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Energy system and energy efficiency improvements and their economic impacts in public buildings

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ABSTRACT

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Energy system and energy efficiency improvements and their economic impacts in public buildings

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Keywords Energy efficiency improvements, public buildings, heat pump, solar *PV*, heat recovery, renovation, techno-economic calculation

The object of the study was to create a model for estimating energy efficiency improvement investments and for comparing profitability of the investments. The technologies studied are heat pumps, solar photovoltaic panels, the efficiency of heat recovery in ventilation and improvements regarding thermal transmittance of the building structures. The calculations and results are presented with case-building, Lappeenranta City Hall.

The electricity demand of the heat pump is estimated with 10 past years' average temperatures and graphs of Coefficient of Performance (*COP*) on a monthly basis. The electricity demand of the heat pump is assumed to be constant in every hour of the month. The production of solar electricity is estimated with simulated data on an hourly basis. Heat losses through structures and ventilation system are calculated with instructions for the Energy Performance Certificate calculations.

As a result for case building, values of Internal Rate of Return (*IRR*) are calculated in a time period of 20 years. For a solar photovoltaic system, the *IRR* is 5.7 %, for a ground source heat pump 13.0–24.1 % and for an air-to-water heat pump from negative to 23.7 %. For improving the thermal transmittance of windows from 2.1 W/(m^{2}K) to 1 W/(m^{2}K) the IRR is −2.0 – −5.1 % and for a heat recovery unit with temperature efficiency of 70 % instead of existing 37 %, 9.0–18.5 %. There is visible potential for energy efficiency improvements, and the improvements are mainly economically profitable.

TIIVISTELMÄ

Mirika Knuutila

Energiatehokkuusparannukset ja niiden taloudelliset vaikutukset julkisissa kiinteistöissä

School of Energy Systems, Energiatekniikan koulutusohjelma

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88 sivua, 17 kuvaa, 25 taulukkoa ja yksi liite

Tarkastajat Ahti Jaatinen-Värri ja Antti Kosonen

Avainsanat Energiatehokkuus, julkiset kiinteistöt, lämpöpumppu, aurinkopaneeli, lämmöntalteenotto, korjausrakentaminen, kustannusanalyysi

Työn tavoitteena oli luoda työkalu, jolla voidaan vertailla eri energiatehokkuusinvestointeja ja niiden kannattavuutta. Työssä käsiteltyjä teknologioita ovat lämpöpumput, aurinkosähköpaneelit, lämmöntalteenottolaitteiston hyötysuhteen parantaminen sekä rakenteiden eristävyyden parantaminen. Työkalun laskentaa ja tuloksia esitellään esimerkkikohteen, Lappeenrannan kaupungintalon, datan avulla.

Työssä arvioidaan 10 vuoden keskilämpötilojen perusteella lämpöpumpun sähkönkulutusta kuukausitasolla. Arvioinnissa käytetään hyväksi maa- ja ilmalämpöpumpulle spesifisiä tehokerroinkäyriä. Aurinkosähkön tuotantoa arvioidaan simuloidun datan perusteella tuntitasolla. Lämpöpumpun sähkönkulutus on oletettu vakioksi kuukauden jokaisena tuntina. Lämpöhäviöt rakenteiden ja ilmanvaihdon läpi lasketaan energiatodistuksen laskentaa mukaillen.

Tuloksena saadaan efektiivisen koron (*IRR*) arvot esimerkkikohteen energiatehokkuusinvestoinneille 20 vuoden tarkasteluajanjaksolla. Aurinkosähkölle efektiivinen korko on 5.7 %, maalämpöpumpulle 13.0–24.1 % ja ilma-vesilämpöpumpulle negatiivisesta 23.7 %:iin. Ikkunoiden eristävyyden parantamiselle nykyisestä 2.1 W/(m^{2}K) arvoon 1 W/(m^{2}K) saadaan *IRR*:lle arvo −2.0 – −5.1 % ja lämmöntalteenottolaitteiston (*LTO*) hyötysuhteen parantamiselle lämpötilahyötysuhteesta 37 % arvoon 70 % saadaan *IRR*:lle arvo 9.0–18.5 %. Kiinteistöstä löytyy energiatehokkuusparannuspotentiaalia, ja parannukset on mahdollista toteuttaa taloudellisesti kannattavasti.

FOREWORD

This study has been carried out at LUT University with data gathered in project *Public-Private Partnership in real estate energy efficiency improvements and finance*.

First, I want to thank Jarmo Partanen and Petteri Laaksonen who believed in me at the first sight and provided me the opportunity to work in this project, and later on write my Master's Thesis related to the theme that has always been close to my heart.

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Lappeenranta, on 24th of May, 2019

Mirika Knuutila

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SYMBOLS AND ABBREVIATIONS

Latin symbols

A	Area of a structure	m^2
c_p	Specific heat capacity	J/(kgK)
d	Days in the examination period, usually month	
E	Energy production	Wh
G	Solar radiation in a month	kWh/m^2
H	Heat flux	W
I_n	Investment	€
i	Interest rate, or Weighted Average Cost of Capital, *WACC*	%
P	Power	W
P	Pressure	Pa
Q	Heat loss through a structure type in the examination period	Wh
q_V	Volume flow	m^3/s
q_{50}	Air leakage rate	$m^3/(hm^2)$
S	Savings	€/y
T	Temperature	K, °C
t	Time	h, min, s
U	Thermal transmittance	$W/(m^2K)$
V	Calculated maximum of the district heating water flow rate	m^3/h
W	Heat load	W/m^2

Greek symbols

ε	Emissivity	
σ	Boltzmann constant, $5.67 \cdot 10^{-8}$ $W/(m^2K^4)$	
α	Heat transfer coefficient	$W/(m^2K)$
ρ	Density	kg/m^3
Δ	Difference	
η	Efficiency	%

Dimensionless parameters

a	discounting coefficient
e	Euler's number, mathematical constant
F	Shadowing coefficient regarding the solar inclination
g	Transmission coefficient
x	Coefficient for storeys in leakage air heat loss calculation

Subscripts

D	Demand
e	Electricity production
H	Higher
Hr	Heat recovery
L	Lower
p	Peak
T	Temperature

Abbreviations

AMR	Automatic meter reading
ASHP	Air source heat pump
AWHP	Air-to-water heat pump
Capex	Investment cost
COP	Coefficient of Performance
CO_2	Carbon dioxide
crf	Capital Recovery Factor
DHW	Domestic Hot Water
EPC	Energy Performance Certificate
FLH	Full Load Hour
GMST	Global Mean Surface Temperature
gr	Gross
GSHP	Ground source heat pump
IRR	Internal Rate of Return

LCOE	Levelized Cost of Electricity
NPV	Net Present Value
nZEB	Nearly Zero-Energy Building
Opex	Management cost
PV	Photovoltaic
VAT	Value added tax

1 INTRODUCTION

In this chapter the background of the study will be presented as well as the target of the study, and the project this study is related to.

1.1 Background of the study

Climate change is a problem caused by humankind, and it needs to be fully considered in today's society. It has been estimated that human actions have caused a 0.8 °C to 1.2 °C increase in global mean surface temperature, *GMST*, compared to the levels of pre-industrialized time (IPCC, 2018, p. 6–10). Impacts of climate change are long-lasting and irreversible, such as loss of ecosystems. The emissions which are present in the system now will still have an impact of 0.5 °C increase in the global mean surface temperature (IPCC, 2018, p. 6–10). It is widely recognized, and stated in the Paris Agreement, that to limit the increase to 1.5 °C would lower the risk of climate change on society (UNFCCC, 2015). As there is need to limit the global warming to not more than 1.5 °C, with the already occurred increase in *GMST* and the existing emissions in the atmosphere, we have to react now.

The increase in *GMST* is caused by emissions such as greenhouse gases, aerosols and their precursors. It has been estimated that to limit the global warming to 1.5 °C, the carbon dioxide (CO_2) emissions must be reduced to zero by 2050, and the non-CO_2 emission must be reduced as well (IPCC, 2018). CO_2 emissions are formed via burning of any fuel: fossil or biomass. Via burning fossil fuels, CO_2 is added to the cycle in the atmosphere, and via burning biomass, the CO_2 already in the cycle is released to the atmosphere again. The CO_2 emissions are inevitable if burning activity occurs. There are also particle emissions originating from burning activities, which are causing premature deaths (Child, 2018).

As a Nordic country, Finland has a long cold season and thus the need for energy especially in space heating is considerable. The majority of emissions from space heating comes from heating residential buildings followed by the space heating of public and

commercial buildings (Ministry of the Environment, 2017, p. 62). For net zero carbon emissions – later on net-negative carbon emissions – and a sustainable future, not only the energy sector but also the energy use in residential and other building sector must be taken into consideration.

The renewal of buildings is rather slow, thus they have a long-term impact on climate. Therefore there must be actions regarding the existing buildings and their energy efficiency. Existing buildings that are undergoing a major renovation process are providing a valuable chance to evaluate and revise energy efficiency of the building.

In the directive 2010/31/EU on the energy efficiency of buildings it has been set that all new buildings have to be nearly zero-energy buildings, *nZEB*, after the year 2020, and new buildings owned or occupied by public authorities have to be nearly zero-energy buildings already after the year 2018 (EU, 2010). From the EU directive point of view, there is also an aim to improve energy efficiency simultaneously to renovation. Major renovation is defined to be a renovation, where the cost of renovation is higher than 25 % of the value of the property, or more than 25 % of the building surface gets renovated (EU, 2010). EU member states will apply one of these two definitions and give the more specific limits regarding the climate of the state for nearly zero energy buildings in their regulations. For the case of Finland the directive has been executed with a change in land use and building legislation.

There are already mature technologies to improve the overall energy efficiency of buildings, such as solar photovoltaic (*PV*) systems and heat pumps. Matured technologies are not prototypes but fully in industrial manufacturing level and in their late maturity stage (IPCC, 2012, p. 337). Industrialized production is visible in prices: the prices of solar *PV* panels have decreased drastically in past few years. Linking the implementation of these mature technologies and the renovation offers a good opportunity for energy efficiency improvements.

In addition, former study by Chegut, et al. (2016) shows that energy efficiency improvements are economically profitable: the energy efficient properties sell for 2.0–6.3 % more than similar but not as efficient properties.

Sustainability is usually described as three spheres: environmental, economic and social sustainability. From environmental perspective energy is saved and CO_2 emissions are decreased through investments in energy efficiency. In economic point of view these investments are profitable, because they increase the value of the building and decrease energy costs. In addition, the social advantage is achieved by offering renovated, comfortable spaces for work and other activities in public buildings, and by creating jobs during renovation.

1.2 Objective of the study

The case building for the study is Lappeenranta City Hall. The scope of the study is existing public buildings undergoing a renovation process in the near future. In this study, a model in the form of an Excel-tool is developed for comparing energy efficiency improvements and their profitability. The model will be used for evaluating the potential and profitability of the energy efficiency investments in multiple buildings, so there should be more precise building specific studies before making an investment decision and an installation.

The objective of this study is to find out how the energy efficiency can be increased so that the energy system cost would decrease. The variables studied regarding the suitability of a technology are maturity of the technology, economic profitability, constraints from the building itself, such as energy demand and the structure of the building, and sustainability. The technologies for energy efficiency improvements are photovoltaic panels, heat pumps, decrease of thermal transmittance e.g. adding insulation, and improvements regarding the heat recovery unit's efficiency.

The material of this study is data collected about Lappeenranta City Hall as a part of the project *Public-Private Partnership in real estate energy efficiency improvements and*

finance, and literature. Structurally, first the case building is presented. Second, matured energy technologies are briefly studied. Third and fourth, the model, its inputs, calculations and results are explained. Finally, the conclusions and discussion are presented. The method of the study is a case study which aims to result in a semi-universally applicable model for comparing energy efficiency improvements and their costs.

1.3 Former studies and *Public-Private Partnership in real estate energy efficiency improvements and finance* - project

There are multiple barriers in doing energy efficiency improvements in the municipal building sector: economic, political and social barriers (Allouhi, et al., 2015). The project *Public-Private Partnership in real estate energy efficiency improvements and finance* targets to solve the financial problem of making energy efficiency improvements to public buildings and to show the investments' influence to cash flow in the long-run.

It seems, that there are few former studies regarding cost optimization of renovation and choosing energy systems for a building. Niemelä (2018) has written a dissertation about the theme in the aspect of what kind of renovation would be cost-optimal for each building type. His results show that for every building type, residential, educational and office buildings, the modern heat pump is the most cost-effective main heating solution (2018, p. 129). A study by Thygesen and Karlsson (2017) gives a conclusion that it would be possible to build less insulated houses with heat pumps and solar photovoltaic system, although in the study there is no economic assessment of it. Litjens, et al., (2018, p. 59) studied combined systems of ground source heat pump (*GSHP*), solar *PV* and battery storage and pointed out that there is a clear correspondence between the attractiveness of the investment and the total avoided CO_2 emissions during the lifecycle. This aspect can also be presented so that the risk of the investment decreases as the risk on climate decreases.

The insulation and own energy production technologies are not commonly seen as two options but as two process steps following each other. In a study by Moldovan, et al.

(2014, p. 116) the basis is first decreasing the energy demand by adding insulation, and after that dimensioning new energy systems for covering the demand left. Nevertheless, the study gives a broad look to the initial cost and different mix of technologies in building application (Moldovan, et al., 2014).

In general studies tend to focus on one aspect of the energy efficiency improvements. The studies are focusing for example either in the building structure or the renewable energy technologies, or only in CO_2 emission reductions but not optimizing the costs. The market potential of the energy efficiency improvement studies and tools is prominent. For example, Aalto University in cooperation with VTT has prepared a multi-objective optimization tool for building performance (Palonen, et al., 2013).

2 BASIC INFORMATION ABOUT THE CASE PROPERTY

Lappeenranta City Hall was completed in 1984. The heated net area is 12 303 m^2 according to the Energy Performance Certificate (*EPC*). The frame work, as well as the façade, is made of concrete. The hall has mainly flat roof with some areas with prominences and sloped roof.

The case building is used as office building and thus the usage group is 3 from the Decree of the Ministry of the Environment (Ympäristöministeriö, 2017a). The Decree gives information, for example, about the heat loads of the building type, which is studied more in chapters 4.2 and 5.1.

The energy consumption of the property in current situation is based on the measured electricity and heating demand. The electricity demand data is obtained from automatic meter reading (*AMR*) measurements made in 2017 on an hourly basis. Electricity in the case building is used in appliances and lights, but also for fans in ventilation, for example. The lighting has been replaced by *LED*-lights. The monthly variation of the electricity demand is shown in Figure 1.

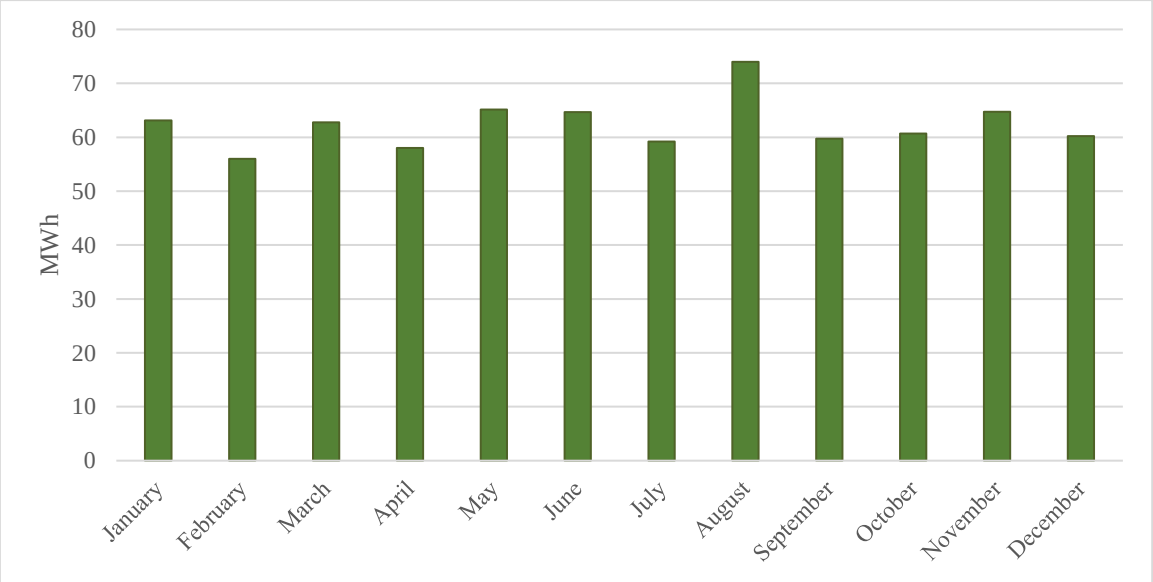

Figure 1. Electricity usage of Lappeenranta City Hall in reference year 2017.

As seen in Figure 1, monthly electricity demand is quite stable throughout the year. Weekly electricity consumption profiles are obtained from the data. In Figure 2 there are weekly profiles of the demand in January and in June for comparison.

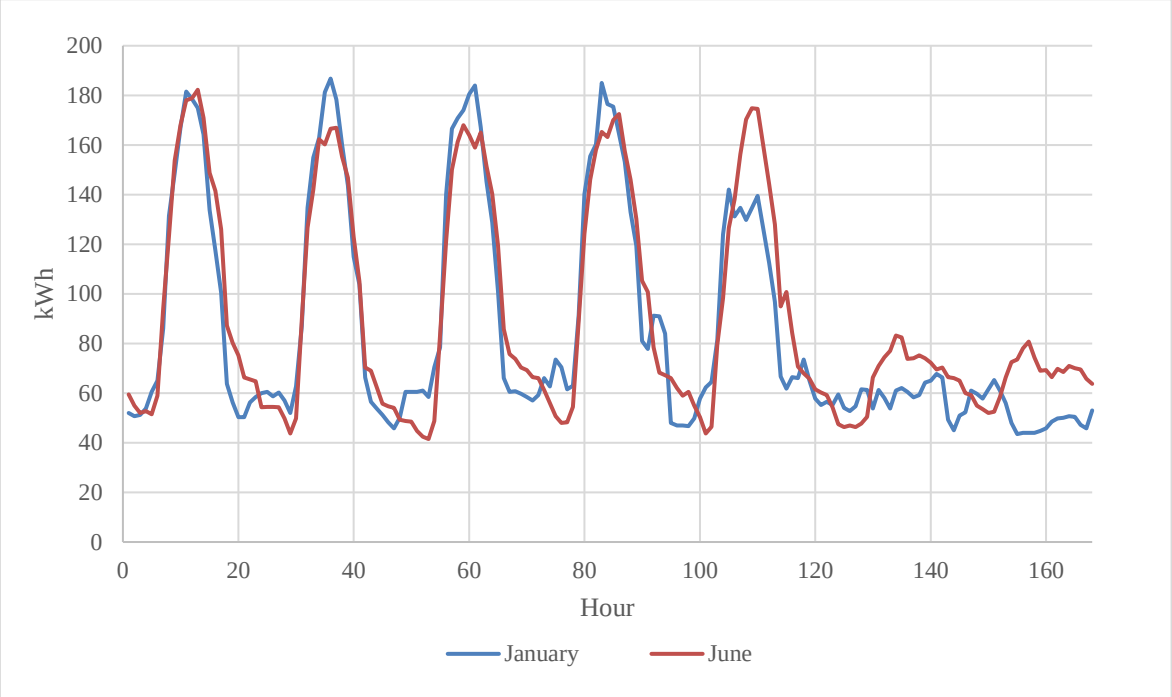

Figure 2. The average weekly profile of electricity usage in the case building in January and June.

As seen in Figure 2, demands in the peak hours are within 10 to 20 kWh from each other when comparing the situations in January and June. For a more specific analysis of the demand, there should be more precise information about the usage and the systems of the building. In addition, the user of the building has a great impact on the electricity usage.

Spaces and cold water, as well as supply air in ventilation, are heated with district heat. The district heating demand covering space heating, domestic hot water (*DHW*) heating and the supply air heating is known on an hourly basis. The need for heat in ventilation is included in space heating demand in the calculations. For simplification, in further calculations the heating demand is handled on a monthly basis. The heat is distributed in the building with radiators using water as a working fluid.

Because only cold water usage is measured, domestic hot water usage is calculated with information from the Decree of the Ministry of the Environment (Ympäristöministeriö, 2017a). Domestic hot water heating energy specified in energy legislation is 6 kWh/m^2 for the net area of the building for office buildings (Ympäristöministeriö, 2017a). Domestic hot water heating demand varies according to use of the building and ground temperature. Ground temperature affects the cold water intake temperature, so it also affects the heating demand of the water. The monthly variation of *DHW* heating demand in a residential building is shown in Table 1.

Table 1. The monthly variation of domestic hot water heating energy demand in a residential apartment building (Seppänen, 2001, p. 247).

Month	1	2	3	4	5	6	7	8	9	10	11	12
% of *DHW* demand	9	8	9	9	9	6	5	7	8	10	10	10

For the calculations, it is assumed that also in an office building the domestic hot water heating need would be distributed as it is in the residential apartment building and in Table 1. *DHW* heat demand is studied monthly, although in reality the need varies also weekly, daily and hourly.

When the *DHW* heating demand is calculated, the separated space heating and *DHW* heating demands can be drawn, as shown in Figure 3.

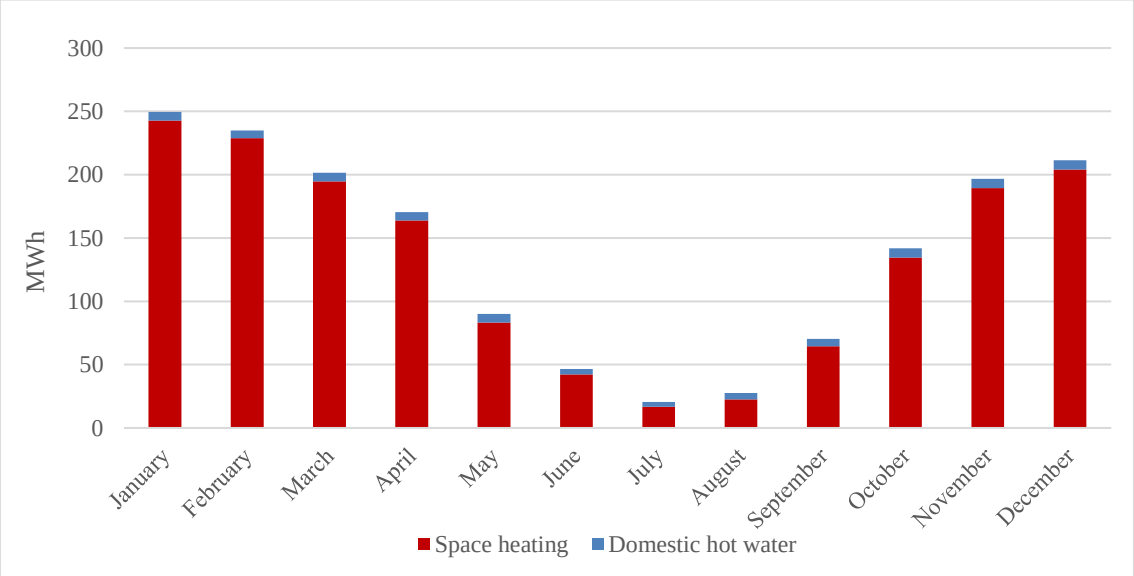

Figure 3. Heat demand of Lappeenranta City Hall in reference year 2017.

The space heating demand varies drastically throughout the year. The highest peak in demand is in January and the lowest demand is in July. The changes in *DHW* heating energy demand are not remarkable.

It should be taken into account that the demands are from a reference year and thus they represent only one year's demands and circumstances. The variation of outdoor temperatures and the use of the building is affecting the electricity demand. For example, in colder days, the heat demand of the ventilation is higher in order to reach the needed supply air temperature. For normalization of electricity demand, recorded dat of electricity demand for example from the past 10 years would be needed. The heat demand is normalized with information of 10 past years' average temperatures in further calculations. Electricity demand is studied hourly and heat demand monthly. In order to calculate heat demand on an hourly basis, the information about heat loads in the building as well as solar radiation load to the building would be needed hourly. The hourly assessment is left for further studies regarding the broadness of this study.

Energy Performance Certificate is obligatory when selling a property (Ympäristöministeriö, 2017b). The Energy Performance Certificate is a computational

certificate of the energy efficiency performance of the building. For the case building there is an Energy Performance Certificate from year 2015 available. The information about the thermal transmittance and area for each existing structure, air leakage rate, the heated net area and the temperature efficiency of heat recovery are obtained from the *EPC* as inputs for calculations presented in chapter 4.1. The energy performance value of Lappeenranta City Hall is 204 kWh_e/m^2y, which corresponds to a rate of E_{2015}. The limit for next rate, D, is 171…200 kWh_e/m^2y, and for the best rate, A, 0…80 kWh_e/m^2y.

Some constraints regarding the building are the location and the building structure. Lappeenranta City has provided an instruction for renewable energy investments and the instructions include the potential of ground source heat pumps in various areas of the city (Rejlers, 2017). According to the map of potential of ground source heat, it seems that investments in ground source heat in the city center area would not be feasible (Rejlers, 2017). This might be due to the esker, which consists of gravel. The investment cost of a ground source heat pump bore well will increase if the well must be drilled through the gravel. The geological research center's "Maankamara"-service states that the depth of the bedrock in the location of Lappeenranta City Hall is approximately 50 meters (Geologian tutkimuskeskus, n.d.). A more precise analysis requires location specific measurement data. In addition to the site's feasibility, there is no sufficient area in the city center available neither for vertical nor for horizontal ground source heat pump's wells and pipe work. Furthermore, the location in a central area makes it hard to implement ground source heat pump pipes, because there is very little or no available land area which is not constructed.

The city planning affects strongly the city center and what can be done there. The conservation of the building might also be a barrier for renovation or any other visible changes, such as the installation of solar *PV* system on the rooftop. In case of Lappeenranta City Hall there are no conservation issues.

The roof structure is a constraint for the implementation of solar panels. The condition of the roof should be evaluated to discover if there should be some fixing or renovation

before the installation of the panels. Furthermore, it needs to be examined whether the structures would carry the extra weight of the panels. The reference panels, Canadian Solar 260–280 W (Canadian Solar, n.d.), weigh 18.2 kg per panel, which corresponds to 11.12 kg/m^2. In addition, the mounting system should be taken into account when calculating the additional load on the roof. The structure point where the attachments are installed should be chosen so that the load from panels would be distributed to suitable structures and a suitable area. The available area for solar panels in the case building is presented in chapter 4.3.

3 TECHNOLOGIES, THEIR FEASIBILITY AND COSTS

Choosing a feasible technology for a building and size, type and the placement of the technology depends on many variables. These variables are building function, form and type, the building's energy demand, building occupancy and usage, location and climate, synergies and conflicts between technologies, regulations, shading from structures and neighboring buildings, capital and maintenance costs and incentives (Day, et al., 2013, p. 206).

In this chapter, the existing and alternative technologies will be reviewed with their main features: maturity, investment and management costs, and CO_2 emissions. In addition, the existing technology base in the building will be reviewed for further discussion of energy efficiency improvements and their cost efficiency.

The mature technologies included in this study are solar photovoltaic system, heat pumps and heat recovery in ventilation. The reason for choosing these technologies to this study is that all of these are fully matured technologies in application. Other options for renewable energy production not included in this study are solar heating, small scale biomass boilers, microscale hydro power and microscale wind turbines (Day et al. 2013, 206).

Fully matured solar power technologies are solar photovoltaic panels, low-temperature heat collectors and passive solar heating in buildings (IPCC, 2012). Passive solar heating is not very relevant when regarding the changes made to existing buildings. Furthermore, low-temperature solar heat is gained mostly in the summer, when there is the lowest need for space heating in the thermal conditions of Finland. In summer the heat demand is almost only for domestic hot water (Day, et al., 2013, p. 211). Thus, this study will only focus on solar *PV* panels.

Small-scale boilers are not included in this study as a renewable energy technology, because of the CO_2 emissions that come from burning, regardless if the fuel would be biofuel. The existing large-scale biofuel boilers are more efficient and produce relatively

less emissions than small ones, so it wouldn't be efficient or economic to replace an existing district heating plant with a smaller biomass boiler.

Also, micro-hydro and micro-wind turbines are not included in this study, because of their un-scalable performance with lower velocities and smaller sizes of turbines in property scale applications.

Some other energy efficiency improvements not included in this study are, for example, changing the lighting to LED-lights, having more energy efficient appliances, adding shadowing structures or installing a reflective sheet to the windows. The load of solar radiation and thus the need for cooling as well as the heating needed in winter can be decreased by the shadowing structures, such as a marquis, or reflective sheets in windows. It should be taken into consideration, that the added shadowing structure increases the need for indoor lighting, though (Seppänen & Seppänen, 1997).

The levelized cost of electricity, *LCOE*, is a good way to compare energy technologies. *LCOE* is calculated with following equation.

$$LCOE = \frac{Capex \cdot crf + Opex_{\text{Fixed}}}{FLH} + Opex_{\text{Variable}} + \frac{Fuel\ cost}{\eta_e} \quad (1)$$

where *Capex* is the total investing cost in €/kWh

crf is the capital recovery factor

$Opex_{\text{Fixed}}$ is the management cost that does not depend on production in €/kWh

FLH is the full load hours

$Opex_{\text{Variable}}$ is the management cost that depends on production in €/kWh

Fuel cost is the fuel price in €/kWh, and

η_e is the efficiency of electricity production.

Capital recovery factor *crf* needed in calculation of *LCOE* is calculated as follows.

$$crf = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (2)$$

where i is the interest rate, which can also be impressed as weighted average cost of capital, *WACC* and

n is the life time of the investment in years.

It is important to choose the weighted average cost of capital wisely in the calculations, because of the remarkable impact it has regarding the results. The values in this study are chosen so that they are comparable, and all calculations made are discussed in order to make the results repeatable.

3.1 Heat pumps

In this chapter, variety of heat pump technologies are presented. Heat pumps are playing a huge role in the electrification of the whole energy system. Through implementation of heat pumps, it is possible to produce heat without burning, if the electricity is produced by wind or solar energy, for example.

The working principle of heat pumps is based on the refrigerant inside the heat pump. The refrigerant evaporates when the heat from the heat source is transferred to it, and a compressor is used to increase the pressure of the refrigerant. In a condenser the heat from the refrigerant is transferred to the heat sink, for example indoor air. The refrigerant is expanded to start the working cycle again.

Heat pumps use electricity, and thus CO_2 emissions in the electricity production must be considered in the sustainability analysis of heat pumps. Heat pumps are not necessarily renewable technologies, but as more renewable capacity is added to the network, they become more sustainable. The renewable energy share of the Finnish energy system was 37 % in the year 2017. The share was dominated by biomass, and grew 6 % from year

2016 (Statistics Finland, 2018). The share of CO_2 neutral production was 54.8 %, which includes production by nuclear power.

In a study by Greening and Azapagic (2012, p. 210) concerning the UK, the total CO_2 equivalent emissions from water and ground source heat pumps are estimated to be 189 g CO_2/kWh, and for air source heat pump the equivalent coefficient is higher, 276 g CO_2/kWh, due to the lower efficiency. In addition to the electricity production, the manufacturing process of heat pumps and their implementation produces CO_2 emissions. The CO_2 emissions are mainly caused by the electricity production, with a share of 95 % of the CO_2 equivalent (Greening & Azapagic, 2012). The CO_2 emissions of a heat pump are highly depended on the whole energy system composition.

When choosing a heat pump, heat delivery in the building defines which options are feasible and economical. As a result, the functioning of the radiator network affects the working of the heat pump. Output power of a heat pump is higher when the temperature level of radiator network is lower (Motiva Oy, 2018a).

3.1.1 **Air source heat pumps, *ASHP*s**

Air-to-air heat pump transfers the heat from outside air via a refrigerant to room air. Air-to-air heat pump can also be used for cooling. Usually heat production via air-to-air heat pump is not enough if there are no other heat production manners available in the building (Motiva Oy, 2018a).

When using air-to-air heat pump in Finnish conditions, the challenges are in the variable temperature of the heat source. Because unlike with the ground, the temperature of the air varies, it means that in the winter time the Coefficient of Performance (*COP*) is lower. Implementation of an air-to-air heat pump in larger buildings requires that the heat distribution network is done by air based heating system.

Air-to-water heat pump transfers heat from outside air via a refrigerant to the water cycle of the heating system. The most feasible application for air-to-water heat pump is an

underfloor or radiator heating with water as a working fluid, because of the same working fluid and the low temperature level (Motiva Oy, 2018a, p. 20). Implementing air-to-water heat pump to a building that has been in district heating system would be possible because both systems use the same working fluid. As with air-to-air heat pump, the challenges are in the variable temperature of the heat source.

Exhaust air heat pump uses exhaust air as its heat source. The heat from exhaust air can be used for heating water and using it as a working fluid in heating system or as domestic hot water. Exhaust air heat pump does not cover the whole energy demand of the building (Motiva Oy, 2018a, p. 31). Technically exhaust air heat pump requires a building with a heating system with water as a working fluid and with a dilution ventilation (Motiva Oy, 2018a, p. 31). The exhaust air heat pump is feasible for a building with just a waste air fan or forced ventilation without heat recovery.

3.1.2 **Ground source heat pumps, *GSHP*s**

Geothermal absorption heat pump utilizes the heat stored in soil, rock or water. Usually the heat comes from a hole drilled to the ground. Other options are, for example, to place tubes horizontally in the ground under the soil frost limit, or on the water bed (Motiva Oy, 2018a, p. 24). In cities, the ground source heat pump is usually more feasible with a vertically drilled hole than with a horizontally drilled hole, because in cities land area is usually more limited and already constructed (Moldovan, et al., 2014).

Air source heat pumps have significantly lower *COP* values in Finnish winter time due to outside temperature conditions. Underground temperature stays stable throughout the year (Motiva Oy, 2018a, p. 24). Regarding this, ground source heat pumps can offer more stable heat production than air source heat pumps.

The energy from the borehole can be extracted by the capacity of 40–60 W/m (Kukkonen, 2000, p. 278). The extraction of 40 W/m is assumed for this study, though the value for extraction can be changed in the model. One bore hole is assumed to be 200 meters deep,

thus there should be 26 boreholes for covering the whole theoretical heating demand of the case building.

A geothermal heat pump dimensioned for full power can cover 95–99 % of building's heat demand (Motiva Oy, 2018a, p. 24). The rest of the heat can be produced with a heating resistor in the heat pump. It is possible to decrease the room temperature in colder times in order to cover more of the demand with the heat pump. The challenge of implementing a ground source heat pump is intermittent running in temperatures between +5 °C and −5 °C, which are common in climate conditions of Finland (Motiva Oy, 2018a, p. 24). The heating power can be adjusted with an inverter control. As a possible solution for intermittent running, also a heat storage could be implemented. In addition, the storage offers an opportunity to use own electricity production not depending on the time it is generated. On the other hand, the challenge with a heat storage and a heat pump is the return temperature of heat pump which is not as high as desired for storage. The storage's role is left for further study.

3.1.3 Costs and conclusion of feasible heat pump types

Studies have stated that ground source heat pump is the most economical solution for buildings both in Finnish conditions (Paiho, et al., 2017) and in southern locations (Aste, et al., 2013). In Finland the life cycle cost in a new apartment building with a ground source heat pump or an air-to-water heat pump (*AWHP*) is 178 €/m^2/25y (Paiho, et al., 2017, p. 401). The costs of heat pumps are thus lower when compared to the life cycle cost of an apartment building with district heating, 219 €/m^2/25y (Paiho, et al., 2017, p. 401). Furthermore, the life cycle costs in buildings with exhaust air heat pumps and air-to-air heat pumps are higher than costs of buildings with *GSHP* or *AWHP* (Paiho, et al., 2017). The costs mentioned are calculated for new buildings, not for improvements done on an existing system, so the cost can vary.

The investment cost for ground source heat pump is hard to evaluate because the cost depends on the bore holes and the drilling process. The prices of the investments based on executed projects are obtained from Haahtela & Kiiras (2015) and are presented in

Table 2. The maintenance cost for GSHP is 1 % of investment and for *AWHP* 1.5 % of the investment (Paiho, et al., 2017, p. 398).

Table 2. Areal prices for heat pump investment (Haahtela & Kiiras, 2015).

		Areal price level		
		75	81	85
Bore hole 200 m	€/piece	6 110.00	6 700.00	7 070.00
Joint pipes from the bore hole	€/grm^2	12.8	15	16
Heat pump (large)	€/kW	300	325	340

The heat pump price is used for both *GSHP* and *AWHP*. For the case of Lappeenranta, the area for estimating the price level is 75. The gross area in Table 2 regarding the joint pipes means the total external area of the building (Haahtela & Kiiras, 2015). Because the gross area of the case building is not known, the heated net area is used in this study instead, because the difference is not remarkable.

3.2 Solar photovoltaic system

From the global energy consumptions perspective, sun is an endless resource. The working principle of solar photovoltaic panels is based on two different semiconductor materials and the photoelectric effect when the sunlight hits the semiconductor materials.

The most common material used for *PV* panels producing electricity is crystallized silicon with a market share of 95 % in year 2017 (Fraunhofer Institut for Solar Energy Systems, 2018). The rest of market share was thin-film *PV* panels. The efficiency of a commercial wafer-based silicon *PV* panel is on average 17 % (Fraunhofer Institut for Solar Energy Systems, 2018).

Maintenance costs of solar *PV* panels are low, about 0.5 % of the investment in the business scale roof-top installations (Simola, et al., 2018). Full load hours of solar *PV* panels in Southern Finland are usually around 800 hours.

An inverter and other appliances including mounting system components are needed for solar PV installation. In Finland the price for the total solar *PV* system installed on a roof-

top in 2017 was 0.9–1.15 €/W_p (*VAT* 0 %) for 10–250 kW system, and for a larger system over 250 kW price was lower, 0.85–1.15 €/W_p (*VAT* 0 %) (Ahola, 2017, p. 8–9). The price of *PV* in Finland has decreased over the last years on average by 0.125 €/ W_p every year (Ahola, 2017). The decrease in prices of *PV* panels is extremely fast, and it has resulted in drastically increased amount of installations worldwide, as shown in Figure 4. The progress proves that solar *PV* is a fully matured technology with growing market potential.

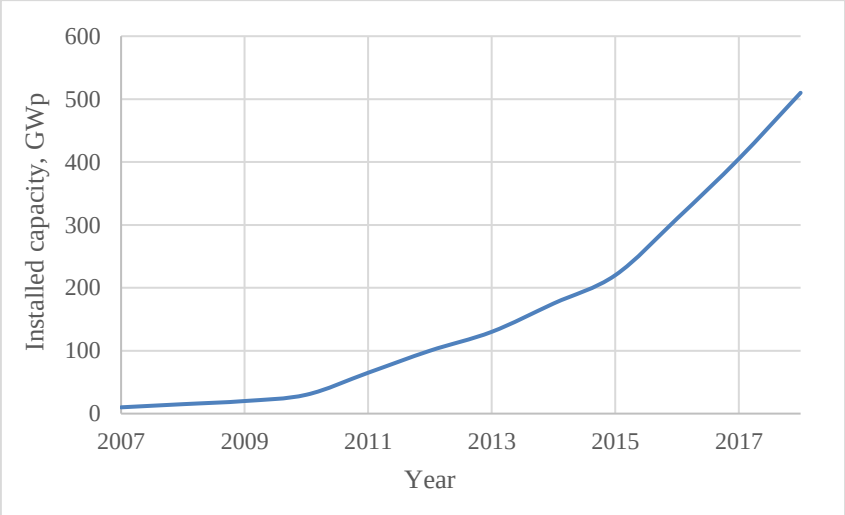

Figure 4. Installed *PV* capacity in the world, after IEA PVPS (2019).

An aspect considering the price of produced energy of solar *PV* system is the tax of energy production and transfer. In Finland bigger than 100 kVA production units with production not more than 800 MWh need to register as electricity tax obliged but are not needed to pay electricity taxes nor the payment for security of supply (Verohallinto, 2016). The limitations with taxation should be checked when dimensioning the *PV* plant.

In a study by VTT the potential of *PV* production on roof tops in Finland is calculated to be 3 TWh/a (Pasonen, et al., 2012). The calculations is done with assumption of 60 % of residential roof tops facing south or almost south covered with panels. The study (Pasonen, et al., 2012) is from year 2012 and the efficiency of the panels is assumed to be only 10 %, so the real potential of solar *PV* in Finland is even higher. Furthermore,

Lassila, et al. (2016), states that there is over 20 GW power generation potential in Finland with roof-top *PV* system installations. In Lappeenranta, the yearly sum of global irradiation meeting an optimally inclined solar *PV* panel is about 1 050 kWh/m^2 (European Comission, 2017).

In this study, the needed surface area for *PV* production is calculated with the information of a reference module Canadian Solar 280 W (Canadian Solar, n.d.). The reference module length is 1 650 mm and width 992 mm, so a peak kilowatt can be obtained from a 5.85 m^2 panel area.

Because the energy conversion process in *PV* panels does not generate any CO_2, the emissions of a solar *PV* panel come only from the manufacturing of panels. The amount of CO_2 emissions is highly dependent on the way electricity is produced in the manufacturing location. Solar cells manufactured in China have an average carbon footprint of 44–67 g CO_2/kWh, when cells manufactured in Europe have a carbon footprint of 24–31 g CO_2/kWh (First Solar, 2018). The solar cell will produce the energy needed in its production in 1–3 years depending on the location.

3.3 Existing technologies

The price and consistency of electricity production and heat production varies across Finland, because there are differences how the energy is produced in different locations. In addition, CO_2 emissions of energy purchase vary according to the source of production.

3.3.1 District heating

Heat for the public buildings in Lappeenranta comes mainly from the district heating network. In the case of Lappeenranta City, over 80 % of needed district heat is produced in the power plant of Kaukaan Voima (Greenreality, n.d. a). The price of district heat in Lappeenranta area is 70.50 €/MWh, which consists of three parts: energy, transfer and flow rate cost. The cost of transfer is 14.50 €/MWh and the cost of energy 56.00 €/MWh (Lappeenrannan Energia Oy, 2019). The prices includes the value added tax (*VAT*) of 24

%. With assumption of flow rate 5 m^3/h, the cost regarding the flow rate can be calculated as follows.

$$\text{Payment} = (1\,735.50 \cdot V + 2\,175.50)\,\frac{€}{y} \quad (3)$$

where V is the calculated maximum of the water flow rate, in m^3/h.

With flow rate of 5 m^3/h, the total cost of district heat is 58.50 €/MWh, *VAT* 0 %.

Motiva (2012) gives for combined heat and power in Finland a value of 217 000 g CO_2/kWh as a CO_2 equivalent. About 70 % from the fuels used for district heat in Kaukaan Voima are stated to be carbon neutral (Greenreality, n.d. b). The fuels for producing district heat are mainly biomass, which eventually has CO_2 emissions. Motiva (2012) states that bio power is CO_2 neutral, creating 0 g CO_2/kWh emissions. The statement is based on the assumption, that the biomass is sustainably gathered, and the CO_2 burned will be bond to new biomass growing. The assumption is only valid when the examination period is long. Meanwhile, the IPCC report (2014, p. 539) states that the CO_2 emissions of forest wood biomass are on average 200 g CO_2 eq/kWh. The calculations include infrastructure and supply chain emissions as well as biogenic CO_2 and Albedo (IPCC, 2014, p. 539).

3.3.2 **Electricity purchased**

There is a contract with the electricity retailer regarding the public buildings in Lappeenranta which states that only bio and wind power based electricity is used (Greenreality, n.d. c). Lappeenranta City has a target of 80 % CO_2 emission reductions by 2030 from the level of year 2007. For purchased wind power, the CO_2 emission equivalent is less than 7 g CO_2/kWh for onshore wind power (Bonou, et al., 2016). For bio power the CO_2 emissions are not unambiguous as explained before.

Electricity market price varies hourly and the changes can be drastic upon time. The yearly averages of the electricity prices from years 2003 to 2018 are presented in Figure

5. The price of renewable electricity is not separately studied, and the current price that is paid for electricity is assumed to be the market price.

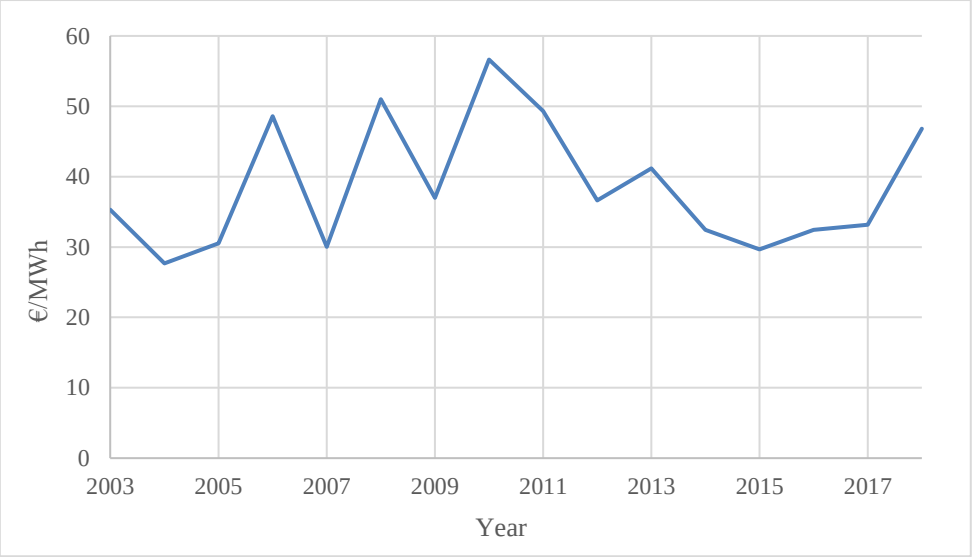

Figure 5. ELSPOT price variance of electricity in Finland, yearly averages (Nord Pool, 2018).

An average price for electricity in Finland from years 2003–2018 is assumed for future electricity price for simplification. The average price is 38.65 €/MWh, covering the energy based share of the price (Nord Pool, 2018). The share of transfer is assumed to be 29 % of the total cost, the share of energy tax 14.5 % and the share of *VAT* 19.4 % correspondingly of the total cost (Vattenfall, n.d.). Thus the result for the total price is 104.36 €/MWh with *VAT*, and 84.09 €/MWh without *VAT*.

In the future electricity could be bought with a long-term contract, for example, from production of a wind park when regarding the electricity purchases in property masses scale. In Finland wind resources are more favorable in the winter and solar resources on the contrary in the summer, so these two sources of electricity could balance each other.

3.3.3 **Ventilation**

In a building there is always a ventilation system for changing the air inside a building in order to maintain healthy and comfortable indoor air quality. About 55 % of a building's

heat loss happens through the exhaust air flow (Seppänen & Seppänen, 1997, p. 60). The two main types of ventilation are natural ventilation and forced ventilation (Seppänen & Seppänen, 1997, p. 166). Usually in larger public buildings the natural ventilation is replaced with forced ventilation. With fan assisted ventilation system, also heat recovery from the exhaust air is possible. Heat recovery decreases the heat demand of the building and it is thus described as an energy efficiency improvement.

The two main types of heat recovery units are regenerative and recuperative heat recovery units. Heat recovery is recuperative if the heat is transferred directly or indirectly from the air flow to another, for example, through a plane separating the two flows. The heat recovery is regenerative if there is a material storing and transferring the heat from the air flow to another. Regenerative heat recovery can also transfer impurities or moisture between the air flows. The recuperative heat recovery is direct when the flows are separated by planes, or indirect when there is a working fluid transferring the heat from flow to another. The indirect recuperative heat recovery makes it possible to lead both inlet and exhaust air flows in the different places (Seppänen, 1996, p. 287). The efficiencies of the different types of heat recovery units are presented in Table 3.

Table 3. Types of heat recovery units and their efficiencies (Seppänen, 1996, p. 286–290).

Heat recovery type	Temperature efficiency
Regenerative	60…80 %
Direct recuperative	50…70 %
Indirect recuperative	
Liquid circulation heat recovery system	45…60 %
Heat pipe radiator	50…80 %

In the case building there is a fan assisted ventilation system with heat recovery. The heat recovery is carried out by liquid circulation heat recovery units in 9 of the 12 supply air units. The ventilation is mainly original from 80’s, and 6 of the heat recovery units have been renewed in the past ten years’ time.

The efficiency of the heat recovery unit in ventilation system can be defined in two ways, by temperature efficiency and yearly efficiency. Temperature efficiency of heat recovery unit means the capacity of the unit to recover the heat measured in standard conditions (Seppänen, 1996, p. 292–297).

$$\eta_{\mathrm{T}} = \frac{T_{\mathrm{Supply}} - T_{\mathrm{Outside}}}{T_{\mathrm{Exhaust}} - T_{\mathrm{Outside}}} \quad (4)$$

where η_{T} is the temperature efficiency of a heat recovery unit

T_{Outside} is the temperature of outside air in Kelvin

T_{Supply} is the temperature of the supply air to the room in Kelvin, and

T_{Exhaust} is temperature of the exhaust air from the room before the heat recovery unit in Kelvin.

Temperature efficiency of the heat recovery unit varies according to the occurring temperatures. According to the Energy Performance Certificate, the temperature efficiency of the heat recovery unit in Lappeenranta City Hall is 37 %. The efficiency is assumed to be a constant. In reality, the results of the ventilation heat losses may be in some temperatures higher and in other temperatures lower than the calculated ones.

Yearly efficiency of a heat recovery unit shows how much of the heat energy needed in the ventilation system can be obtained through the heat recovery. According to the *EPC*, the yearly efficiency of the heat recovery unit in Lappeenranta City Hall is 27 %.

$$\eta_{\mathrm{a}} = \frac{Q_{\mathrm{Hr}}}{Q_{\mathrm{D}} - Q_{\mathrm{Hr}}} \quad (5)$$

where η_{a} is the yearly efficiency of a heat recovery unit

Q_{Hr} is the heat recovered by the heat recovery unit in Wh, and

Q_{D} is the total heat demand of the heat recovery unit in Wh.

The temperature efficiency values and thus the yearly efficiency values are both quite low when comparing to the modern heat recovery units, which have, for example, a temperature efficiency of 73 % up to 85 % (FläktGroup Finland Oy, n.d.). The low value of temperature efficiency might be due to the fact that there is no heat recovery in all supply air units, and the value from *EPC* is thus an average from those existing and those with no heat recovery. The calculations are made assuming that the whole average supply air flow goes through heat recovery.

The average air flow of both supply and exhaust ventilation units are given in the *EPC*, and for Lappeenranta City Hall they are both 27.53 m^3/s. The air flow seems quite high, so for a more precise assessment, the average supply air flow is calculated with the information of the driving cycle and the supply air devices. The information is obtained from the management of the building, and the supply air flows are obtained from the equipment list of supply air devices. The driving cycle of the supply air devices and their usage is calculated so that the sizing supply air flow of each supply air device in an hour is multiplied with the hours the ventilation is running on the full capacity. In an example case the supply air unit is running in full capacity five days a week during work hours, defined to be from 6 to half past 17, and not running outside these hours. The share of full capacity hours in a week, t_{Week}, can be calculated in the example case as follows.

$$t_{\mathrm{Week}} = (17.5 - 6) \cdot 5\ h = 57.5\ h$$

The average supply flow is calculated to be 20.8m^3/s. According to the management the running of certain supply air units is limited to 50 % capacity when outside temperature is under −12 °C. In the calculations the hourly temperature data from year 2017 is assessed, and according the data there is in total one week with outside temperature under −12 °C in the year 2017 (Finnish Meteorological Institute, n.d.). In further studies it should be taken into account that exhaust air flows from point sources of dirty air should not be taken through heat recovery unit. The occurring ventilation's heat losses as well as the current insulation and effects of structural thermal transmittance to the heat losses are presented in chapter 4.1.

4 INPUTS FOR THE MODEL

The input data is gathered on the first tab of the Excel-tool. In addition to the consumption information, inputs from Energy Performance Certificate and its legislation as well as weather data are needed. Some input values are estimated before calculations, such as available rooftop area for *PV* panels, and radiator area.

4.1 Inputs regarding the building structure and systems

In Lappeenranta City Hall, the heated net area is 12 303 m^2. Furthermore, air leakage rate, 4 $m^3/(hm^2)$, is obtained from the *EPC* for further use. In addition, the temperature efficiency of the heat recovery unit is obtained, as well as average supply air flow for comparison to the calculated one.

Information about the area and thermal transmittance of each structure are obtained from the *EPC* to the model. As calculated in the Certificate, the specific heat loss in W/K is obtained from the information of the thermal transmittance and area of the surface as follows.

$$H = U \cdot A \tag{6}$$

where H is the specific heat loss through a structure type in W/K

U is the thermal transmittance in W/m^2K and

A is the area of a structure type in m^2.

The results of heat losses as well as the total areas and thermal transmittances of the structures of the building are presented in Table 4. The table is based on the *EPC* and its presentation, so the values can be easily modified to the model from the *EPC*.

Table 4. The structural heat losses of Lappeenranta City Hall.

Structure	Total area of each structure m^2	Thermal transmittance W/m^2K	Heat loss W/K	Share of the heat loss %
Wall	4 443	0.28	1 244	19 %
Roof	3 029	0.22	666	10 %
Base floor	3 029	0.35	1 060	16 %
Windows	1 421	2.1	2 984	45 %
Outside door	97	1	97	1 %
Cold bridge			604	9 %

The share of heat loss through each structure, which is presented in Table 4, is also visualized in Figure 6. In City Hall's case, the thermal transmittances are quite high compared to the modern standards, which are, for example, for windows 1.0 W/m^2K and for walls 0.17 W/m^2K (Ympäristöministeriö, 2013). The high values of thermal transmittances are due to the old age of the case building.

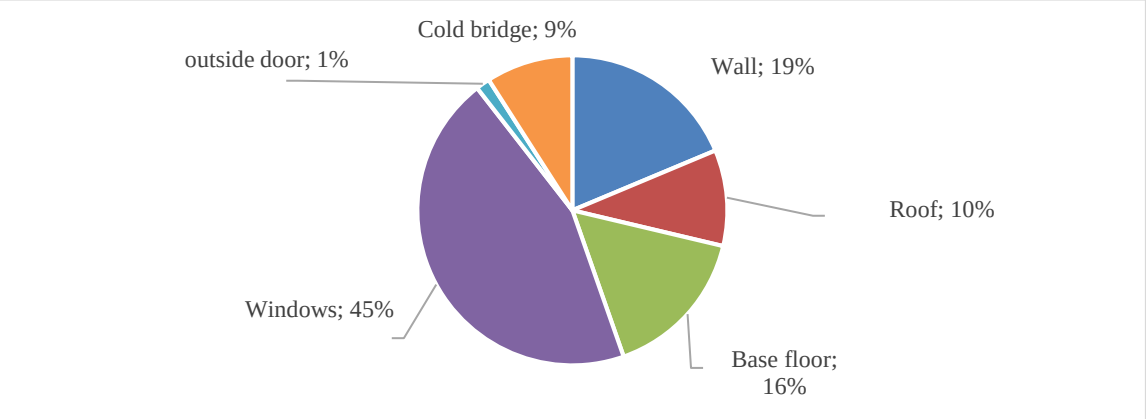

Figure 6. Share of heat loss through each structure type. Thermal transmittance and structure areas are obtained from Energy Performance Certificate.

Furthermore, the direction and area of the windows to each compass points are separated in the *EPC*, presented in Table 5. The thermal transmittances of all windows are given separately if there would be some windows with different *U*-values, as well as the transmission coefficient *g*. Calculating the solar load inside the building requires information about the direction of windows, which is studied more in chapter 5.1.

Table 5. The directions of the windows and area to each direction.

Direction of windows	Area of windows m^2	Thermal transmittance W/m^2K	$g_{perpendicular}$
North	445	2.1	0.6
North-East			
East	183	2.1	0.6
South-East	166	2.1	0.6
South	227	2.1	0.6
South-West			
West	400	2.1	0.6
North-West			

It should be noted that all the information about the structure is from the Energy Performance Certificate and there are no information about whether the information is an estimate or from the real structure thermal transmittance calculations.

4.2 Legislation data and weather data

With the information of the usage group of the property the Decree of the Ministry of the Environment can be used to obtain inputs about building usage for calculation (Ympäristöministeriö, 2017a). Table 6 and Table 7 include information from the Decree's sections 4, 11 and 12. The capacity usage as well as the time of use is shown in Table 6.

Table 6. Information of the building usage according to the building types by use (Ympäristöministeriö, 2017a).

Use	Usage group	Time	Time of use		Capacity usage
			In a day h / 24 h	In a week d / 7 d	
Small residential building	Group 1	00:00–24:00	24	7	lighting 0.1, others 0.6
Residential apartment building	Group 2	00:00–24:00	24	7	lighting 0.1, others 0.6
Office building	Group 3	07:00–18:00	11	5	0.65
Commercial building	Group 4	08:00–21:00	13	6	1
Hotel, caring institution	Group 5	00:00–24:00	24	7	0.3
School, kindergarten	Group 6	08:00–16:00	8	5	0.6
Sport hall	Group 7	08:00–22:00	14	7	0.5
Hospital	Group 8	00:00–24:00	24	7	0.6
Other; logistical building, indoor ice rink or swimming pool	Group 9				

The time of use in percentage is calculated with the information from the table as follows.

$$n_{\text{Time of use}}\,[\%] = \frac{\text{Time of use in a day } [h] \cdot \text{Time of use in a week [d]}}{24\,h \cdot 7\,d} \qquad (7)$$

In the usage group of office buildings, the time of use results in 33 %. The capacity usage, in other words how much people are attending the building and what share of the appliances and lights are on, can be read directly from Table 6. For the case building capacity usage is thus 65 %.

Information for calculating the internal heat loads and hot water heating energy demand based on the usage group can be obtained from Table 7.

Table 7. Information for calculating the heat loads and hot water usage in different building types by use (Ympäristöministeriö, 2017a).

Usage group	Internal heat load			Domestic hot water heating energy need
	Lighting W/m^2	Appliances W/m^2	Humans W/m^2	kWh/(m^{2}a)
Group 1	6	3	2	35
Group 2	9	4	3	35
Group 3	10	12	5	6
Group 4	19	1	2	4
Group 5	11	4	4	40
Group 6	14	8	14	11
Group 7	10	0	5	20
Group 8	7	9	8	30
Group 9				

The average outside temperatures in a month in Lappeenranta are obtained from Finnish Meteorological Institute (2019). For normalization point of view, the average temperatures of ten past years are calculated for each month. The results are presented in Table 8.

Table 8. Average temperature of years 2008–2018 on a monthly basis as well as the average temperatures of the reference year 2017 (Finnish Meteorological Institute, 2019).

	Average temperatures of 2008–2018 °C	Average temperatures of 2017 °C
January	−7.62	−4.7
February	−6.25	−5.5
March	−2.57	−0.4
April	3.77	1.1
May	11.27	8.3
June	14.58	12.6
July	18.21	15.5
August	16.05	15.3
September	11.24	10.3
October	4.65	4.2
November	0.82	0.7
December	−3.74	−0.8

Regarding Table 8, the year 2017 had higher temperatures in the winter and lower temperatures in the summer than the average temperatures have been for past 10 years. Overall, the average temperature of 2017 was 0.5 °C higher than the 1981–2010 average, and in past five years, the average temperature of 2017 is closest to the average of the 1981–2010 (Finnish Meteorological Institute, n.d.). If the heat demand of the building would not be known, the heating degree day could be obtained from the Finnish Meteorological Institute and demand could be calculated.

4.3 Additional input values

Additional information still required, include heat transfer area of the radiators, the underfloor heating area, the available roof top area for *PV* system and the amount of stories for air leakage rate calculations.

The heating system blueprints of Lappeenranta City Hall are studied for estimating the radiator heat transfer surface area. In Lappeenranta City Hall the radiators are mainly one plane radiators, but there is a share of convectors and some two panel radiators as well. The surface area of the heat transfer is the heat transfer area of the radiators. The area is obtained for Lappeenranta City Hall by calculating and summing the amount and size of each existing radiator. The heating system blueprint shows that there are in total 352 radiators in the City Hall, and their total panel area is 160 m^2. The area of the average radiator front panel is thus about 0.45 m^2. For simplification, the radiators are assumed to be all the same size, having only one panel, 1500 mm long and 300 mm high. With the information from the radiator manufacturer Purmo (2014, p. 14), the heat transfer area of one panel radiator in the average size can be estimated to be 3.43 m^2. Therefore, the total heat transfer area for the radiators is estimated to be 1 208 m^2.

The heat transfer distribution, the share of radiation and convection, can be estimated for each radiator type from Table 9. For one-panel radiators used in Lappeenranta City Hall, the share of radiation and convection is 50 %, respectively.

Table 9. Share of radiation and convection heat transfer in radiator types (Savo, 2017).

Radiator type	Share of radiation heat transfer	Share of convection heat transfer
1 plane radiator	50 %	50 %
2 plane radiator	30 %	70 %
3 plane radiator	25 %	75 %
Convector	15...10 %	85…90 %

If the case building would have floor heating as the main heating distribution way, there is an option for it in the model. The assumption for underfloor heating area is 80 % of the heated net area, and the share of radiation heat transfer is 60 % (Seppänen & Seppänen, 1997). The share of heat from underfloor heating ending up to heat the inside air is assumed to be 70 %.

The available area for the *PV* panels is estimated from roof top blueprints. There are a lot of ducts and some height differences on the roofs, which might shadow the panels. In total a 300 m^2 area is estimated to be available and applicable for *PV* panel installation. Out of the available area 70 % is assumed to be the actual area for panels. The decrease of panel area is due to the fact that the roof is a flat roof and the panels will be installed in an angle, thus shadowing would occur if there is no space between the panels.

The amount of stories, in this case 6, is obtained for the calculation of the leakage air effect. The factor for stories, *x*, is obtained from the Table 10.

Table 10. Table for obtaining the factory for stories in calculation of air leakage flow rate (Ympäristöministeriö, 2017a).

Amount of stories	Factor for stories
1	35
2	24
3	20
4	20
5	15
>5	15

The factor used later on in the calculation of air leakage and its effect on heat demand is thus 15.

4.4 Current consumption

Hourly and monthly electricity consumption is given as an input. Heat consumption is given monthly. The *DHW* heating energy demand is separated from the heat demand because the needed temperature for it is different from the needed temperature for the space heating. The calculation of *DHW* heating demand is presented in chapter 2. The consumption values are shown in Table 11.

Table 11. The consumption of electricity and heat in reference year of 2017.

Consumptions in monthly range	Electricity consumption MWh	Total heat consumption MWh	Space heating MWh	Domestic hot water MWh
January	63	249	243	6.6
February	56	235	229	5.9
March	62	201	195	6.6
April	58	170	164	6.6
May	65	90	83	6.6
June	64	47	42	4.4
July	59	20	17	3.7
August	73	28	22	5.2
September	59	70	64	5.9
October	60	142	134	7.4
November	64	197	189	7.4
December	60	211	204	7.4
	748	1 661	1 587	73.8

5 MODEL FOR ENERGY EFFICIENCY TECHNO-ECONOMIC CALCULATIONS AND COMPARISON, AND RESULTS OF CALCULATIONS

In this chapter the model for energy efficiency techno-economic calculations and comparison is presented. The calculations of the model, in this case of an Excel tool, are explained so that the results are comparable and repeatable. All assumptions and simplifications are explained and reasoned, thus in further studies they can be taken into account. After each calculation chapter there is a chapter related to the results of the calculations.

5.1 Insulation and ventilation calculations

Studying the effects of insulation shows whether a decrease in thermal transmittance would be more economical than adding another energy efficiency technology or not. The theoretical heating demand is calculated with the current thermal transmittances. After that there are two calculations, one with lower thermal transmittance and one with a more efficient heat recovery unit.

There are three types of heat losses in a building: those occurring through surfaces, those occurring through ventilation and those occurring when there is additional heating need for heating up the leakage air. First, the heat loss through all the structures of the building in a month is calculated. The thermal transmittances and areas of each structure are all obtained from the inputs.

$$Q_{\text{Loss}} = \Delta T \cdot \sum(U \cdot A) \cdot d \cdot 24\ h \tag{8}$$

where Q_{Loss} is the heat loss occurring through the building's structure in Wh/month

ΔT is the temperature difference through the surface, in this case the difference between the average outside temperature of the month and the desired indoor temperature, and

d is the days in a month.

Heat loss from ventilation is the energy loss upon the waste air release. The amount of waste energy can be calculated as follows.

$$Q_{\text{Loss,ventilation}} = c_{\text{P,air}} \cdot \rho_{\text{air}} \cdot q_{\text{V}} \cdot (1 - \eta_{\text{T}}) \cdot \Delta T \cdot d \cdot 24\ h \quad (9)$$

where $Q_{\text{Loss,ventilation}}$ is heat loss through warm waste air flow in Wh/month

q_{v} is the calculated average supply air flow, 20.8 m^3/s, and

ΔT is temperature difference between supply air, 17 °C, and the outside air, whose temperature varies each month.

The temperature efficiency varies according to outside air temperatures, but in the calculations it is assumed to be constant. The assumption results in some inaccuracy in the results.

Leakage air coming to a building through tiny gaps in the structures needs to be heated as well. The heat loss to leakage air can be calculated with the air leakage rate, which can be obtained with an airtightness measurement of a 50 Pa difference between the indoor and outdoor pressure. For the case building the air leakage rate, q_{50} = 4 $m^3/(hm^2)$, is obtained from the *EPC*. The value in EPC is a typical estimation and it is likely not based on real measurements. The following equations (10) and (11) are obtained from Decree of Environmental Ministry (2017a), section 17 and 25.

$$q_{\text{V,Leakage air}} = \frac{q_{50}}{3600 \cdot x} \cdot A_{\text{Surface}} \quad (10)$$

where $q_{\text{V,Leakage air}}$ is the leakage air flow rate in m^3/s

q_{50} is the air leakage rate in m^3/hm^2, and

A_{Surface} is the overall area of outside surface of the building in m^2.

The factor for stories, *x*, converts the measured q_{50} to a lower pressure difference in a normal situation in the building (Immonen, 2013, p. 65). From the leakage air flow rate the heat loss through leakage air is calculated as follows.

$$Q_{\text{Loss,leakage air}} = \rho_{\text{air}} \cdot c_{\text{p,air}} \cdot q_{\text{V,Leakage air}} \cdot d \cdot 24\ h \quad (11)$$

where $Q_{\text{Loss,leakage air}}$ is the heat flux needed to heat the leakage air in Wh

ρ_{air} is the density of air in kg/m^3, and

$c_{\text{p,air}}$ is the specific heat capacity of air in J/kgK.

Heat load of the building is calculated with the known heat load sources in the building. The heat loads are humans, lights, appliances and solar radiation. Human sourced heat load as well as appliance and lighting sourced heat loads are assumed to be standard throughout the year, only affected by the fact that the amount of days in a month varies. The heat load of humans and appliances can be calculated with the inputs from Energy Efficiency Legislation and Instruction.

$$Q_{\text{Load,standard}} = n_{\text{Capacity}} \cdot n_{\text{Time of use}} \cdot \left(W_{\text{Humans}} + W_{\text{Appliances}} + W_{\text{Lights}}\right) \cdot A_{\text{Net}} \cdot d \cdot 24 \quad (12)$$

where $Q_{\text{Load,standard}}$ is the heat load by humans in Wh/month

n_{Capacity} is the capacity usage of the building, lighting and the appliances

W_{Humans} is the heat load factor for humans in W/m^2

$W_{\text{Appliances}}$ is the heat load factor for appliances in W/m^2

W_{Lights} is the heat load factor for lighting in W/m^2, and

A_{Net} is the heated net area in m^2.

Solar radiation heat load varies throughout the year. The radiation coming through the building's windows can be calculated as follows. Curtains are not taken into account, thus the coefficient for the curtains' shadowing effect is 1.

$$Q_{\text{Load,sun}} = \sum\left(g_{\text{Perpendicular}} \cdot G \cdot F \cdot A_{\text{Windows}}\right) \cdot d \cdot 24\ h \quad (13)$$

where $Q_{\text{Load,sun}}$ is the heat load from sun in Wh/month

$g_{\text{Perpendigular}}$ is the coefficient for transmission of perpendicular solar radiation through the window (Ympäristöministeriö, 2012)

G is the radiation from the sun in a month in kWh/m^2, and

F is the total shadowing coefficient affected by the solar inclination angle, ring shadowing and curtains, if present.

The ring shadowing coefficient is not studied separately, so it is assumed to be the reference value of 0.75 (Ympäristöministeriö, 2018, p. 32). Only the heat load through the windows is considered in the Energy Efficiency Legislation. In reality, the walls and the roof will warm up in the sun as well. The radiation from the sun in a month from every direction and the shadowing coefficients are obtained from the instructions and examples of calculating the heat loads of a building, presented in Table 12 and Table 13 (Ympäristöministeriö, 2017a).

Table 12. The solar radiation from different directions for weather districts I and II (Ympäristöministeriö, 2011). Lappeenranta belongs to district II.

[kWh/m^2]	North	North-East	East	South-East	South	South-West	West	North-West
January	6.2	4.7	3.8	9.5	12.9	9.5	3.8	4.7
February	17.3	13.8	15.6	31	41.4	30.9	15.6	14
March	40.3	38.1	48.5	75.1	89.5	69.4	43.7	36.9
April	43.9	56.3	79.9	101.1	107.3	101.6	80.6	56.8
May	57.8	82.1	112.8	123.3	116	117.5	104.5	76.3
June	70.6	87.9	109.6	109.9	101.6	110.9	111.2	89.1
July	66.3	91.1	118.8	123.1	115.5	128.6	122.7	91.2
August	50	66.4	91.8	106	100.4	92.8	78.8	61.1
September	32.9	37.5	56.5	83.9	100.5	87.3	59.3	38.1
October	17.9	15.6	17.5	28.3	37	30	18.8	15.7
November	7.2	5.5	5.1	12.3	16.8	12.3	5.1	5.6
December	4.2	3.2	2.6	8.4	11.8	8.8	2.9	3.2

Table 13. The shadowing coefficient F which is due to different angles of inclination of the sun (Ympäristöministeriö, 2018). It is assumed in the reference that there is no shadowing from above or from the sides, and the shadowing inclination of the surroundings is 15 °.

	North	North-East	East	South-East	South	South-West	West	North-West
January	0.98	0.92	0.86	0.805	0.75	0.805	0.86	0.92
February	0.96	0.895	0.83	0.795	0.76	0.795	0.83	0.895
March	0.96	0.895	0.83	0.815	0.8	0.815	0.83	0.895
April	0.93	0.88	0.83	0.83	0.83	0.83	0.83	0.88
May	0.93	0.89	0.85	0.875	0.9	0.875	0.85	0.89
June	0.86	0.845	0.83	0.87	0.91	0.87	0.83	0.845
July	0.9	0.875	0.85	0.88	0.91	0.88	0.85	0.875
August	0.88	0.84	0.8	0.8	0.8	0.8	0.8	0.84
September	0.95	0.89	0.83	0.82	0.81	0.82	0.83	0.89
October	0.96	0.905	0.85	0.805	0.76	0.805	0.85	0.905
November	0.96	0.91	0.86	0.795	0.73	0.795	0.86	0.91
December	0.98	0.955	0.93	0.83	0.73	0.83	0.93	0.955

In the Lappeenranta City Hall there is shadowing from sides, so in reality, the load from solar radiation is lower than calculated. There is a possibility in the Excel-tool to decrease only some of the window's thermal transmittance. From the calculated heat losses and heat loads, the theoretical heating demand can be obtained as follows.

$$Q_{\text{Theoretical}} = Q_{\text{Loss,structure}} + Q_{\text{Loss,ventilation}} + Q_{\text{Loss,air leakage}} - Q_{\text{Load,standard}} - Q_{\text{Load,sun}} \quad (14)$$

where $Q_{\text{Theoretical}}$ is the theoretical heating demand in Wh/month.

5.1.1 Results of insulation and ventilation calculation

The initial values of indoor temperature and supply air temperature are 21 °C and 18 °C respectively. Usually the supply air temperature is a bit lower than the desired room temperature. Results of the heat loss and heat load calculations are collected to Table 14.

Table 14. The theoretical space heating demand with the indoor temperature of 21 °C and supply air temperature of 18 °C.

	Heat loss, structure	Heat loss, ventilation	Heat loss, leakage air	Heat load, humans and appliances	Heat load, solar	Theoretical space heating demand
	MWh	MWh	MWh	MWh	MWh	MWh
January	142	303	0.031	53	4	388
February	122	259	0.029	48	12	321
March	117	243	0.025	53	29	278
April	83	163	0.019	51	41	153
May	48	79	0.010	53	53	22
June	31	39	0.007	51	53	0
July	14	−2	0.003	53	58	0
August	25	23	0.005	53	41	0
September	47	77	0.011	51	32	41
October	81	158	0.018	53	12	174
November	97	196	0.022	51	5	238
December	122	257	0.027	53	3	324
	927	1794	0.207	619	343	1938

The results show that the calculated theoretical space heating demand in Lappeenranta City Hall is 22 % more than the real demand, 1 587 MWh/y. The reasons can be, for example, that the ventilation is not used as it is said it would be used, or that the ventilation

supply temperature is not the assumed one. Furthermore, it should be taken into account, that the reference demand is a demand from one year and the theoretical demand is calculated with ten past year's average temperatures. The next calculations, shown in Table 15, are made with a lower indoor air temperature of 18 °C and supply air temperature of 17 °C.

Table 15. The theoretical space heating demand with the indoor temperature of 18 °C and the supply air temperature of 17 °C. The reference year's space heating demand is presented for comparison in the column far right.

	Heat loss, structure	Heat loss, ventilation	Heat loss, leakage air	Heat load, humans and appliances	Heat load, solar	Theoretical space heating demand	Real space heating demand in 2017
	MWh	MWh	MWh	MWh	MWh	MWh	MWh
January	127	291	0.028	53	4	361	243
February	108	248	0.026	48	12	297	229
March	102	231	0.022	53	29	251	195
April	68	151	0.015	51	41	127	164
May	33	68	0.007	53	53	0	83
June	16	28	0.004	51	53	0	42
July	−1	−14	0.000	53	58	0	17
August	10	11	0.002	53	41	0	22
September	32	66	0.007	51	32	15	64
October	66	146	0.014	53	12	147	134
November	82	185	0.019	51	5	212	189
December	108	245	0.023	53	3	297	204
	752	1655	0.168	619	343	1708	1587

When the desired indoor air temperature is lowered to 18 °C and the supply air temperature to 17 °C, the calculated theoretical demand meets the real space heating demand with eight percentage difference. This difference is acceptable because the theoretical values are calculated with the 10 past years' temperatures whereas the real

demand is from year 2017. As seen in Table 8, the temperatures in 2017 are higher in the winter time than in the past 10 years' average, which results in lower heating demand for the year 2017 when compared to the calculated value. All the following calculations are made with the assumption of lower temperature of 18 °C indoors and supply air temperature of 17°C.

The theoretical demand is yet distributed differently. In the real situation there is some space heating demand in the summer but the calculations show no demand for space heating in the summer time, which is due to the monthly assessment. However, the theoretical heating demand shows higher demands in the winter than the real measurements. The difference is most likely due to the normalization. The negative heat losses in structure and ventilation mean that the temperature difference's direction is changed and that outside air is warmer than inside, and thus the temperature difference causes a heat load instead of a heat loss. In theoretical heating demand the cooling need is not taken into account, which means there is a restriction in the model that the theoretical heating demand cannot be below zero.

The results show that the effect of the leakage air heat loss is small compared to the other heat losses. The share of ventilation heat loss is twice as much as the other heat losses, therefore the heat recovery unit has a major effect on the final heating demand, as visualized in Figure 7.

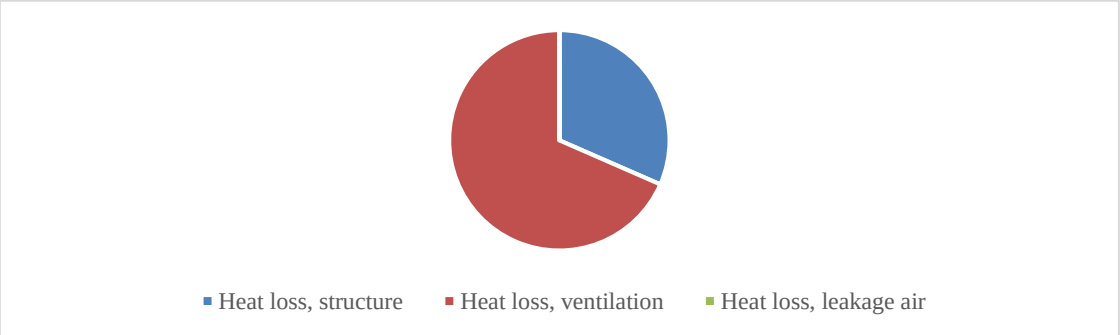

Figure 7. The share of ventilation heat loss is dominant, about 69 % of the total heat losses of the building. The share of structural heat losses is 31 %. The leakage air has a minor share not visible in the picture.

When deciding whether to decrease the thermal transmittance of windows, walls, or both, the heat loss through each structure determines the structures which have the biggest effect, presented in Figure 6. The major part of structural heat loss, 45 %, is occurring through the windows, and the second largest part through the walls. The theoretical heating demand is calculated with new windows with thermal transmittance of 1.0 W/m^2K (Rakennustieto Oy, 2014, p. 71). The result for the theoretical heating demand with new windows is presented in Figure 8.

The temperature efficiency of the heat recovery unit can be, for example, up to 85 % (FläktGroup Finland Oy, n.d.). In this study, the temperature efficiency is raised to 70 % from current value of 37 %. The result for the theoretical heating demand with a new heat recovery unit is presented in Figure 8.

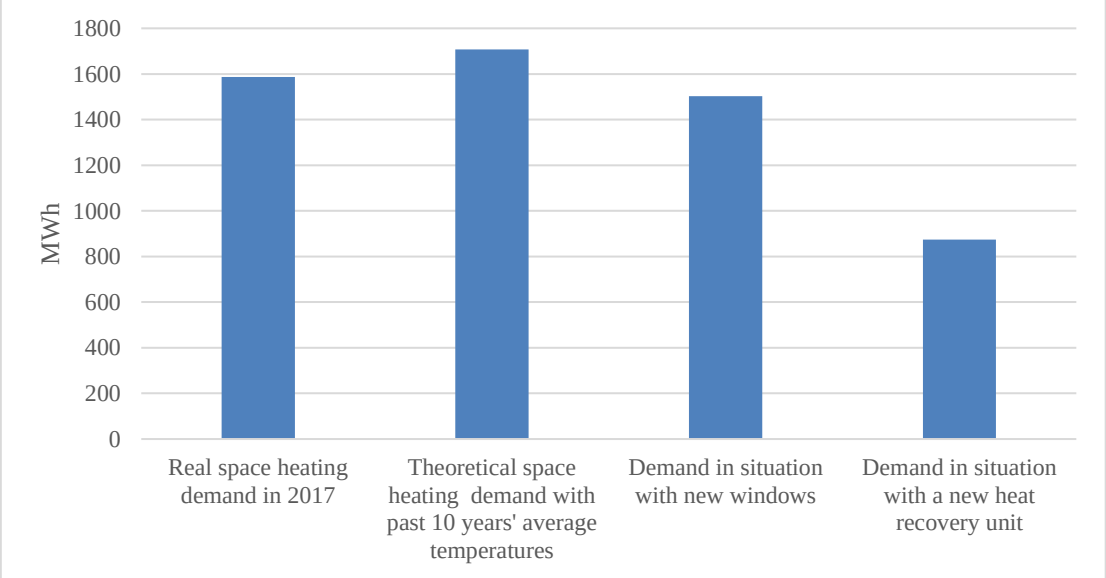

Figure 8. The real space heating demand from reference year as well as the theoretical heating demands in three different situations: current situation, with new windows and with a new heat recovery unit.

The result show that there is potential to save 205 MWh per year when replacing the windows with more efficient ones, and 834 MWh savings potential per year when

changing the heat recovery unit to a more efficient one. The comparison is made between the theoretical space heating demand and new calculated heat demands.

5.2 Heat pump and the radiator network

The heat pump's performance depends on the temperature of the heat source and the needed output temperature. Theoretical *COP* for heating is calculated as follows.

$$COP = \frac{T_{\mathrm{H}}}{T_{\mathrm{L}} - T_{\mathrm{H}}} \tag{15}$$

where T_{H} is the higher temperature, the temperature of the working fluid in Kelvin, and

T_{L} is the lower temperature, the temperature of the source of the heat, ground, water or air, in Kelvin.

The temperature in the ground stays stable throughout the year, but the air temperature varies drastically. Because the *COP* depends on the temperature of the heat source, for ground source heat pump the average *COP* is higher in the winter time than for the air-sourced heat pumps.

The theoretical *COP* polynomial function is calculated and drawn as a function of temperature difference between a heat source and the working fluid according equation (15). The real *COP* cannot be greater than the theoretical *COP*. The real *COP* values both for air source heat pump and for ground source heat pump are drawn to Figure 9. The reference values used for air sourced heat pump are from a VTT report, and they are measured in a test from a real air-to-air heat pump (VTT Expert Services Oy, 2018). The measured *COP* includes defrost periods typical for an air source heat pump, which are not occurring when using a ground source heat pump. For ground source heat pump the reference values of *COP* are from a journal article (Valizade, 2013). The two green dots are *COP* values stated by a *GSHP* manufacturer (NIBE Energy Systems, n.d.), and they seem to be very close to the reference values from the article.

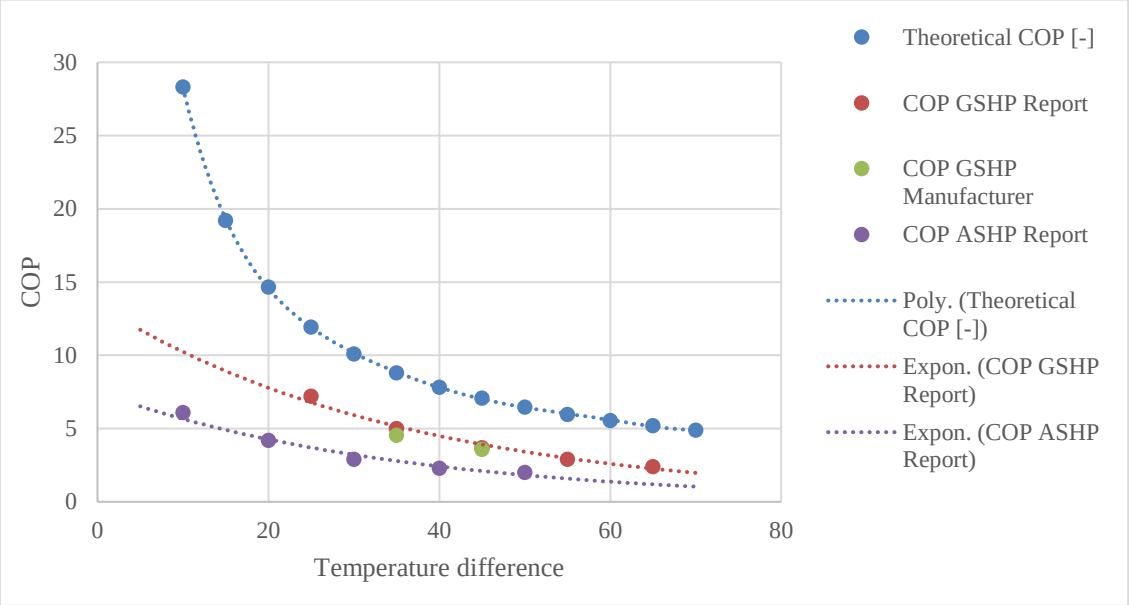

Figure 9. The theoretical *COP* as well as real *COP*s for a ground source heat pump (Valizade, 2013) and an air source heat pump (VTT Expert Services Oy, 2018) as a function of temperature difference of heat source and heat sink.

Figure 9 shows that an increase in the temperature difference decreases the *COP*. An exponential function is fit to each of the value set. The functions are extrapolated, because there are values for only a given range of temperature difference. The extrapolation adds uncertainty to the results.

Although the site of Lappeenranta City Hall is not the most feasible for ground source heat pump installation, the calculations for *GSHP* are made in order to make a *GSHP* investment comparable for further use of the tool. Furthermore, the ground source heat pump's effects on energy efficiency and its profitability can be estimated. In addition, if there is a water area nearby the building as a feasible heat source, the temperature of the ground can easily be replaced by water source temperatures.

The target is to account the electricity consumption of the heat pump monthly. The electricity consumption can be calculated as follows.

$$E_{\text{Electricity}} = \frac{Q_{\text{Heat}}}{COP} \tag{16}$$

where $E_{\text{Electricity}}$ is the electricity consumption of the heat pump in kWh, and

Q_{Heat} is the need of heat energy in kWh.

The *COP* values are calculated with either of the exponential function obtained from the Figure 9. In the model, the *COP* is restricted so that it does not get values under one, although the exponential function will also get values under one.

$$\begin{cases} COP_{GSHP} = 13.468 \cdot e^{-0.027 \cdot \Delta T} \\ COP_{AWHP} = 7.5125 \cdot e^{-0.028 \cdot \Delta T} \end{cases} \quad (17)$$

where ΔT is the temperature difference between the heat source and the heat sink.

The ground temperature in Finland in a depth of 200 m varies between +2 and +8 °C depending on the time of the year (Kukkonen, 2000, p. 278). In this study the ground temperature is assumed to be +5 °C throughout the year. The past 10 years' average temperatures of outside air are utilized, Table 8. The temperature of the working fluid must be calculated ensuring that the heat flux is enough to keep the building warm. Thus in colder times the working fluid temperature will be higher than in the summer. In addition, the heat transfer system affects the temperature of the working fluid. In underfloor heating there is more area for heat transfer, which leads to lower temperature of the working fluid than in radiator-based heat transfer.

When the radiator network is working with a district heat source, the inlet temperature of the working fluid coming into the radiator is usually 70 °C, 80 °C or 90 °C and the outlet temperature is correspondingly 40 °C, 50 °C or 70 °C. The inlet and outlet temperatures have been decreasing due to safety reasons, and nowadays the sizing temperatures are usually 70 °C and 40 °C. The sizing temperatures in Lappeenranta City Hall are 80 °C and 50 °C according to the heating blueprints.

The radiators are dimensioned to provide the heat for the room with the inlet water flow in design temperature. The heat left is lead with the outlet flow back to the heat exchanger

and to the district heating plant. In district heating system the outlet temperature from the radiator varies according to how much heat is needed.

In the case of a heat pump as a heat source, the inlet temperature to the radiator is lower than in district heating system, because of the heat pump's optimum working curves. The heat pump has a maximum temperature, for example 65 °C, which it can produce. Thus the heat pump should be running so that the temperature difference between the working fluid and the heat source is as low as possible. Temperature difference optimization leads to the situation that with a heat pump, only the needed heat is produced, and the inlet temperature of the radiator is varying in contrast to the variating outlet temperature of the district heating system.

In principle, if the radiator area is greater, the temperature of the working fluid can be lower, and consequently the electricity need of the heat pump decreases because of the higher *COP* in lower temperature difference.

The working fluid temperature is needed to establish the *COP*, and it is calculated via the needed heat transfer from the radiators to keep the building at a desired temperature.

$$\frac{0.5 \cdot Q}{d \cdot 24\,\mathrm{h}} = A \cdot \varepsilon \cdot \sigma \cdot (T_s^4 - T_\infty^4) \qquad (18)$$

where Q is the needed heat energy to keep the building warm, in Wh

d days in the examination period, now in a month

A is the heat transfer area, for Lappeenranta City Hall estimated to be 1 208 m^2

ε is the emissivity of the radiator, now assumed to be 1 according to Seppänen (2001, p. 166)

σ is the Boltzmann constant, $5.67 \cdot 10^{-8}$ W/(m^2K^4)

T_s is the mean surface temperature of the radiator in Kelvin, and

T_∞ is the needed indoor temperature in Kelvin.

The required temperature for radiation heat transfer is obtained with the equation (18). The factor 0.5 for heat energy, *Q*, is because the equation only accounts for the radiation heat transfer, see Table 9. The projection in radiation heat transfer is not taken into account for simplification.

A radiator transfers heat to the room air by radiation as well as by convection heat transfer. The temperature needed for convective heat transfer is also estimated as follows.

$$\frac{0.5 \cdot Q}{d \cdot 24\ \mathrm{h}} = A \cdot \alpha \cdot (T_\mathrm{s} - T_\infty) \qquad (19)$$

where α is the heat transfer coefficient W/m^{2}K.

As in the radiation heat transfer calculation, the factor 0.5 for heat energy, *Q*, is because the equation is made for the convection heat transfer part.

In natural convection, the heat transfer coefficient is under 10 W/m^{2}K. On a radiator's surface colder air rises from the bottom of the panel in laminar flow, which turns to turbulent flow between the heights of 0.3–1.5 m of the panel (Seppänen & Seppänen, 1997, p. 61–63). In practice the radiator's temperatures and other measures are sized so that the flow turns turbulent. In a turbulent flow the heat transfer coefficient is in range of 10–100 W/m^{2}K (Seppänen & Seppänen, 1997, p. 61–63). For a 300 mm high radiator panel, the value 10 W/m^{2}K is used. A more precise value for the convective heat transfer could be obtained from precise heat transfer calculations.

The average temperature is calculated as a weighted average of the temperature of the convection heat transfer and the temperature of the radiation heat transfer with the information of the shares of both heat transfer types. The calculated temperature is the mean temperature of the radiator's surface. It is assumed that for a radiator the average surface temperature equals the average working fluid temperature. The working fluid comes into the radiator in a higher temperature and leaves in a lower temperature after

the heat transfer. Thus the temperature which the heat pump needs to generate is higher than the average temperature of the working fluid.

The outlet flow temperature is assumed to be the same as in the room, 18 °C. In reality, the heat transfer has always a temperature difference, so the outlet working fluid will be in a higher temperature than the room air. The power output and the effects of the existing radiator's sizing are not taken into account and their precise effect on the results are left for further research. From the average working fluid temperature, the inlet temperature of the working fluid is calculated as follows.

$$T_{\mathrm{Inlet}} = T_{\mathrm{Average}} + (T_{\mathrm{Average}} - T_{\mathrm{Outlet}}) \quad (20)$$

Temperature of working fluid is calculated for each month of the year with the theoretical heating demand. The results of the working fluid temperature is an estimate due to the simplifications made.

The monthly *COP* values are calculated from the working fluid temperatures. In reality, the demand varies due to varying of outdoor temperature hourly. It is assumed that the heat pump electricity demand would be stable throughout each month for simplicity. The electricity demand of the heat pump is presented also in hourly range for further use in the electricity demand assessment.

DHW heating is studied separately from space heating. The value of 55 °C is chosen for temperature of *DHW*. The electricity demand needed for *DHW* heating is added to the electricity demand for space heating to obtain the total electricity demand of the heat pump.

The working fluid temperature, *COP* and the electricity demand of an *AWHP* is calculated the same way as for the *GSHP* above. The only difference is the reference temperature for *COP* calculation which is now the average outside air temperature. The change of the heat source in the calculations affects the results so that the air source heat pump needs more electricity to function than the ground source heat pump.

Underfloor heating can be calculated almost in the same way as the radiator heating. One difference is that the share of the heat warming the surrounding structures of the floor must be taken into account. The results of underfloor heating temperature calculations are not presented, because in the case building, the underfloor heating is not the main heat distribution way.

5.2.1 **Results of heat pump calculation**

The working fluid temperatures in the radiator network are calculated with a radiator area value of 1 208 m2, and the results are shown in Table 16. The values are calculated for the theoretical heating demand in current situation in order to make the results comparable to the theoretically calculated values with energy efficiency improvements. The values for the working fluid temperature are valid for a GSHP as well as AWHP system.

Table 16. The average working fluid temperature calculation with 50 % to 50 % radiation and convection share in heat transfer, and results for maximum working fluid temperature on the far right.

Month	Average working fluid temperature, radiation °C	Average working fluid temperature, convection °C	Average working fluid temperature °C	Maximum working fluid temperature °C
January	48.7	38.1	43.4	68.8
February	46.3	36.3	41.3	64.6
March	40.3	32.0	36.1	54.2
April	30.3	25.3	27.8	37.6
May	18.0	18.0	18.0	18.0
June	18.0	18.0	18.0	18.0
July	18.0	18.0	18.0	18.0
August	18.0	18.0	18.0	18.0
September	19.5	18.9	19.2	20.4
October	31.6	26.2	28.9	39.8
November	37.7	30.2	33.9	49.9
December	43.9	34.5	39.2	60.4

The radiator inlet temperature is calculated to be from a maximum of 68.8 °C in the winter to as low as 18 °C in the summer. As the assumption is made that the outlet temperature of the radiator is the same as the room temperature, 18 °C, the months with 18 °C as maximum working fluid temperature in space heating do not actually need any heating. In reality, there is need for space heating also in May, June, July and August, which is seen in the reference year's demands. In these calculations, those months only have demand for *DHW* heating, because of the simplification in monthly assessment of the heating demand. Furthermore, room specific requirements, for example wet room heating, are not taken into account in this study. In further studies the heating demand should be taken into account on an hourly basis to obtain more precise results.

The temperature differences as well as the results for *COP* values and the electricity demand of a *GSHP* are presented in Table 17.

Table 17. The temperature differences to ground and *COP* values for space and *DHW* heating in a *GSHP* system in current situation.

Month	Temperature difference of *GSHP* system, space heating	*COP*, space heating	Temperature difference of *GSHP* system, *DHW* heating	*COP*, *DHW* heating	Electricity demand in current situation, MWh
January	63.8	2.4	50.0	3.5	152.2
February	59.6	2.7	50.0	3.5	112.1
March	49.2	3.6	50.0	3.5	72.3
April	32.6	5.6	50.0	3.5	24.7
May	13.0	9.5	50.0	3.5	1.9
June	13.0	9.5	50.0	3.5	1.3
July	13.0	9.5	50.0	3.5	1.1
August	13.0	9.5	50.0	3.5	1.5
September	15.4	8.9	50.0	3.5	3.4
October	34.8	5.3	50.0	3.5	30.1
November	44.9	4.0	50.0	3.5	54.9
December	55.4	3.0	50.0	3.5	100.5
					555.8

The *COP* values for *DHW* heating are stable throughout the year, because the temperature difference between the ground and the *DHW* is stable. In reality, the temperature of the ground varies a bit, as stated before.

Electricity demand of the *AWHP* can be calculated the same way as for the *GSHP*. The results for working fluid temperature presented in Table 16 are relevant for the *AWHP* system as well. Therefore the remaining calculations are made for temperature differences between the heat source, the outside air, and the heat sink, as well as the *COP*s and the electricity demand. The results are presented in Table 18.

Table 18. The temperature differences to ground and coefficient of performance for space heating and *DHW* heating in an *AWHP* system.

Month	Temperature difference of A*WHP* system, space heating	*COP*, Space heating	Temperature difference of A*WHP* system, *DHW* heating	*COP*, *DHW* heating	Electricity demand in current situation, MWh
January	76.4	1.0	62.6	1.3	366.5
February	70.9	1.0	61.3	1.4	292.2
March	56.8	1.5	57.6	1.5	168.3
April	33.8	2.9	51.2	1.8	47.5
May	6.7	6.2	43.7	2.2	3.0
June	3.4	6.8	40.4	2.4	1.8
July	−0.2	7.6	36.8	2.7	1.4
August	2.0	7.1	39.0	2.5	2.0
September	9.1	5.8	43.8	2.2	5.2
October	35.2	2.8	50.3	1.8	56.5
November	49.0	1.9	54.2	1.6	115.8
December	64.1	1.2	58.7	1.5	243.2
					1303.3

Because the outside air temperatures are lower than the temperatures of the ground, the temperature differences are higher and the *COP* values lower for the *AWHP* system, which results in higher electricity demand for an *AWHP* compared to a *GSHP*. The electricity demand results of both a *GSHP* and an *AWHP* are visualized in Figure 10.

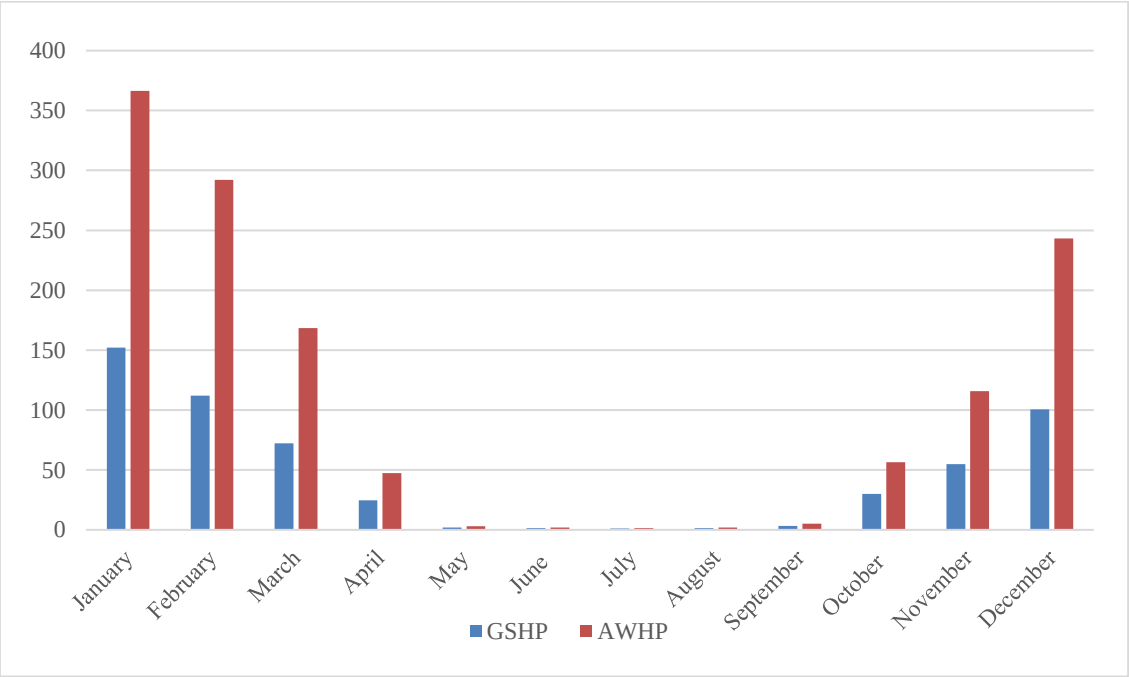

Figure 10. A *GSHP* and an *AWHP* electricity demands in current situation.

Similar calculations are made for a situation with new windows with thermal transmittance of 1 W/m^{2}K and for a situation with new heat recovery unit. The exact results for working fluid temperatures and *COP* values are presented in Appendix I. The results for monthly electricity demands are presented in Table 19 for a *GSHP* and Table 20 for an *AWHP*.

Table 19. A *GSHP* electricity demand in a situation after window renovation, in a situation with a new heat recovery unit and in the current situation for comparison.

Month	*GSHP* electricity demand in current situation MWh	*GSHP* electricity demand after window renovation MWh	*GSHP* electricity demand with a new heat recovery unit MWh
January	152.2	125.1	51.6
February	112.1	90.3	37.0
March	72.3	55.7	22.5
April	24.7	17.4	6.1
May	1.9	1.9	1.9
June	1.3	1.3	1.3
July	1.1	1.1	1.1
August	1.5	1.5	1.5
September	3.4	1.7	1.7
October	30.1	24.6	11.4
November	54.9	46.1	21.3
December	100.5	83.7	36.6
	555.8	450.3	193.9

Table 20. An *AWHP* electricity demand in a situation after window renovation, in a situation with a new heat recovery unit and in the current situation for comparison.

Month	*AWHP* electricity demand in current situation MWh	*AWHP* electricity demand after window renovation MWh	*AWHP* electricity demand with a new heat recovery unit MWh
January	366.5	335.5	137.6
February	292.2	234.4	94.7
March	168.3	129.1	51.4
April	47.5	33.3	11.7
May	3.0	3.0	3.0
June	1.8	1.8	1.8
July	1.4	1.4	1.4
August	2.0	2.0	2.0
September	5.2	2.7	2.7
October	56.5	46.1	21.2
November	115.8	96.8	44.4
December	243.2	201.9	87.1
	1303.3	1088.0	459.1

The ratios between the electricity demand of the *GSHP* and the reference theoretical heating demands are decreasing as the theoretical heat demand decreases. In the current situation for *GSHP* it is 31 %, whereas the same ratio for situation after window renovation is 29 % and after the heat recovery renewal 20 %. For *AWHP* the ratios are 73 %, 69 % and 48 % respectively. The decrease of the ratio is due to the decreasing temperature needed in order to heat the building, which leads to higher *COP* values. The results for yearly electricity demands are visualized in Figure 11.

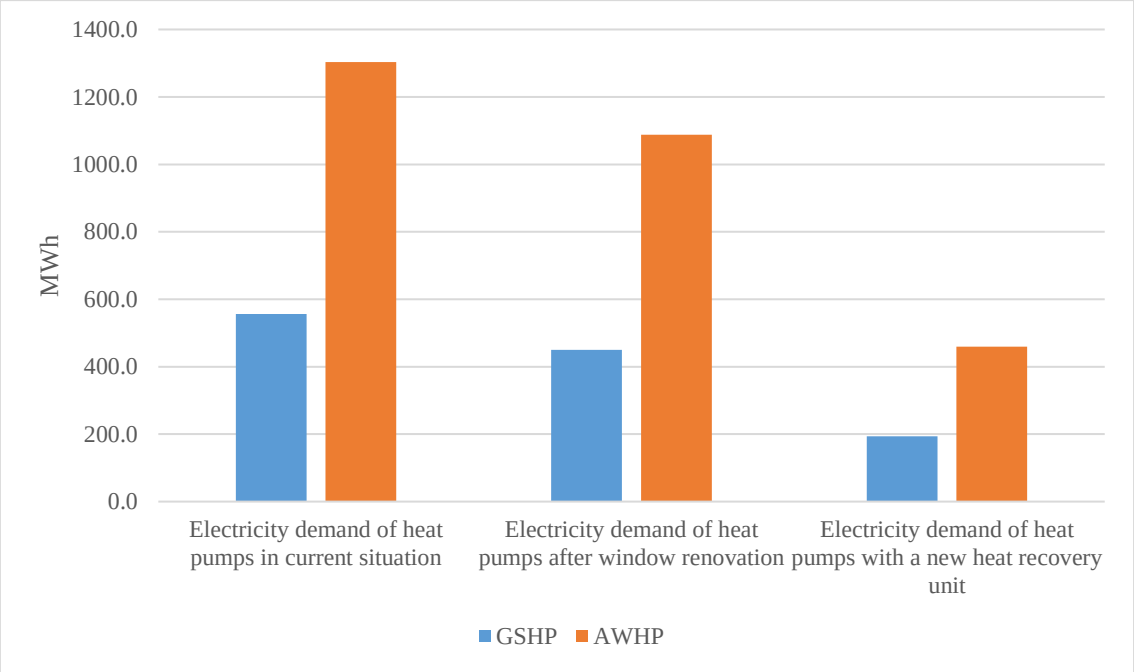

Figure 11. The electricity demands of *GSHP* and *AWHP* in current situation, after window renovation and with a new heat recovery unit.

The results show that the lowest electricity demand in a year for a heat pump is in a situation with new heat recovery unit with a ground source heat pump. The electricity demand of an *AWHP* is over twice as much as the electricity demand of a *GSHP*.

5.3 Solar photovoltaic panels

A limiting factor for solar *PV* is the available roof area in the case building. The roof area should be non-shaded. An important constraint for a rooftop *PV* system is the demand of

the building, which determines how much of the production energy can be used in the location. It is widely recognized that it is preferable to use as much of the produced electricity as possible in the production location.

Different methods for sizing the solar *PV* system are baseload sizing, peak load sizing, average summer day load sizing, average annual consumption with net zero energy goal, electricity self-sufficiency, the available non-shaded roof area as a constraint and available financial resources as a constraint (Motiva Oy, 2018b). A study by Simola, et al., (2018) states, that oversizing the solar *PV* system from optimum does not decrease the Internal Rate of Return (*IRR*) remarkably. In this study, the sizing is made based on the available rooftop area: the whole non-shaded available area is covered with panels. The optimization of the plant size is left for further research.

The solar *PV* production data is simulated with *Homer Beta 2.68* in Lappeenranta for a 15 ° tilt angle. The data is obtained hourly and in unit of kWh/kW_p. The data for *PV* production and usage is considered on an hourly basis because of the variable nature of solar production. The hourly solar *PV* production is calculated with the input data of available roof area. From the reference module (Canadian Solar, n.d.) a peak kilowatt can be obtained from a 5.85 m^2 panel area.

$$P_{PV} = \frac{A_{\mathrm{Roof}}}{P_{\mathrm{kWp/m2}}} \tag{21}$$

where P_{PV} is the power of the roof top system in kW_p

A_{Roof} is the available non-shadowed roof top area in m^2, and

$P_{kWp/m2}$ is the power from the reference panel that can be obtained in one square meter in kW_p/m^2.

The hourly *PV* production can be calculated from the simulated data as follows.

$$E_{PV} = P_{PV} * E_{\mathrm{kWh/kWp}} \tag{22}$$

where E_{PV} is energy produced by the panel system in an hour in kWh

$E_{kWh/kWp}$ is simulated energy production from a peak kilowatt system in kWh.

When the hourly energy production of the *PV* plant is known, it is compared to the hourly electricity demand of the building to calculate the amount of energy which can be used by the building itself. Furthermore, the calculated electricity demand for the heat pump must be considered in the building's electricity demand. The hour-based demand assessment is more accurate than a monthly assessment because of the variation of the *PV* production and the electricity demand.

5.3.1 Results of solar *PV* calculation

For a 300 m^2 rooftop area with a fill rate of 70 %, a 36 kW_p system can be installed. The modelling data is for 15 ° panel inclination and to direction south. Due to the orientation of the building, the *PV* plant would likely be installed in direction of south-west or south-east, which will decrease the electricity production. However, according to Korhonen (2016, p. 19), changing the *PV* plant direction between south-west and south-east does not decrease the production remarkably. The total monthly production of the *PV* plant is presented in Figure 12.

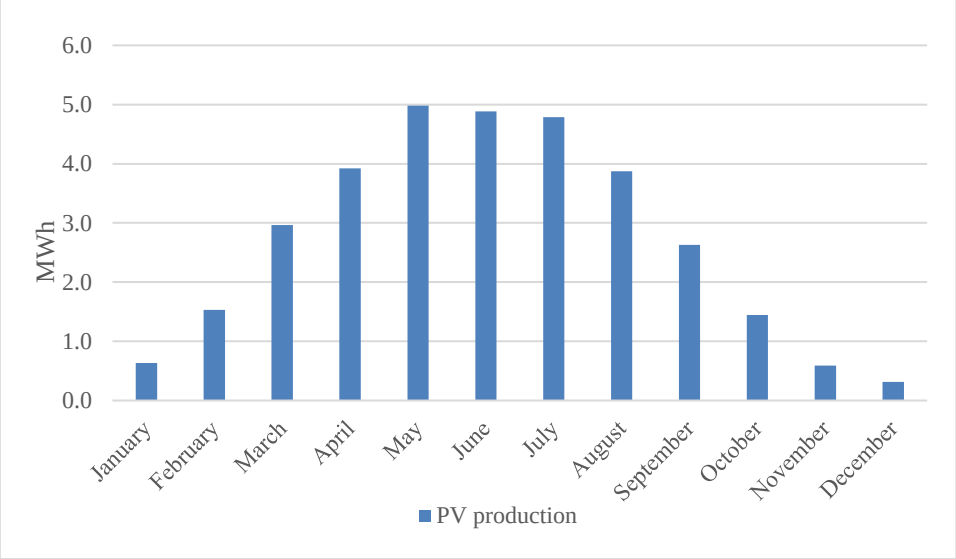

Figure 12. *PV* production of a 36 kW_p sized *PV* plant on the roof of Lappeenranta City Hall.

The *PV* production shown in Figure 12 is studied hourly in order to obtain precise information about the share of the production which cannot be used directly in the case building. The production of the *PV* plant as well as the own usage of the production is presented in Table 21.

Table 21. The production of the *PV* plant and its effect on the electricity purchase.

Month	Current electricity consumption MWh	Total production of the *PV* plant MWh	Own usage of the *PV* production MWh	New electricity purchase after the *PV* system investment MWh
January	63	0.6	0.6	63
February	56	1.5	1.5	54
March	63	3.0	3.0	60
April	58	3.9	3.9	54
May	65	5.0	5.0	60
June	65	4.9	4.9	60
July	59	4.8	4.8	54
August	74	3.9	3.9	70
September	60	2.6	2.6	57
October	61	1.4	1.4	59
November	65	0.6	0.6	64
December	60	0.3	0.3	60
Total	748	32.6	32.6	716

The result is that all the production of the *PV* plant can be used on site, because the size of the plant is relatively small.

5.4 Financial assessment

The economic assessment is made without taking into account value added tax. Thus the used investment costs as well as the electricity and district heating price has a *VAT* of 0 %. The required prices for assessment are electricity price for purchasing, electricity price for selling production to grid, and district heat price. The prices are assumed to stay stable in the future for simplification. Electricity price for purchasing is assumed to be 84.09 €/MWh and for selling to the grid 38.65 €/MWh. Price of district heat is 53.58 €/MWh. An additional value needed is interest rate, *i*, and it can be chosen to be 5 % in the

calculations. The interest rate can be moderate, because the studied investments are not very risky. The risk of investment increases the interest rate. All of these values can be changed in the model if needed.

The economic assessment is made by calculating the discounted cumulative net cash flow. An estimation of the payback time can be obtained from the net cash flow. The yearly savings are calculated for every investment. Expenses are obtained from the information about the management cost as a percentage of investment cost. The net savings, the difference of savings and expenses, are discounted to the present year by a discounting coefficient. The discounting coefficient, *a*, for each year is calculated as follows.

$$a = \frac{1}{(1+i)^n} \tag{23}$$

where n is the current year for which the coefficient is calculated.

The discounted net cash flow is the sum of the discounted net cash flow of the previous year and the discounted net savings. For the first year, the last discounted net cash flow is the investment cost. The investment's payback time with the current interest rate can be estimated from the point where the discounted net cash flow turns positive.

The Internal Rate of Return (*IRR*) can be a more feasible tool than the discounted net cash flow for comparing investment options. The *IRR* is the interest rate with which the Net Present Value (*NPV*) of the investment after the chosen examination period would be zero. The *IRR* can be solved from the following equation.

$$NPV = \sum_{n=1}^{N} \frac{I_n}{(1+IRR)^n} = 0 \tag{24}$$

where NPV is the net present value in euros

N is the holding period of the investment in years, and

I_n is the total investment cost in euros.

The *IRR* shows the economical profitability of an investment. Therefore, the profitability of investments can be compared to each other utilizing the *IRR* values.

5.4.1 Results of financial assessment

The yearly production of the *PV* plant is 32.56 MWh, and the investment cost is assumed to be 900 €/MWh (Ahola, 2017), which is the lower limit of the range. The lower value is chosen because the prices have been coming down, and the used reference values are from year 2017. The management costs are assumed to be 0.5 % of the total investment (Simola, et al., 2018). Due to the material of the *PV* panel, the efficiency of the panel decreases every year in use. The decrease is taken into account in the calculation with an assumption of yearly decrease of 0.5 % of efficiency (Simola, et al., 2018).

The yearly savings, S_n, are the difference between the prices paid for yearly electricity demand currently without own production, and with own production. The possible sales are accounted in the savings calculated as follows.

$$S_n = \left(100\ \% - (n-1) \cdot 0.50\ \%\right) \cdot Own\ usage \frac{\text{MWh}}{\text{y}} \cdot 84.09 \frac{€}{\text{MWh}} + (Production - Own\ usage) \cdot 38.65 \frac{€}{\text{MWh}} \quad (25)$$

The *PV* plant net cash flow and the *IRR* are calculated twice: first in current situation and second with increased electricity demand. The result for the cumulative discounted net cash flows of the *PV* plant investment are visualized in Figure 13.

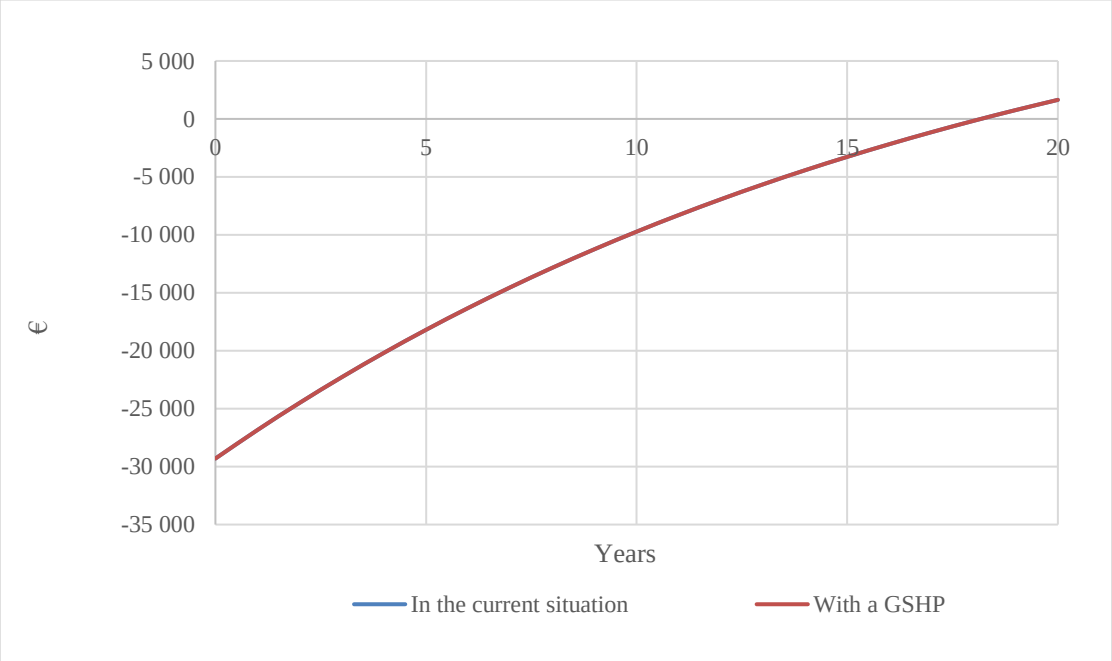

Figure 13. The cumulative discounted net cash flow for the PV plant investment in current situation as well as in situation with more electricity demand, e.g. the heat pump, i = 5 %.

As a result, payback time for this *PV* plant investment with interest rate of 5 % would be a bit over 18 years. The situation with heating from a heat pump results in the same plot curve. The bent shape of the curve results from discounting.

For *PV* system investment in both situations the *IRR* is 5.7 % with an examination period of 20 years. The same values are due to the same amount of own consumption. If the plant would be bigger, there might be some differences in the share of own consumption.

The lifetime of a *PV* panel is usually 20–30 years (Simola, et al., 2018). For example, the reference *PV* panel has a 25 years linear power output guaranteed with 80 % of the original efficiency (Canadian Solar, n.d.). With the information that the *PV* plant will still run after the chosen investment period without major new investments, the investment might get more appealing.

For a heat pump investment, the yearly savings are the difference between the price paid for district heating and the price paid for electricity demand of the heat pump. The cash

flow is calculated in current situation and with a *PV* plant. The *PV* plant lowers the electricity price paid when using the heat pump and thus increases the profit from the investment. With a 36 kW *PV* plant, the electricity price decreases from 84.09 €/MWh to 81.99 €/MWh.

Furthermore, the net cash flow is calculated for situations with lower heat demand: after the window renovation and with a new heat recovery unit. The investment cost of *GSHP* is presented in previous chapter 3.1.3, and in total for a system covering the current demand the investment cost is 373 843 €. The management cost is 1 % of the investment cost (Paiho, et al., 2017, p. 398).

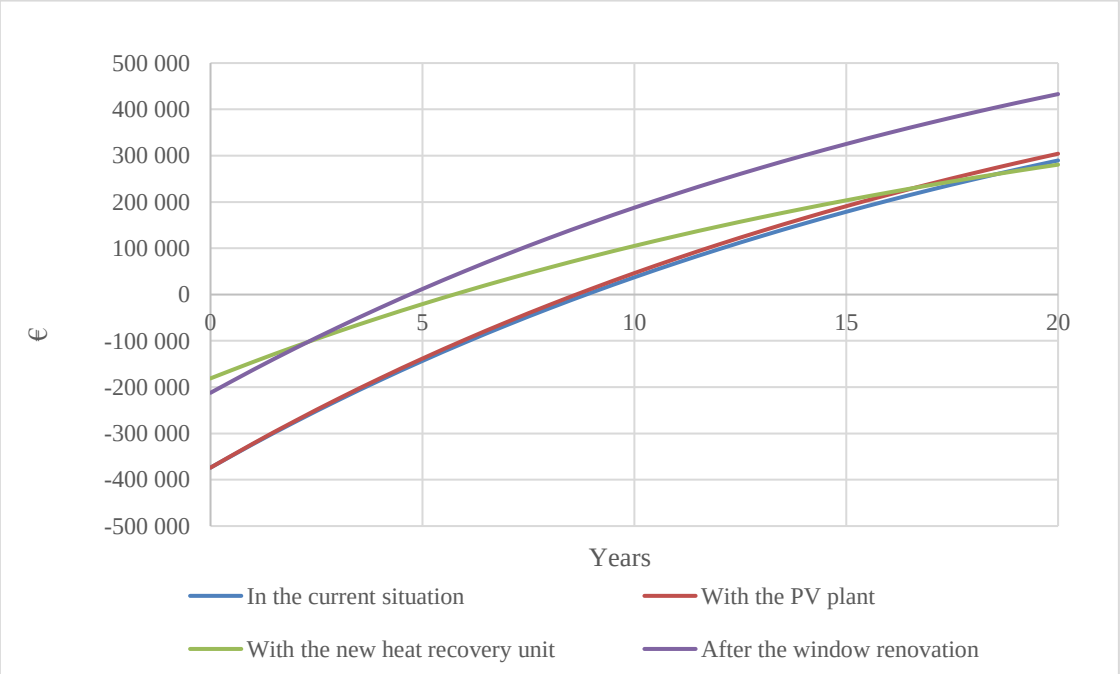

Figure 14. The cumulative discounted net cash flow of the *GSHP* investment in the current situation, with the PV plant, after the window renovation and with the new heat recovery unit, *i* = 5 %.

The reason why the curves in Figure 14 start from different values of y-axis is that the investment cost of the heat pump decreases as the demand decreases.

In the *GSHP* system the *IRR* for the current situation is 13.0 % and for a situation with a *PV* plant 13.4 %. The payback time with a 5 % interest rate is a bit under 9 years for the current situation. In situation with the new heat recovery unit, the heat pump needs less electricity, because the needed temperature is lower and thus the *COP*s are higher. The savings in the cumulative net cash flow are calculated while comparing the situation of the heat coming from a heat pump to the situation where heating comes from district heating with lower heating demand. The *IRR* for *GSHP* with a new recovery unit is 19.9 %. After window renovation the *IRR* is even higher, 24.1 %, although the heat demand is higher than in situation with a new heat recovery unit. The difference can be explained by the investment cost and the fact that the investment of the bore hole decreases as the heat demand decreases, but the investment in joint pipes does not decrease. The yearly management costs, as a percentage of investment cost, effects the net savings and thus the *IRR* value directly.

For the *AWHP* investment a similar calculation is made. The investment cost of *AWHP* pump includes only the heat pump part and unlike the *GSHP*, there is no need for external wells. The investment cost for a 203 kW heat pump is 61 019.28 € according to Haahtela & Kiiras (2015), see Table 2. The cost for an air source outside unit is not mentioned in Haahtela & Kiiras (2015), so it is assumed to be the same as the heat pump cost. The total investment cost is thus 122 038 € in the current situation. The management cost for *AWHP* is 1.5 % of the investment (Paiho, et al., 2017, p. 398). The cumulative discounted net cash flows are presented in Figure 15.

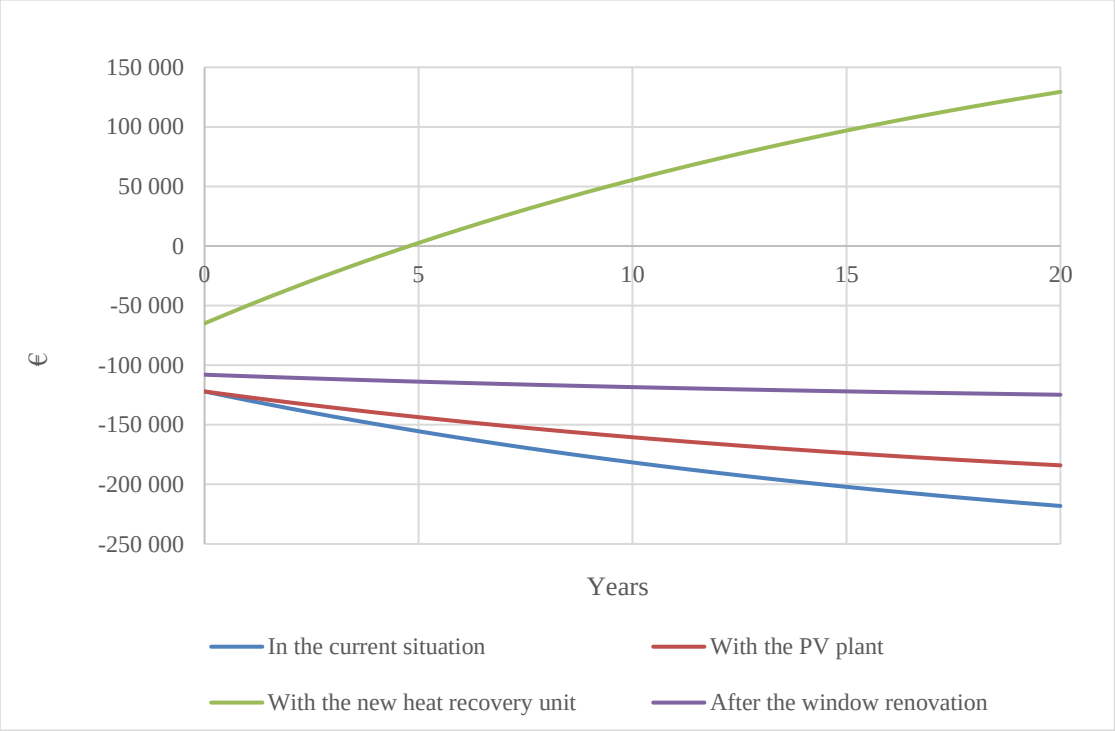

Figure 15. The cumulative discounted net cash flow of the *AWHP* investment in the current situation, with the PV plant, after window renovation and with the new heat recovery unit, i = 5 %.

The *IRR* values for an *AWHP* system in the current situation, in a situation with a *PV* plant and in a situation after window renovation are negative. The Excel-function does not calculate the values because there are no positive values in the net savings. The profitability of the *AWHP* increases in the situation with remarkably lower heating demand in the building with the new heat recovery unit. The electricity demand of an *AWHP* in situation with new heat recovery unit is in the same scale than the electricity demand of a *GSHP* in situation now, as seen in Figure 11. The *IRR* in situation with the new heat recovery unit is 23.7 %. The investment cost for *AWHP* is much lower than for a *GSHP* system because of the additional wells of the *GSHP* system, though *AWHP*'s efficiency is not as good as for a ground sourced system.

The air-to-water heat pump would thus be a feasible solution for crowded city center, if the heat recovery is implemented first in order to decrease the demand. If taking into

account the exact situation of the radiator network, it most likely has to be updated to meet the needs of the heat pump, which will increase the investment cost for both ground and air sourced heat pump.

Decreasing the thermal transmittance of the windows is done by replacing an old window with a new one. The demolition and refuse of the old window costs 26 € per 3.6 m^2 sized window, and a new window with thermal transmittance of 0.9–1.0 W/m^2K costs 258 € per a 1.44 m^2 sized window (Rakennustieto Oy, 2014, p. 71). From this information the total investments of window renovation are calculated. The total investment cost is presented in Table 22.

Table 22. The cost of decreasing the thermal transmittance of windows (Rakennustieto Oy, 2014).

Cost of renovating the windows		Lappeenranta City Hall
Area of windows	m^2	1 421.0
Total cost of demolition of old windows	€/m^2	7.2
New window with U = 0.9-1.0 W/m2K	€/m^2	179.17
Total investment	€	264 831.77

Window renovation profitability is calculated with two options for heating solution, the current solution which is district heating, and a ground source heat pump. The ground source heat pump is chosen to determine lower profitability for comparison with lower electricity demand. The heating demand with a new U value of 1.0 W/m^2K is 1 576 MWh, which results in electricity demand of 450 MWh for the ground source heat pump. The cumulative discounted net cash flows are presented in Figure 16.

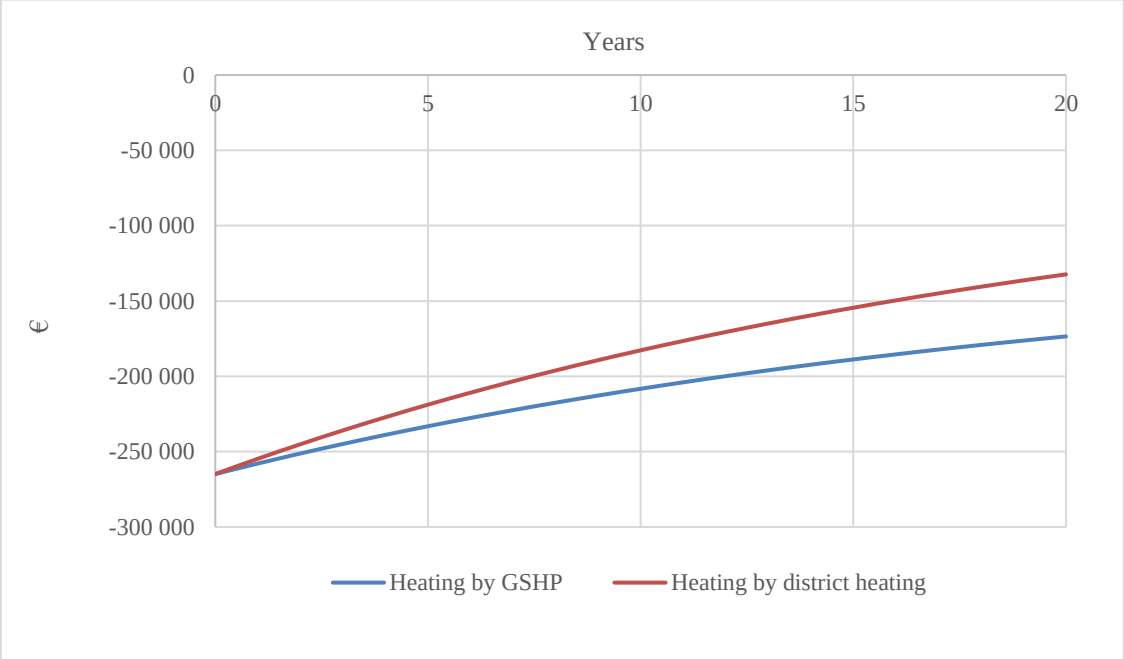

Figure 16. The cumulative discounted net cash flow of the window renovation in the current situation and in a situation with a *GSHP*, i = 5 %.

With the cost information shown in Table 22, operational costs of 0.5 % of investment and the new heating demand, the results for *IRR* are −2.0 % for district heating solution and −5.1 % with a *GSHP*. With a negative *IRR*, the investment is not profitable.

As a reference, the estimations are given for costs when decreasing the wall thermal transmittance. The process of adding insulation to the existing wall is by pulling down the outer part of the wall and building it again with more insulation. Although the insulation material itself does not cost much, about 1 €/m^2, the process is expensive (Vehmas, 2019). The cost of each process step is presented in Table 23.

Table 23. The cost of decreasing the thermal transmittance of walls (Vehmas, 2019).

Cost of renovating the walls		Lappeenranta City Hall
Area of walls	m^2	4 443
Total cost of demolition of old wall	€/m^2	75
New wall with U = 0.17 W/m2K or less	€/m^2	180
Total investment	€	1 132 965.00

The investment cost for adding insulation to the walls is substantially greater than for renovating the windows. When looking at the results of the economical profitability of the window renovation and the share of the heat loss occurring through the wall, it is clear that wall renovation would not be profitable.

For the new heat recovery unit investment, the net cash flow calculation is made twice, with a heat pump and with district heat as the heat source. The investment costs for a heat recovery unit is shown in Table 24. The prices are based on the existing heat recovery unit investments in new building construction sites (Haahtela & Kiiras, 2015), and thus they are not specific for a heat recovery unit with a 70 % temperature efficiency. However, they provide a scale of the investment. It should also be taken into account that the existing ventilation system is from 80's and thus it might not be possible to only change the heat recovery unit. If the whole ventilation system needs to be renovated, the investment costs would be higher.

Table 24. Investment costs for heat recovery units by the air flow and area (Haahtela & Kiiras, 2015). Lappeenranta is in the price area 75.

		Areal price level		
m^3/s		75	81	85
4.0-6.0	€/piece	19 100	20 100	20 800
6.0-10.0	€/piece	25 200	26 500	27 500
10.0-13.0	€/piece	30 500	32 100	33 200

The investment cost can be calculated with 12 supply air units in the case building and average supply air flow of 20.8 m^3/s. The renewal need of the ventilation system is not taken into account. Currently there are many smaller ventilation units, which increases the renewal cost of the heat recovery system. The investment cost of the heat recovery might decrease if the ventilation system is renewed and some ventilation units are combined, thus there will be more and bigger heat recovery units. The cumulative discounted net cash flows are presented in Figure 17.

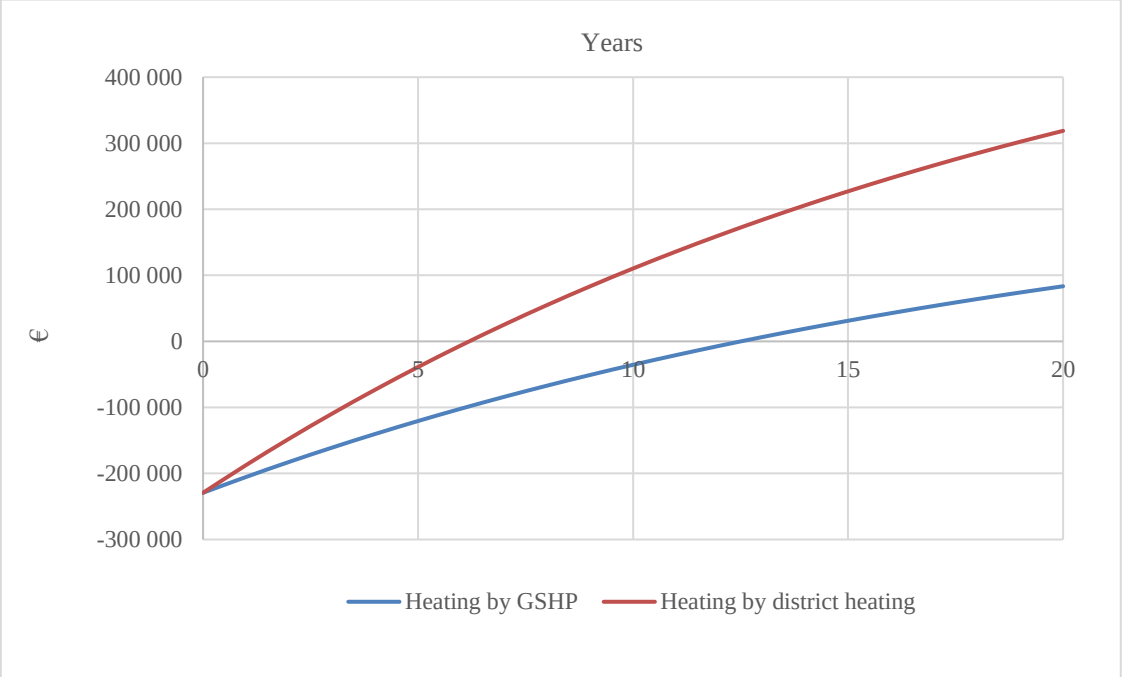

Figure 17. The cumulative discounted net cash flow of heat recovery unit investment in current situation and with a *GSHP*, i = 5 %.

With the investment cost of 229 200 €, the *IRR* for a heat pump heated system would be 9.0 % and for a district heated system 18.5 % in a 20 years examination period. The profitability of the investment decreases for a case of heat coming from a heat pump when compared to the situation when the heat is coming from the district heating. The decrease of profitability is due to the lower price of heat energy in a heat pump system. The potential for energy efficiency as well as profitability of the heat recovery investment is prominent.

6 DISCUSSION AND CONCLUSION

In this chapter, the results are discussed and final conclusions are made. Furthermore, the reliability of the calculations is briefly assessed as well as the aspects for further research.

6.1 Discussion

The aim of this study was to create a model for comparing energy efficiency improvements and their profitability, and to decrease energy system cost and increase the energy efficiency of a building. From the case building point of view, three of the five studied energy efficiency improvements have a positive *IRR* in all compared situations. The final result of the feasibility of every investment depends on the investor, if the *IRR* is high enough. The results are presented in Table 25.

Table 25. Results of *IRR* calculations for different situations and energy efficiency improvements. The value "negative" means the Excel does not calculate the value because there are no positive values in the net savings.

*IRR*s	In the current situation	With the *PV* plant	With window renovation	With the new heat recovery unit	Heating by a *GSHP*
PV	5.7 %				5.7 %
GSHP	13.0 %	13.4 %	24.1 %	19.9 %	
AWHP	negative	negative	negative	23.7 %	
Window renovation	−2.0 %				−5.1 %
Heat recovery unit	18.5 %				9.0 %

In the current situation the heat recovery unit with temperature efficiency of 70 % has the highest profitability, followed by the *GSHP* and *PV* system. The *GSHP* system is not feasible for the case building due to the central location. The *AWHP* gets profitable if the demand is decreased with more efficient heat recovery in the ventilation. Thus the temperature differences of the heat pump system decrease and the *COP* values increase. In the current situation and with i = 5 %, the two improvements with a payback time under ten years are a new heat recovery unit and a *GSHP*.

The current energy system of the case building is presented throughout this study, and all improvements calculated can be installed to the case building, excluding the *GSHP* installation due to the lack of space. The solar *PV* plant's production responds to the electricity demand of the building, because the size of the plant is moderate. The current energy systems in the building should be studied further in terms of the radiator network and the ventilation system.

The investment and management costs are the most significant variables affecting the results. The current prices of technologies are reliable, because they are based on existing sales, and the technologies considered are in their mature stage. When regarding, for example, recent changes in *PV* panel prices, it could be assumed that the investment cost of *PV* will continue to decrease while the market is not yet in a saturation point. The fact that the energy efficiency improvements should be done to the existing building and its systems affects the investment costs. The model is built so that it is applicable also for other buildings. The variables in the model can be changed in further use of the model, when there are, for example, more precise information about the costs.

Regarding the renovation, there would be a perfect chance to implement new systems, but there will be additional costs which have not been taken into account in this study. For example, if the radiator network needs to be renovated in order to have a low temperature heat system, e.g. a heat pump, the investment cost for both heat pump types will increase and thus the profitability will decrease. On the other hand, if the radiator network should be renovated anyway, the heat pump investment could be combined to the renovation in order to obtain benefit from the synergy. Another source of uncertainty for particularly the heat pump investment is the estimated radiator area, which affects the needed working fluid temperature remarkably.

The changes in electricity or district heat price would affect the results drastically. The increase in district heat price would increase the profitability of the investments, and the increase in electricity price would lower it. The district heating payment regarding the maximum flow rate varies if the heat demand changes, but it is assumed to be constant in

this study. In calculations with lower heating demand the assumption will lead to a bit more profitable results than in reality. This impact is decreased in the study by assuming a lower maximum flow rate in the known range of maximum flow rates, which will decrease the payment.

The desired indoor temperature and the supply air temperature in the calculations are quite low due to the ventilation's heat loss and the intention of matching the theoretical heating demand to the reference year's demand. If the needed indoor temperature would be greater, e.g. 20 °C or 21 °C, which are common and recommended values for the indoor temperature, heat pump's electricity demand would increase. Furthermore, the heat loss of the ventilation would be greater if the temperature of the supply air would increase. These scenarios cannot be compared to each other directly, because in this case the theoretical heat demand is greater than the existing one. The theoretical heating demands are the base of the calculations for the electricity demand of the heat pumps. Because the theoretically calculated heating demand in winter time is higher than in the real reference values, the calculated heat pump electricity demand could actually be lower in some year's outdoor temperature conditions. The increasing feasibility of the heat pump is due to the fact that in summer time, the *COP* is higher and in winter time it is lower because of the temperature difference.

In addition, it should be taken into account that many values of the calculation have been taken from the *EPC*, and the Certificate does not explain whether the values are based on real measurements or are they typical estimate values. The more specific effects of assumptions and simplifications could be studied in future.

Usually when talking about energy efficiency, there is an assumption made that the demand of the building should first be decreased to have the demand as low as possible. The assumption is seen in energy efficiency legislation as well. The legislation states that during the renovation thermal transmittance of the structures should be decreased. Results of this study show that the demand decreasing steps are not feasible with the traditional and existing energy systems, such as district heating. The economic feasibility of these

demand decreasing acts decrease further when the new energy systems are implemented into the system. The demand decreasing acts show their profitability when the *IRR* values of other investments are calculated. The ground source heat pump investment shows higher *IRR*s for the case with lower thermal transmittance of windows.

In legislation there are obligations to decrease the thermal transmittance in structures in renovation. When the energy efficiency improvements are planned and implemented in the building block-wise, for example the wall's thermal transmittance should be half of the one before (Ympäristöministeriö, 2013). As the result of the present study the decrease in the thermal transmittance increases the profitability of heat pump investments but it is not an economically feasible act by itself. There are also obligations for when the technical systems of the building are renovated. For example, the yearly efficiency of heat recovery unit should be at minimum of 45 % after the renovation (Ympäristöministeriö, 2013). Based on the results of the present study, the heat recovery unit has a crucial role on the building's energy efficiency.

It should also be acknowledged that the thermal transmittance decrease as an energy efficiency improvement method has its risks. There is a risk that the building will have damage regarding moisture if the insulation adding process fails. The behavior of the wall changes when insulation is added to the walls (Ojanen, n.d.). The change increases the risk of the moisture gathering inside the structure and cause damage, if the insulating process is not planned carefully. On the other hand, there are some risks with other energy efficiency improvement methods, too. The risks usually have to do with unsuccessful designing and planning of a system.

This study shows the same result as in Niemelä's dissertation (2018). It is cost-effective to improve energy efficiency of the building with modern energy system solutions rather than with decreasing the thermal transmittance of the building structure. Furthermore, the present study states that a heat pump is a cost-effective heating technology compared to district heating, which is a similar result as in Niemelä's study (2018).

In a further study it would be reasonable to calculate what would be the profitability of a heat pump investment with only partial heating demand of the building and that another additional heat source or a storage would be used. In public property scale advantages of both electricity and heat storages should be studied further, as well as the effects on demand side in the community's electricity network and possibilities of demand response. Furthermore, the CO_2 emission reduction of the efficiency improvements could be calculated.

6.2 Conclusion

The conclusion of this study is that there is potential for energy efficiency improvements in Lappeenranta City Hall, and this energy efficiency potential can be reached in a financially profitable way. The most profitable energy efficiency improvement in the case building is a new heat recovery unit, followed by ground source heat pump and solar *PV* system installation on the rooftop. The decrease of thermal transmittance of the structures and an *AWHP* has an *IRR* value below zero in most situations. Thus the energy system improvements are usually more cost-effective than improvements regarding the building structure. The model can further be used for other larger scale buildings.

7 SUMMARY

The object of this study was to create a model for energy efficiency improvement profitability comparison in existing buildings going through a renovation process. The goal was to decrease the energy system cost and increase the energy efficiency of the building. The case building was a larger scale public building, Lappeenranta City Hall. The overall result was that there is potential to increase the energy efficiency in the case building, and that the improvements can be executed in an economically profitable way.

The energy efficiency improvement technologies studied were heat pumps, solar *PV* panels, decrease of thermal transmittance of structure and installing a more efficient heat recovery unit to the ventilation system. The effects of these improvements were studied on a monthly basis apart from the solar *PV* production and consumption, which was studied hourly. The heat demand is normalized with the past 10 years' average temperatures. The electricity demand is obtained from a reference year 2017 and is thus representing only one year's demand.

The results for profitability of the energy efficiency improvements in case building are compared with *IRR* values calculated for each investment. For solar photovoltaic, the *IRR* is 5.7 %, for ground source heat pump 13.0–24.1 % and for air-to-water heat pump from negative to 23.7 %. When improving the thermal transmittance of windows from 2.1 W/m^2K to 1 W/m^2K the IRR is −2.0 – −5.1 % and when installing a new heat recovery unit with temperature efficiency of 70 % instead of existing 37 %, *IRR* is 9.0–18.5 %. Renovation needs of the existing radiator network and ventilation system are not included in the investment costs.

The effects of the improvements on CO_2 emission should be studied in further studies, as well as an energy storage's role in building scale applications. The model can be modified in further use by adding more options of energy efficiency improvements, changing the costs according to their change in future and assessing, for example, the radiator network effects on the heat transfer more precisely.

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APPENDIX I

Table I. Working fluid temperature results for *GSHP* and *AWHP* in a situation after window renovation.

Month	Average working fluid temperature, radiation °C	Average working fluid temperature, convection °C	Average working fluid temperature °C	Maximum working fluid temperature °C
January	46.4	36.4	41.4	64.8
February	43.8	34.5	39.2	60.3
March	37.5	30.1	33.8	49.6
April	27.6	23.6	25.6	33.2
May	18.0	18.0	18.0	18.0
June	18.0	18.0	18.0	18.0
July	18.0	18.0	18.0	18.0
August	18.0	18.0	18.0	18.0
September	18.0	18.0	18.0	18.0
October	29.9	25.1	27.5	37.0
November	35.9	29.0	32.4	46.9
December	41.8	33.1	37.4	56.9

Table II. *COP*s of *GSHP* system as well as the total electricity demand in a situation after window renovation.

Month	Temperature difference of *GSHP* system, space heating	*COP*, space heating	Temperature difference of *GSHP* system, *DHW* heating	*COP*, *DHW* heating	Electricity demand in a situation after window renovation, MWh
January	59.8	2.7	50.0	3.5	125.1
February	55.3	3.0	50.0	3.5	90.3
March	44.6	4.0	50.0	3.5	55.7
April	28.2	6.3	50.0	3.5	17.4
May	13.0	9.5	50.0	3.5	1.9
June	13.0	9.5	50.0	3.5	1.3
July	13.0	9.5	50.0	3.5	1.1
August	13.0	9.5	50.0	3.5	1.5
September	13.0	9.5	50.0	3.5	1.7
October	32.0	5.7	50.0	3.5	24.6
November	41.9	4.3	50.0	3.5	46.1
December	51.9	3.3	50.0	3.5	83.7
					450.3

Table III. *COP*s of *ASHP* system as well as the total electricity demand in a situation after window renovation.

Month	Temperature difference of *AWHP* system, space heating	*COP*, space heating	Temperature difference of *AWHP* system, *DHW* heating	*COP*, *DHW* heating	Electricity demand in a situation after window renovation, MWh
January	72.4	1.0	62.6	1.3	335.5
February	66.6	1.2	61.3	1.4	234.4
March	52.2	1.7	57.6	1.5	129.1
April	29.4	3.3	51.2	1.8	33.3
May	6.7	6.2	43.7	2.2	3.0
June	3.4	6.8	40.4	2.4	1.8
July	-0.2	7.6	36.8	2.7	1.4
August	2.0	7.1	39.0	2.5	2.0
September	6.8	6.2	43.8	2.2	2.7
October	32.4	3.0	50.3	1.8	46.1
November	46.1	2.1	54.2	1.6	96.8
December	60.6	1.4	58.7	1.5	201.9
					1088.0

Table IV. Working fluid temperature results for *GSHP* and *AWHP* in a situation with a new heat recovery unit with temperature efficiency of 70 %.

Month	Average working fluid temperature, radiation °C	Average working fluid temperature, convection °C	Average working fluid temperature °C	Maximum working fluid temperature °C
January	36.8	29.6	33.2	48.3
February	34.5	28.1	31.3	44.6
March	29.3	24.7	27.0	35.9
April	21.5	20.0	20.7	23.5
May	18.0	18.0	18.0	18.0
June	18.0	18.0	18.0	18.0
July	18.0	18.0	18.0	18.0
August	18.0	18.0	18.0	18.0
September	18.0	18.0	18.0	18.0
October	24.4	21.7	23.1	28.1
November	29.0	24.5	26.8	35.5
December	33.4	27.3	30.4	42.7

Table V. *COP*s of *GSHP* system as well as the total electricity demand in a situation with a new heat recovery unit.

Month	Temperature difference of *GSHP* system, space heating	*COP*, space heating	Temperature difference of *GSHP* system, *DHW* heating	*COP*, *DHW* heating	Electricity demand after new heat recovery unit, MWh
January	43.3	4.2	50.0	3.5	51.6
February	39.6	4.6	50.0	3.5	37.0
March	30.9	5.8	50.0	3.5	22.5
April	18.5	8.2	50.0	3.5	6.1
May	13.0	9.5	50.0	3.5	1.9
June	13.0	9.5	50.0	3.5	1.3
July	13.0	9.5	50.0	3.5	1.1
August	13.0	9.5	50.0	3.5	1.5
September	13.0	9.5	50.0	3.5	1.7
October	23.1	7.2	50.0	3.5	11.4
November	30.5	5.9	50.0	3.5	21.3
December	37.7	4.9	50.0	3.5	36.6
					193.9

Table VI. *COP*s of *AWHP* system as well as the total electricity demand in a situation with a new heat recovery unit.

Month	Temperature difference of *AWHP* system, space heating	*COP*, space heating	Temperature difference of *AWHP* system, *DHW* heating	*COP*, *DHW* heating	Electricity demand after new heat recovery unit, MWh
January	55.9	1.6	62.6	1.3	137.6
February	50.8	1.8	61.3	1.4	94.7
March	38.5	2.6	57.6	1.5	51.4
April	19.7	4.3	51.2	1.8	11.7
May	6.7	6.2	43.7	2.2	3.0
June	3.4	6.8	40.4	2.4	1.8
July	-0.2	7.6	36.8	2.7	1.4
August	2.0	7.1	39.0	2.5	2.0
September	6.8	6.2	43.8	2.2	2.7
October	23.5	3.9	50.3	1.8	21.2
November	34.7	2.8	54.2	1.6	44.4
December	46.5	2.0	58.7	1.5	87.1
					459.1