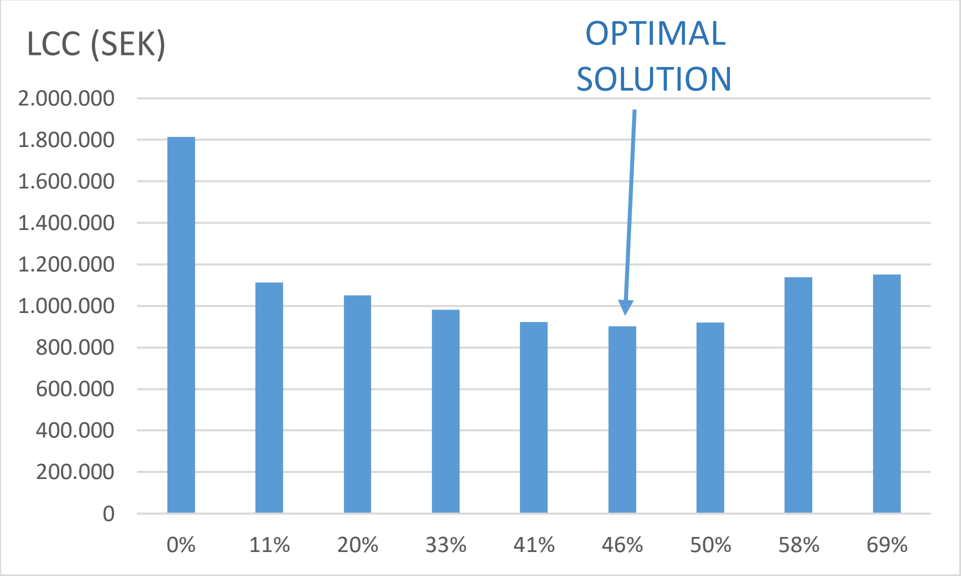

Fig. 24: LCC summary category 3

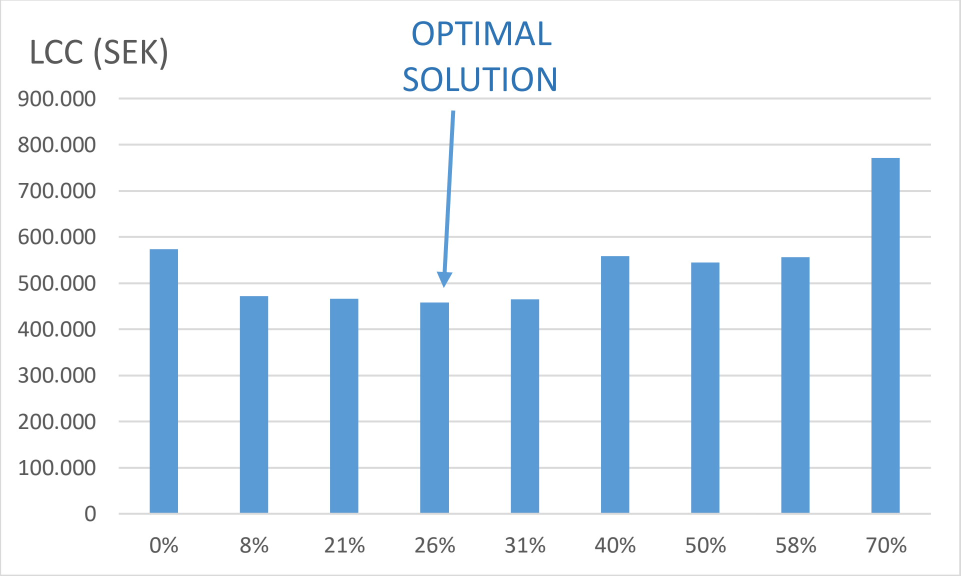

Fig. 25: LCC summary category 4

In general, a significant increase in LCC occur when wall insulation or/and new windows are installed. Finally, for the 70% energy target it is interesting to notice that it cannot be reached even using all the EEM with the maximum thickness available and the best quality windows from an energy performance point of view, for category 1 and 2. Nevertheless, it can be achieved for category 3 and 4 without the necessity of resort maximum thickness of insulation. Finally, ground water heat pump is not selected as optimal heating system for the 70% energy target in category 4, where wood boiler was cost-optimal.

6.3. Economic calculations

Table 27 summarizes the reference case and optimum case LCC, showing the economic savings achieved by the energy renovation.

Table 27: LCC and saving

LCC	Category 1	Category 2	Category 3	Category 4
REFERENCE (KSEK)	1.500	1.336	1.813	573
OPTIMUM (KSEK)	917	814	902	458
SAVINGS	39%	39%	50%	20%

Note that category 3, the stone building, has the highest saving possibilities attributed to its highest LCC. Moreover, category 4, story house as the smallest building type, has the lowest saving possibilities because LCC optimum corresponds to lower percentage decrease compared to category 1-3.

Table 28 shows an interesting approach to see how profitable the investment on the energy renovation can be. The table shows how many SEK are saved per saved kWh, i.e. the cost efficiency for the specific target. The largest saving are for the 10% energy target, which is the lowest investment on energy renovation. A payment occur when trying to reach the 70% energy target, except for the stone building, category 3, indicating that the energy renovation is profitable here also compared to before energy renovation.

Table 28: Category 1 SEK saved per kWh

	Energy target							
SEK_{saved}/kWh_{saved}	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**Optimal**
Category 1	64.7	34.1	**22.8**	11.1	9.5	7.1	-3.5	**22.8**
Category 2	60.0	32.8	**21.9**	16.1	9.9	7.7	-1.6	**21.9**
Category 3	62.8	36.8	24.1	20.5	16.9	11.0	9.1	**18.7**
Category 4	36.6	15.1	10.5	1.1	1.7	0.9	-8.5	**13.2**

Ground water heat pump is the optimal heating system for every building category. Weather-stripping, roof insulation and floor insulation are cost-effective EEM for every building category and LCC optimum.

Below, in Fig. 26 it is compared economically for the reference case district heating and groundwater heat pump. The solutions correspond to the same cost-optimal energy renovation strategy, i.e. the same energy use is obtained. There it shows the running cost in red and the installation cost in blue for each category. The main point to note is the higher running cost of the district heating, attributed, among others, to the high efficiency (COP) of the groundwater heat pump. This is also influenced for the price model of the district heating system and the electricity price model as well as the life time of the heating systems, which is 25 years for both systems in this case. Even if the installation cost of the district heating is small compared with the installation cost of the groundwater heat pump.

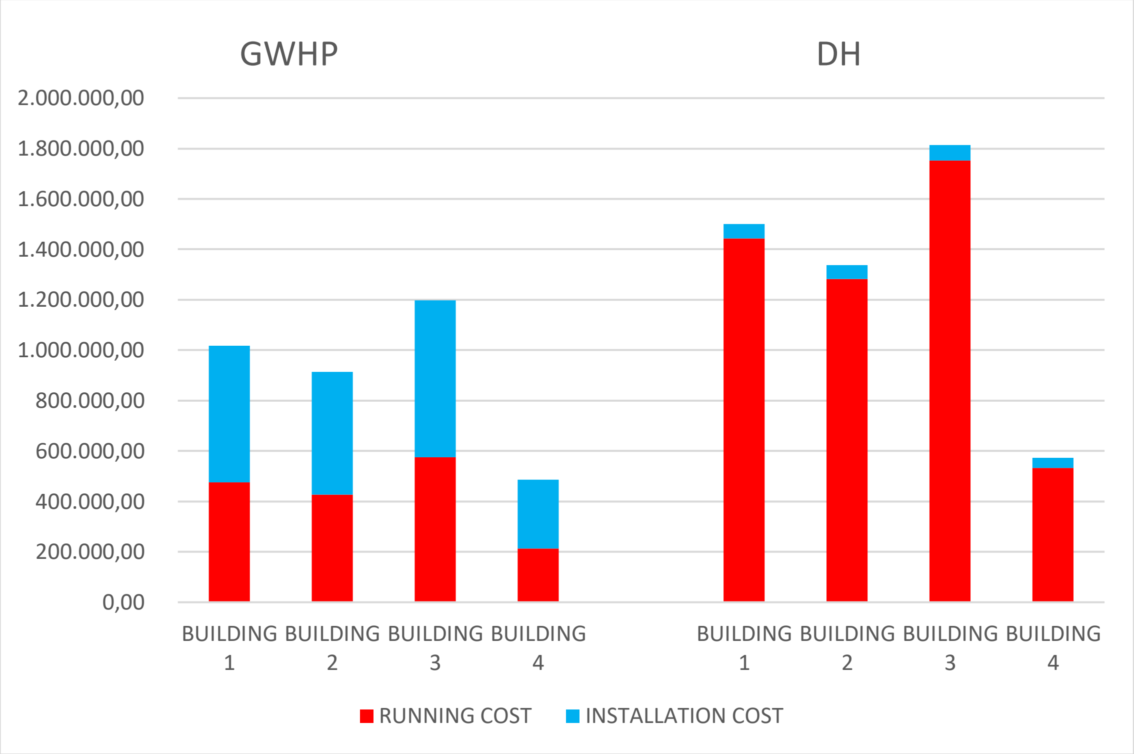

Fig. 26: GWHP Vs District Heating

6.4. Environmental calculations

Depending on the energy source, the CO_2 emissions will vary. Looking at [53] and [54] CO_2 equivalent from district heating is 30 kg/MWh and from electricity use, the average in Sweden is 11 kg/MWh. Below, in Table 29, values of CO_2 equivalent emissions for the reference case and the optimum case are given. The percentage decrease in emissions, as well as the building residential area, are also shown in the table.

Table 29: CO_2 equivalent comparison between reference and optimum cases

	Category 1	**Category 2**	**Category 3**	**Category 4**
Reference (Kg CO_2 eq/m^2)	5.74	5.49	6.90	5.84
Optimum (Kg CO_2 eq/m^2)	0.47	0.44	0.43	1.50
Savings	92%	92%	94%	74%
Residential Area (m^2)	467	434	485	180

Table 30 shows the specific CO_2 emissions for every case studied. This is the specific CO_2 emission for the reference case, with the district heating as heating system. Also, the specific CO_2 emission for the different study cases. That is groundwater heat pump, except for the category 4 for 70% target, which is wood boiler.

Table 30: CO_2 equivalent for all cases

Kg CO_2eq/m^2	Category 1	Category 2	Category 3	Category 4
Reference	5.74	5.49	6.92	5.84
10%	0.60	0.57	0.72	0.62
20%	0.53	0.50	0.65	0.53
30%	0.47	0.44	0.54	0.47
40%	0.43	0.38	0.47	0.41
50%	0.35	0.33	0.40	0.36
60%	0.28	028	0.30	0.31
70%	0.25	0.23	0.26	0.31*

* For the category 4, at 70% energy target, wood boiler is the heating system chosen so the CO_2 eq. emissions are 4 Kg/MWh [54].

Note that for the specific CO2 emissions the residential area reduction due to the wall insulation implementation is considered. Fig. 27 shows a visualization of Table 30. Where the reference case has more than 6 times more CO_2 equivalent emissions per square meter. Once the EEM have been implemented the CO_2 equivalent emissions per square meter are between 0.72 and 0. 23. For category 1 the reduction factor is 23, for category 2, 3 and 4 is 23.8, 26.5 and 18.8 respectively.

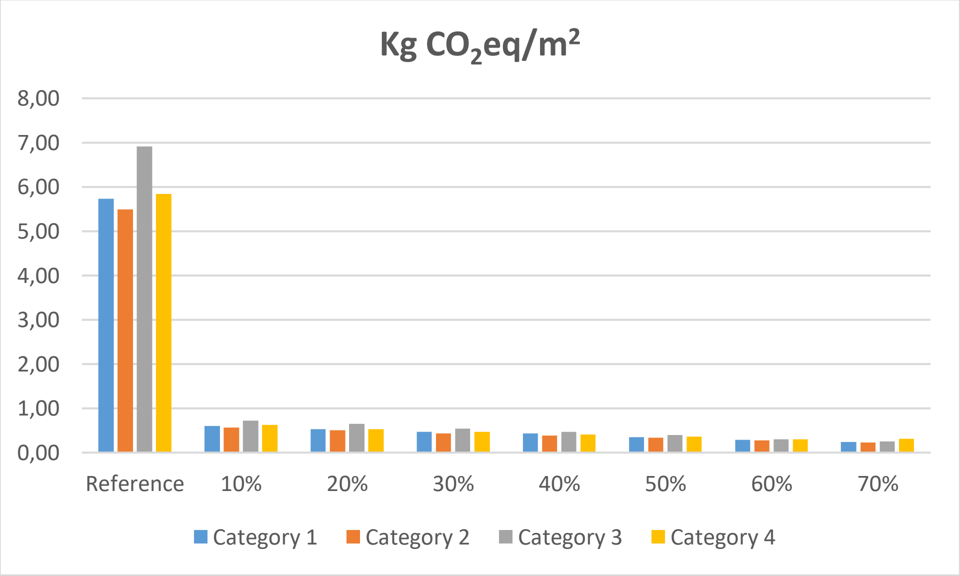

Fig. 27: Kg CO_2eq/m^2

7. Discussion

This chapter discuss the method when using OPERA-MILP in the thesis followed by a discussion of the input data and the assumptions considered finalizing with the results.

7.1. Method

The use of OPERA-MILP during the thesis carries a number of limitations, as mentioned in section 1.4. The EEMs that are applicable in OPERA-MILP affect the possibility to decrease the energy use of the buildings, but also the LCC.

When working with OPERA-MILP it is important to know the strengths and weaknesses of the software. It uses low computational resources that enable time-efficiency analysis. It is possible to perform several optimizations, including post-optimization work, within one hour for an experienced OPERA-MILP engineer. In addition, the software only require basic data about the building, such as U-values, window sizes and directions etc. The software is adapted for residential buildings, with rather high energy use, due to its simplified energy model. No consideration is taken for comfort cooling, which is common in buildings used as offices. Buildings with complex energy systems, and high thermal performance, often need complex simulation software that takes into account thermal storage etc.

In OPERA-MILP, the energy calculations are executed on monthly mean temperatures, so it is not considered if the temperature grows during the day and is reduced during the night. This in turn affects the heat demand of the building due to the building thermal storage capacity of the building. Also, there is no consideration of the over temperature during summer months. When there is no need for space heating, but it is for hot water. The internal gains are added on a monthly base, but this energy cannot be used for this. However, this will not be the case during times when temperature decreases and space heating is needed.

These simplifications evidently affect the heat demand of the building but the energy calculations still give an approximate value of the heat demand. This affirmation was proven by Milić [17] when comparing OPERA-MILP performance with IDA ICE, a dynamic calculations software tool. The differences in calculated energy use were estimated to a maximum of 11% annually. The corresponding figure is 8% in terms of building power demand.

7.2. Input data

A prime factor on all the results of the thesis is the input data. This applies to the heating systems efficiencies, assumed life length, cost functions, etc. However, realistically, the implementation of a heating system in a building and its costs are unique for a specific building. This also applies to the input data for the energy calculations: building component properties and indoor and outdoor temperatures. The mentioned input data are in many cases estimated for general cases. All parameters affect the outcome of the optimization.

Also worth mentioning, regarding the input data, is the efficiency of the groundwater heat pump. That high efficiency compared with the other heating systems makes it such a suitable and optimal heating system, even though the big installation investment required. However, it is important to be aware of the correlation between all pre-set conditions in OPERA-MILP and the cost-optimal energy renovation strategy. This means that assumed lifetimes strongly affect the selection of an optimal solution.

The assumptions regarding electricity production and biomass are vital for the environmental performance of the buildings. If marginal electricity production was considered instead of the Swedish average, the emissions would be 933 kg/MWh [54] compared to 11 kg/MWh. This correspond to a factor 84.8 times bigger.

7.3. Results

For the implementation of heating not only the cost functions, efficiencies and life lengths of the heating systems are important factors. In addition, cost for the fuels is another important factor. It can be seen when comparing district heating and ground water heat pump running costs. Due to its high efficiency and the low price of electricity in Sweden, heat pumps are cost optimal for buildings with high-energy use according to the costs used in this investigation. This is also the reason for the selection of wood boiler in category 4 target 70%. Its lower investment costs compared to heat pump together the lower energy use in that building results in a different cost-optimal heating system.

It is crucial to point out the calculations of the profitability to energy renovate. The LCC and the energy use is lowered in all cases, except for the 70% target in the wood buildings. In this case the energy use is lowered, but the LCC is not. This makes this target not profitable compared with the reference case, from the economical point of view.

Like during the thesis the building studied are models from a categorization it is not possible to ensure that the selected heating system, ground water eat pump, can be installed in every building. This can be because of factors such as that the possibilities does not exist to install a borehole at the location.

Out of the boundaries of this thesis, but also a point to deliberate, is to consider the possible reduction of the renting price of the building. This can happen when implementing inside wall insulation that consequently leads to living area reduction.

8. Conclusion

LCC optimization is a key step in the energetic renovation of historic buildings. This optimization can be developed in a time-efficient procedure thank to low computational resources tools as OPERA-MILP. In this study, the effects from cost-optimal energy renovation in terms of LCC and renovation strategy depending on different energy targets are investigated. This is performed by using LCC optimization software OPERA-MILP. Multiple optimizations have been carried out for four building typologies situated in Arboga, Sweden.

During the thesis, it is obtained that the groundwater heat pump is the optimal solution in every case, except the target 70% decrease in energy use in category 4. The thesis shows also that weather-stripping, along with floor and roof insulation are cost-effective at LCC optimum. It is important to note that the selected EEMs are all economically viable due to the reduction in LCC compared to before energy renovation, which is 30% for category 1 and 2, 50% for category 3 and 20% for category 4. It is also shown that the profitability of the investment varies between the different categories and for the different energy targets. The stone building, category 3, is always profitable, for every energy target. This is not the case for the wood buildings, categories 1, 2 and 4, where the 70% target is not profitable from an economical perspective. Moreover, after renovation the CO_2 equivalent emissions from the buildings have been reduced, obtaining savings higher than 70% on CO_2 equivalent emissions per MWh.

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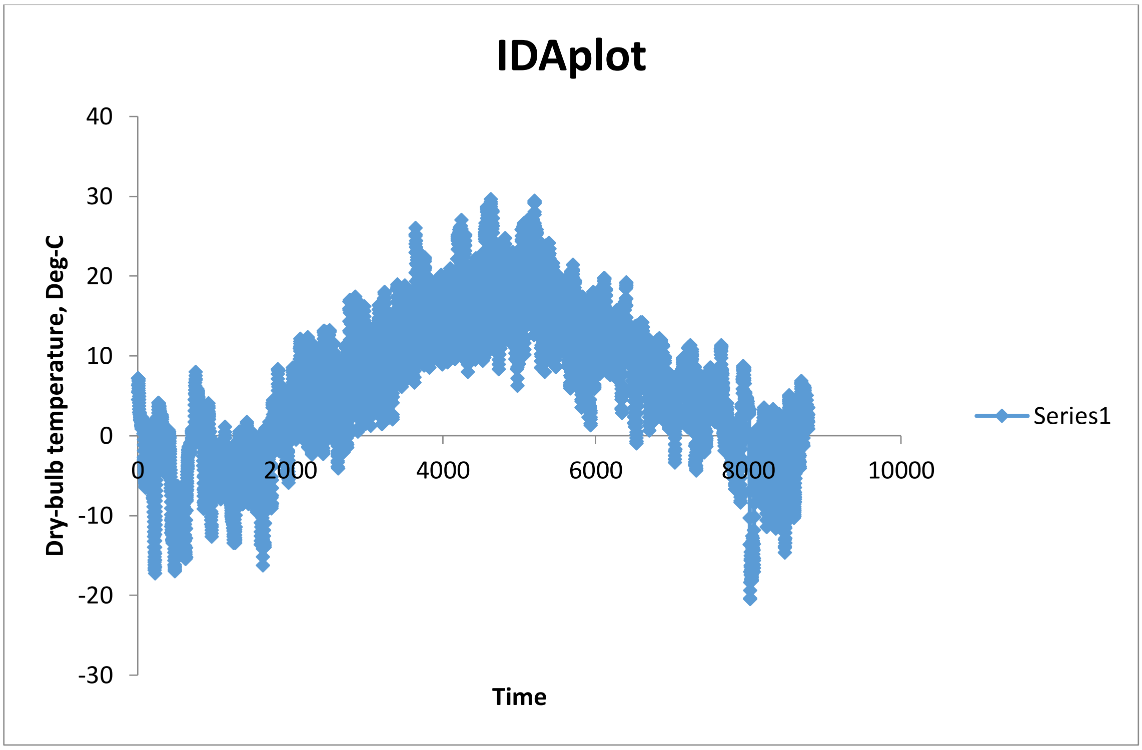
APENDIX I



	Days	Hours	Accumulated	AVERAGE (°C)	Dh (°C·h)
January	31	744	744	-4.10	3050.90
February	29	696	1440	-3.11	2163.10
March	31	744	2184	-0.39	290.60
April	30	720	2904	5.83	4197.10
May	31	744	3648	10.40	7735.80
June	30	720	4368	15.43	11109.20
July	31	744	5112	17.95	13358.40
August	31	744	5856	15.76	11727.40
September	30	720	6576	11.16	8034.70
October	31	744	7320	6.71	4988.80
November	30	720	8040	1.70	1221.30
December	31	744	8784	-2.53	1882.50
ANNUAL		8784		6.26	5813.32

APENDIX II

Solar irradiation for the windows model

	North	Est	South	West
	kWh/m2	kWh/m2	kWh/m2	kWh/m2
January	2.2	3.8	12.6	3.6
February	6.7	12.3	29.1	11.2
March	16.4	30.9	54.6	29.7
April	24.9	65.6	74.3	53.7
May	35.5	68.1	63.0	60.7
June	41.0	74.1	65.3	65.8
July	41.0	75.5	78.2	80.1
August	29.3	56.5	71.8	63.7
September	16.9	37.7	60.7	38.7
October	7.9	15.2	44.3	18.1
November	2.8	6.0	25.0	7.2
December	1.1	3.3	16.0	2.9