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Optimal production and use of solar electricity in municipal nearly Zero Energy service buildings

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Master of Science Thesis

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Like other EU countries, Finland must implement the EU Energy Performance of Buildings Directive (EPBD), requiring all new buildings to be nearly Zero Energy Buildings from the year 2021. Municipal buildings are required to be nearly Zero Energy Buildings from the year 2019. This thesis investigates municipal service buildings and the role of solar photovoltaics (PV) in improving their energy performance, in view of the future nZEB regulation.

Three case study municipal service buildings from Tampere, Finland, are modelled and their energy performance is simulated. The service buildings include a day-care centre, a school and a renovated old people's home. Simulation-based optimization is employed to find the optimal solar panel areas and inclinations for each case study building. The objectives to be minimized are net present value (NPV) of system life-cycle cost for 20 years and building primary energy consumption. A standard commercially available solar panel type is assumed. Electricity pricing is based on current rates.

It is found that own solar PV generation can lower the service building energy performance considerably, if there is enough roof space for panel installation. With current electricity tariffs, PV generation is financially profitable in the old people's home, where it can bring a maximum profit of 2,7–3,6 €/m^2, depending on the main heating solution. The maximum profit occurs with 461 m^2 of solar panels, with inclination angle of 48°, and combined with an air-to-water heat pump. With this arrangement, the primary energy use of the building is lowered by 13%. Generally solar PV production is a more profitable combination with a heat pump solution than with district heating.

Solar PV generation does not create a net profit in the day-care or school building, because unlike the old people's home, they are closed during the summer. The profitability of solar PV generation also depends on the basic heating solution, electricity tariffs, the future behaviour of real interest rate, energy price escalation and solar panel pricing. Sensitivity analysis and additional optimization cases reveal that even for the day-care and school buildings, financial profitability is not far away. If considering the measured electricity use from the whole property of the day-care centre, installing solar PV is profitable even at current electricity tariffs and installation prices, creating a maximum profit of 1,6–1,8 €/m^2.

Key recommendation for municipalities is to design new care housing buildings with enough south-facing roof area for a large solar PV system. Solar PV production should be first implemented in buildings that are occupied throughout the year, and can utilize as much as possible of the own generation. When considering the profitability of the solar PV installation, it is necessary to know the actual electricity consumption arising from the whole property, and not just the building. For educational buildings, solar PV is the best candidate for the buildings that are open also in the summer, e.g. those day-care centres that do not close for the summer holiday. Even if the future nZEB targets do not necessitate own solar PV generation in municipal service buildings, both the financial profitability and the energy efficiency improvements should encourage municipal solar PV installations, especially in nursing homes.

Keywords Nearly Zero Energy Building (nZEB), photovoltaics, service buildings, multi-objective optimization, building simulations, life-cycle cost

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Rakennusten energiatehokkuutta koskevan EU-direktiivin (Energy Performance of Buildings Directive, EPBD) mukaan uusien rakennusten tulee olla lähes nollaenergiarakennuksia vuodesta 2021. Uusien kunnallisten palvelurakennusten tulee olla lähes nollaenergiarakennuksia jo vuodesta 2019. Tässä DI-työssä selvitetään, millä tavoin kunnallisissa palvelurakennuksissa voidaan hyödyntää aurinkosähkön tuotantoa rakennusten energiatehokkuuden parantamiseksi. Tapaustutkimuskohteiksi valittiin kolme Tampereella sijaitsevaa kunnallista palvelurakennusta (koulu, päiväkoti ja peruskorjattu vanhainkoti). Simulaatioihin perustuvan monitavoiteoptimoinnin avulla määritettiin rakennuksille optimaalisia aurinkopaneelialoja ja aurinkopaneelien kallistuskulmia. Monitavoiteoptimoinnissa minimoitavat tavoitefunktiot olivat elinkaarikustannusten nykynettoarvo sekä rakennusten primäärienergian kulutus. Aurinkopaneelien oletettiin olevan keskivertoa, helposti saatavilla olevaa mallia. Sähkön hinnat perustuivat todellisiin hintoihin tutkimuskohteissa.

Tutkimuksen tulokset osoittavat, että aurinkosähkön omatuotanto voi alentaa kunnallisten palvelurakennusten energiankulutusta merkittävästikin, mikäli soveltuvaa asennuspinta-alaa on riittävästi. Sähkön nykyhinnoilla aurinkosähkön tuotanto omaan käyttöön on taloudellisesti kannattavaa vanhainkodissa, jossa se voi tuoda voittoa enimmillään 2,7–3,6 €/m^2, riippuen pääasiallisesta lämmitysratkaisusta. Suurin voitto 3,6 €/m^2 toteutuu paneelialalla 461 m^2, paneelien kallistuskulmalla 48° ja yhdistettynä lämmöntuotantoon ilma-vesilämpöpumpulla. Suurimman taloudellisen tuoton tuovalla paneelialalla vanhainkodin energiatehokkuuskin paranee 13%. Yleisesti ottaen aurinkosähköä on kannattavampaa toteuttaa lämpöpumppu- kuin kaukolämpökohteissa. Aurinkosähkön omatuotanto ei nykyhinnoilla kannata näiden tapaustutkimuskohteiden osalta päiväkodissa tai koulussa. Toisin kuin vanhainkoti, nämä rakennukset ovat kesäaikana vailla käyttöä. Aurinkosähkön kannattavuus riippuu myös lämmitysratkaisusta, sähkön hinnoista, energian ja reaalikorkojen ennustetusta hintakehityksestä sekä aurinkopaneelien investointikustannuksesta. Herkkyystarkastelut paljastavat, että myös päiväkodissa ja koulussa aurinkosähkön taloudellinen kannattavuus on lähellä toteutumista. Kun päiväkodin osalta tarkastellaan mitattua sähkönkulutusta koko tontilta, aurinkosähkön omatuotanto on päiväkodissa kannattavaa jo nykytilanteessa. Tällöin se voi tuoda voittoa enimmillään1,6–1,8 €/m^2.

Uusiin vanhainkoteihin ja muihin hoivakoteihin tulisi alusta lähtien suunnitella riittävästi etelään suuntautuvaa kattopinta-alaa suurenkin aurinkopaneelijärjestemän asentamista varten. Aurinkosähkön tuotanto kannattaa erityisesti palvelurakennuksissa, jotka ovat ympärivuotisessa käytössä ja joissa voidaan hyödyntää mahdollisimman suuri osa tuotetusta sähköstä paikan päällä. Kun aurinkosähkön asentamista harkitaan, tulisi ottaa huomioon sähkönkulutus koko tontilla, eikä ainoastaan rakennuksessa itsessään. Opetus- ja varhaiskasvatusrakennusten osalta aurinkosähköä kannattaa asentaa ennen kaikkea rakennuksiin, jotka ovat toiminnassa kesälläkin: esimerkiksi päiväkoteihin, joissa järjestetään päivähoitoa myös kesäkaudella. Vaikka uudet lähes nollaenergiarakentamisen tavoitetasot eivät edellyttäisikään hajautettua sähköntuotantoa kunnallisissa palvelurakennuksissa, oma energiantuotanto voi olla sekä taloudellisesti kannattavaa että parantaa rakennuksen energiatehokkuutta, ja kuntien tulisi edistää sitä etenkin hoivakodeissa.

Avainsanat Lähes nollaenergiarakentaminen, aurinkosähkö, palvelurakennukset, monitavoiteoptimointi, rakennussimulaatiot, elinkaarikustannus

Preface

The research work documented in this M.Sc. thesis report was performed at Aalto University Department of Mechanical Engineering, Energy Efficiency and Systems group. The instructor of the thesis at Aalto was Dr. Juha Jokisalo and the work was supervised by professor Kai Sirén, both from the Energy Efficiency and Systems group.

The thesis was undertaken as a part of a double degree programme Master of Science in Innovative and Sustainable Energy Engineering (ISEE), awarded jointly from Aalto University and KTH Royal Institute of Technology. At KTH, the instructor of the thesis work was Shahid Hussain Siyal and the supervisor was professor Mark Howells, both from the Division of Energy Systems Analysis, Department of Energy Technology.

The thesis work forms a part of "Comprehensive development of nearly zero-energy municipal service buildings" project, or COMBI. The project is undertaken by Aalto University, Tampere University of Technology and Tampere University of Applied Sciences. Funding for the project has been granted by the European Regional Development Fund, as a part of Innovative Cities project of the Finnish Funding Agency for Innovation (TEKES). Funding has also been received from private companies. It has been my pleasure to participate in this project.

I would like to give special thanks to Juha Jokisalo for his excellent instruction, and to Kai Sirén for his encouraging supervision. Both were essential for completing the work. I also thank Shahid Hussain Siyal and Mark Howells for being my instructor and supervisor at KTH. Shahid Hussain Siyal has been very helpful with practical matters concerning the ISEE programme at KTH, and likewise Börje Helenius with matters concerning the ISEE programme at Aalto.

I received a personal travel grant from the ERASMUS programme, for which I am grateful. I thank Riikka Jääskeläinen from Aalto University for her help in the grant application process.

I further extend my thanks to Mika Vuolle and Erkki Karjalainen from Equa Simulation Finland Oy for their help with IDA ICE building simulation software, Matti Palonen from Granlund Oy (previously from Aalto University) for his help with MOBO optimization software, and for Antti Tikka from Tampereen Sähkölaitos for his help with data gathering.

Lastly, I thank my husband Eero and my son Pyry for their endless patience and goodwill.

Table of Contents

Abbreviations

A2WHP	Air-to-water heat pump
AHU	Air handling unit
BRITA in PuBs	Bringing Retrofit Innovation to Application in Public Buildings
CHP	Combined heat and power
COMBI	Comprehensive development of nearly Zero Energy municipal service buildings
DH	District heating
DHW	Domestic hot water
EAP	(Finland's) Energy Audit Programme
EPBD	Energy Performance of Building Directive
EPBD CA	Concerted Action EPBD
ESBO	Early Stage Building Optimization tool
EU	European Union
EU ETS	EU Emissions Trading System
FINVAC	The Finnish Association of HVAC Societies
GHG	Greenhouse gas
GSHP	Ground source heat pump
GUI	Graphical user interface
HVAC	Heating, ventilation and air conditioning
IDA ICE	IDA Indoor Climate and Energy
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
LCC	Life-cycle cost
MATLAB	MATrix LABoratory (a numerical calculation software)
MOBO	Multi-Objective Building Optimization tool
NetZEB	Net Zero Energy (/ Emissions) Building
NPV	Net present value
NREL	National Renewable Energy Laboratory (U.S. Department of Energy)
NSGA-II	Non-dominated Sorting Genetic Algorithm II
NZEB	Net Zero Energy (/ Emissions) Building

nZEB	Nearly Zero Energy (/ Emissions) Building
PB	Pellet boiler
PV	Photovoltaic
RE	Renewable energy
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
SBO	Simulation-based optimization
TAMK	Tampereen ammattikorkeakoulu
	(Tampere University of Applied Sciences)
TUT	Tampere University of Technology
VAT	Value added tax
ZEB	Zero Energy (/ Emissions) Building

1 Introduction

1.1 Background

The global energy sector is currently undergoing a tremendous change. In December 2015, the first legally binding global climate agreement was reached between 195 nations. The agreed action plan is to limit global warming to “well below 2 ºC” compared with pre-industrial levels, preferably even to a maximum of 1,5 ºC. According to Intergovernmental Panel on Climate Change (IPCC), limiting warming below 2 ºC requires the global greenhouse gas emissions to decline to zero or nearly zero by the end of the century [1]. If this target is to be reached, the shift into low-emission energy generation is inevitable.

In addition to low-emission energy generation, energy saving and energy efficiency measures must be implemented in all energy consuming sectors. In the EU, buildings consume 40% of primary energy, and are responsible for 24% of the greenhouse gas emissions (e.g. [2]). The energy efficiency of the EU building stock must be improved, in order to diminish the greenhouse gas (GHG) emissions from the building sector.

According to the EU Energy Performance of Buildings Directive (EPBD), all new public buildings in the EU should be so-called nearly Zero Energy Buildings (nZEB) from the year 2019 onwards. For private buildings, the deadline is set two years further: all new private buildings should be nZEB buildings from the year 2021. [3] The new legislation is formulated and adapted in each member state’s own national building code, and this legislative work is currently undergoing in those EU member states that haven’t passed the legislation yet, Finland included [2].

The EU building sector must now adapt rapidly to fulfil the new nZEB requirements. Public buildings, which shall comply with the directive already from 2019 onwards, include municipal service buildings such as schools, day care buildings, health service buildings, old people’s homes and other care buildings. Service buildings have widely varying functions, and need specialized solutions for improving their energy efficiency. At the same time, they often have stricter indoor condition requirements than private homes (e.g. air quality). “One solution fits all” is not a helpful approach, and research is needed to identity the best energy solutions for different classes of service buildings.

This Master’s thesis, performed jointly for Aalto University and KTH Royal Institute of Technology, is motivated by these challenges in the European building sector. The work was undertaken as a part of a research project named COMBI, short for “Comprehensive development of nearly Zero Energy municipal service buildings”. Service buildings generally refers to private service buildings as well as public service buildings, but in this project the focus is on municipal (public) service buildings.

Seven research groups from Aalto University, Tampere University of Technology (TUT) and Tampere University of Applied Sciences (TAMK) participate in the COMBI project. Other collaborators in the project include the cities of Tampere and Helsinki, seven municipalities near Tampere (Kangasala, Lempäälä, Nokia, Orivesi, Pirkkala, Vesilahti, Ylöjärvi) and 38 companies from the Finnish building and construction sector. Funding is granted from the European Regional Development Fund and the Finnish Funding Agency for Innovation (Tekes), an also from the collaborating companies. [4]

In 2015–2017, five work packages are carried out in the framework of the COMBI project:

WP1: Organising and reporting
WP2: Architecture and spaces
WP3: Structures and indoor air
WP4: Building services and energy production
WP5: Building processes

Work packages are divided into research tasks. The research work presented in this Master's thesis report was performed under WP4, which is a work package coordinated by Aalto University Department of Mechanical Engineering. Work package 4 includes the following research tasks:

T4.1 Optimal choice and use of heating and cooling systems
T4.2 Optimal self-production and use of electricity
T4.3 Total optimization of the building and its energy systems
T4.4 Renewable energy production off-site and its implications on optimal technology solutions
T4.5 Societal and legal aspects of renewable energy production off-site
T4.6 Implications of building automation system solutions and electric power control
T4.7 Energy efficient lighting solutions

Task 1 of WP 4 was to determine optimal heating and cooling solutions for municipal service buildings, with the aim of reaching low building primary energy consumption in a cost-optimal manner. This work package was performed at Aalto University by Jonathan Nyman, who examined three municipal service buildings as case studies. The three case studies represented different types of municipal service buildings: a retrofitted old people's home from the 1950's, a newly built day-care centre, and a school building which was then under construction and started operation in August 2016. Optimal heating and cooling systems for these buildings were selected using building simulations and multi-objective optimization. [5]

The research work undertaken in this thesis builds on the results from Nyman [5]. Task 4.1 was to select the optimal heating and cooling solutions for the case-study buildings, without considering the possibility of on-site renewable electricity production. This thesis investigates the feasibility of on-site renewable electricity generation, and poses the question: what if the selected case-study municipal service buildings also incorporated some renewable energy production, in the form of solar photovoltaics (PV)? How much could self-production of solar electricity lower the building's primary energy consumption? How is this done in a cost-optimal manner?

The work was conducted under the instruction and supervision of Dr. Juha Jokisalo and professor Kai Sirén from Aalto University, Department of Mechanical Engineering, Energy Efficiency and Systems group. The work was also monitored and supervised by Shahid Hussain Siyal and professor Mark Howells from KTH Royal Institute of Technology, School of Industrial Engineering and Management, Department of Energy Technology.

1.2 Research objectives

The objective of the thesis report is to answer the following research questions:

- How much can on-site solar PV generation lower the purchased energy consumption of a municipal service building? How much does this vary according to building type and function?
- Is on-site PV production likely to aid in fulfilling the (future) nearly Zero Energy Building criteria?
- What is the cost-optimal manner for utilizing on-site solar PV generation in municipal service buildings? What is the cost-optimal size of the installation, when life-cycle costs are considered?
- In case a cost-optimal optimal amount of solar PV production emerges, what are the implications for municipal service building architecture? Do the selected case-study buildings have the necessary roof area for the optimal amount of production?

The investigation builds on the three case studies that have been examined in previous work [5]. For the three municipal service buildings in question, the optimal basic heating and cooling solutions have already been selected. Now the simulation and optimization work is carried out further: what if these previously simulated municipal service buildings also had solar panels? How well can the production be matched with the energy consumption of the building in each case? Matching the generation with the consumption is one of the main challenges in the feasibility of producing renewable energy on-site, and should be carefully considered. This can be done with the help of a building energy simulation programme.

Different municipal service buildings have different usage profiles: a nursery home typically houses residents at all times, whereas a school or a day care building is primarily occupied during the daytime and typically closed during the holidays. How does the optimal amount of solar energy production depend on the building usage profile?

The optimal heating solutions for all case study buildings are based on the use of heat pumps: either a ground-source heat pump (GSHP) or an air-to-water heat pump (A2WHP). In actuality the case study buildings receive their heat from the municipal district heating (DH) network. How is the feasibility of on-site solar PV generation affected, in case the actual heating mode of district heating is assumed?

The methods for answering these research questions are building simulations done with IDA ICE simulation programme, life-cycle cost (LCC) analysis, and multi-objective optimization with MOBO optimization tool, using a NSGA-II evolutionary algorithm. Research methods and data gathering are explained in detail in Chapter 6.

This study is an investigation in the building energy performance and solar PV life-cycle cost, rather than in the solar PV technology. The specifications of the solar PV modules used in the optimizations represent a current, off-the-shelf model. More expensive and more efficient models would yield different solutions, and possibly better overall energy performance for the buildings.

Considering storage technologies, such as batteries, could also be fruitful, in case the objective of the research was to explore the full future potential of solar energy in the Finnish municipal building sector. However, the aim of this research is to optimize the use of the current technology, rather than investigate the most promising emerging technologies. The most advanced, cutting-edge solar PV models and storage technologies are therefore not considered here: with the current electricity storage prices, investment in energy storage is not the cost-optimal solution.

1.3 Structure of the thesis

The chapters of this thesis report form three broad sections: introduction and background (Chapters 1–5), documenting the research methods (Chapters 6–8), and lastly presenting the results and discussing their conclusions (Chapters 9–10).

Chapter 2 of the report gives a brief introduction to the energy use of the Finnish building stock, with emphasis on municipal and other service buildings. Chapter 3 starts by an introduction to the terminology used in energy efficient building research, listing the most common acronyms for different types of energy efficient buildings. Chapter 3 continues with the discussion of various nZEB / ZEB calculation methodologies, and lastly outlines both the EU nZEB targets and the Finnish process towards implementing them.

Chapter 4 gives examples of nZEB service building pilot projects, both in Finland and elsewhere in Europe. Chapter 5 discusses the current state of distributed solar PV generation in buildings and its outlook in Finland. Chapter 5 finishes the background review, and reporting of the original research work begins in the following chapters. There is no single chapter dedicated to literature review, because the relevant literature is introduced in each section.

Methodology and data sources for the thesis work are discussed in Chapter 6. Chapter 7 introduces the three case study service buildings: Luhtaa day-care centre, Vehmainen school and Jukola old people's home. This chapter also gives more detailed insight into the buiding models used in the building energy simulations. As the last chapter in the methods section, Chapter 8 describes the structure and the sequence of the optimization cases.

Chapter 9 presents the results from the optimization cases. The cases with modelled energy consumption are discussed first, and lastly Luhtaa day-care is investigated as a special case, where the measured electricity consumption is incorporated into the model. Chapter 10 finishes the thesis report with a summary of the findings and conclusions. Finally, some recommendations are given to the municipalities, based on the conclusions.

2 Energy use of the building stock

2.1 Current Finnish building stock energy use

One of the main functions of a building is to provide a comfortable indoor climate. This is especially important in cold climates such as Finland's. While creating a liveable indoor climate, it is now becoming crucially important that the building sector does not harm or damage the outside climate.

In 2012, the gross floor area of the Finnish building stock was 450 million m^2, and growing at a yearly rate of 1,1–1,9% [6]. Buildings consume approximately 38% of end use energy and 41% of primary energy used in Finland. They are responsible for 32% of the Finnish greenhouse gas emissions [7]. In comparison, in the whole EU buildings also consume approximately 40% of primary energy, and are responsible for 24% of the EU greenhouse gas emissions (e.g. [2]).

The energy efficiency of the total Finnish building stock (both residential and service buildings) has improved steadily in the past decades. Between 1970 and 2000, the heating energy use per square meter has approximately halved (Figure 1), as the buildings have become more energy efficient [8]. For electricity consumption, the trend is the reverse: between 1970 and 2000, the total building electricity use has approximately doubled (Figure 2). This trend reflects the growing use of electrical equipment in homes and service buildings during those three decades [9]. In these statistics, "service buildings" refers to private as well as public service buildings.

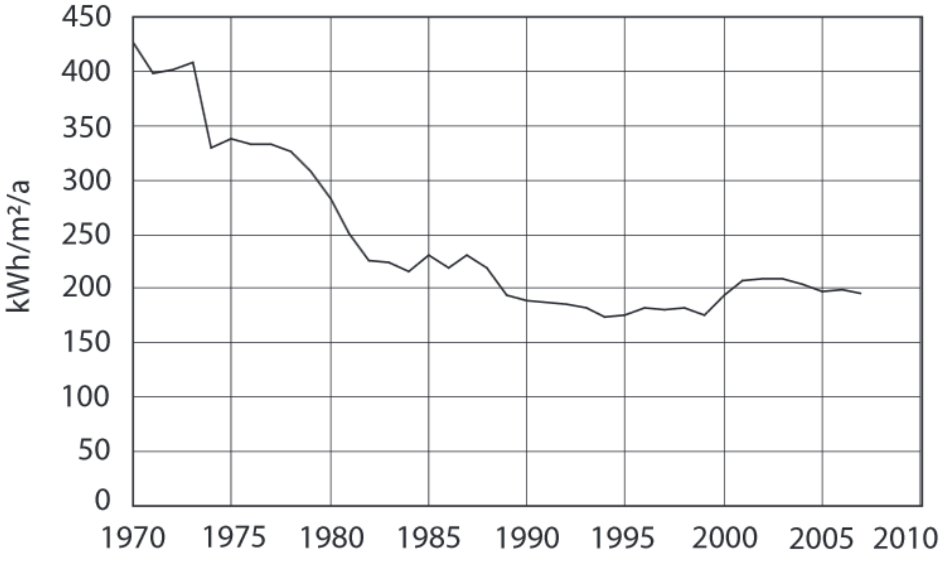

Figure 1. Use of heating energy in the Finnish residential and service buildings 1970–2007, based on [8].

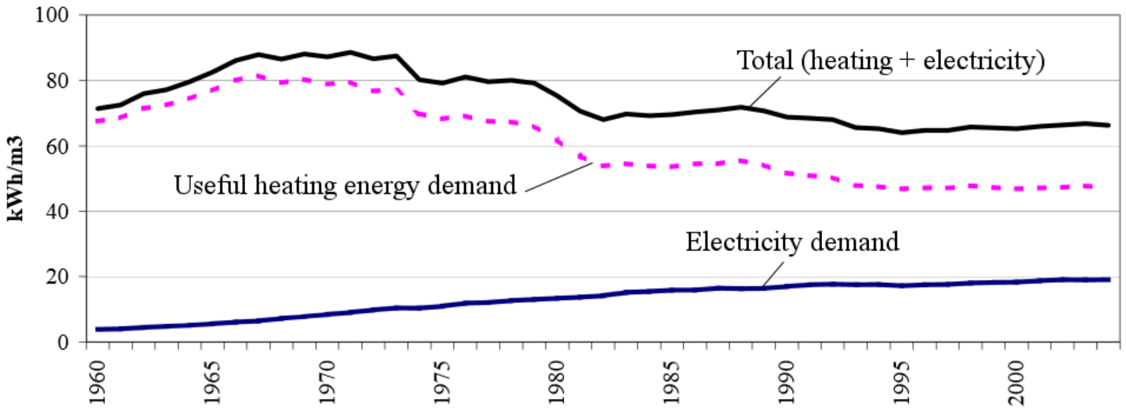

Figure 2. Use of heating and electrical energy in the Finnish residential and service buildings 1960–2003, from [9].

Switching away from the fossil fuels is a trend already visible in the heating of Finnish buildings. In 2013, heat pumps overtook oil as a heat source in Finnish residential buildings (Figure 3). Solar thermal and solar PV solutions are also on a strong growth track in Finland, and there is a significant and financially feasible potential for solar PV and solar heat collectors also in the Finnish building sector. In the Finnish climate and geographical conditions, solar energy can only provide a part of the building energy solution. Luckily, solar energy functions well in the existing and emerging hybrid solutions. For example, solar heat collectors can improve the COP of a heat pump, and help to increase the life-time of a biofuel boiler. [10]

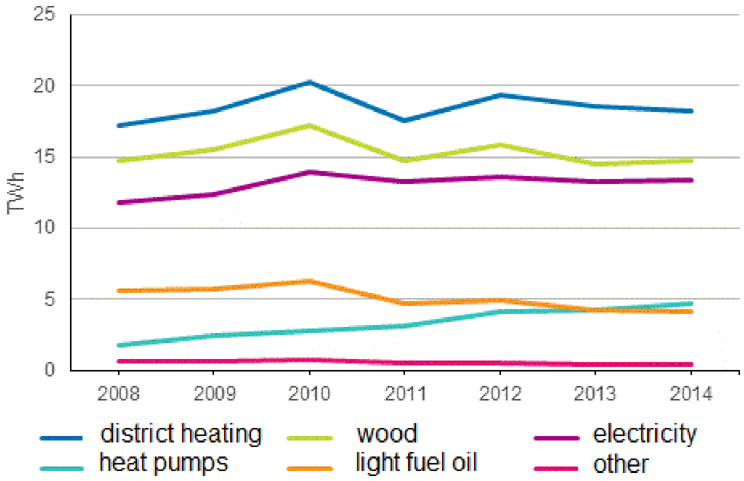

Figure 3. Heating solutions in Finnish residential buildings 2008–2014, based on [11].

To meet the national and EU climate targets, the overall Finnish building sector energy consumption must decline. Further fuel switching away from fossil fuels is necessary, and more energy efficiency improvements are needed, both for old and new buildings. Not all the low-hanging fruits have been gathered yet: there exists a significant energy saving potential for the current building stock. According to Finland's Energy Audit Programme (EAP), the average energy saving potential (based on building energy audits performed in 2008–2013) was 12% for heating energy and 7% for electricity. This represents the energy saving potential attainable without major building renovations. Often the energy savings could be reached without any investment in equipment, mainly by adjusting the building energy systems and/or building user behaviour. This building energy saving potential could also bring an estimated monetary saving of 13%. [12]

Implementing the EU nZEB targets, discussed in Chapter 3.3, is one of the key measures to start cutting down the energy use and GHG emissions of the new buildings. It is now imperative to find ways to improve the energy performance of all buildings, and to identify the most feasible methods and solutions that can be applied in the new municipal service buildings already in the near future. Energy efficiency improvements in the existing buildings can bring monetary profit, instead of incurring costs. The same may be true for new buildings as well: energy-efficient solutions can be financially profitable as well.

2.2 Building energy use indicators and requirements

Energy consumption of a building depends to a large degree on the type and intended use of the building. The current national building code of Finland classifies the Finnish building stock into following categories of intended use [13]:

1. Single-family houses and terraced or otherwise attached houses
2. Blocks of flats
3. Office buildings
4. Commercial buildings
5. Accommodation buildings
6. Educational / day-care buildings
7. Sports halls (ice rinks and swimming pools excluded)
8. Hospitals
9. Other buildings

The focus of this research project is municipal service buildings, and the case studies investigated in this work package are selected from categories 5 (old people's home) and 6 (school, day-care centre).

The Finnish national building code defines the following building energy use indicators [13]:

Energy use [kWh/m^{2}a] is the annual amount of energy required by heating, cooling and electricity within the building, not accounting for generation or distribution losses.

Delivered energy use [kWh/m^{2}a] indicates how much energy a building must acquire annually from the various energy distribution networks (heating, cooling, electricity, fuel). In case the building has individual energy generation, this value is lower than the building energy use.

Building E-value [kWh/m^{2}a] is an indicator of the building's energy performance, calculated in a standardized manner. E-value is derived from the building's delivered energy use in a year, assuming a standard usage specified by the national building code. Sources of delivered energy are assigned different energy carrier factors in the E-value calculation [14].

The national building code specifies the energy efficiency requirements for both new and renovated buildings. A partial list of the current requirements is presented in Table 1, according to the building usage. In case different parts of the building have different uses, they can also have different E-values. If a portion of a building dedicated to particular usage comprises less than 10% of the heated net area, its share can be allocated under other kinds of usages. [13]

In the future new buildings must fulfil the nZEB requirements set by the national building code, and also other requirements specified by the legislation. These pertain to e.g. thermal transmittance of the building envelope and energy efficiency of the ventilation. The future E-value requirements for the new buildings are of special interest in this study.

When a building is renovated, it must fulfil one of three options: the requirements for the building energy use (not the same as building E-value), the specific requirements for building envelope, or the E-value requirements. In the case of a renovated building, the new E-value requirement is expressed as a portion of the old E-value. [15] Energy use requirements and E-value requirements for new and renovated buildings are listed in Table 1 ([13], [15]).

Table 1. The current E-value requirements by building type, according to the Finnish national building code ([13], [15]).

Building type	E-value requirement, new building [kWh/m^{2}a]	Energy use requirement, renovated building [kWh/m^{2}a]	E-value requirement, renovated building (expressed in relation to the E-value before the renovation)
1) Single-family houses and terraced / attached houses	≤ 130…229	≤ 180	E-value$_{new}$ ≤ 0.8 x E-value$_{old}$
2) Blocks of flats	≤ 130	≤ 130	E-value$_{new}$ ≤ 0.85 x E-value$_{old}$
3) Office buildings	≤ 170	≤ 145	E-value$_{new}$ ≤ 0.7 x E-value$_{old}$
4) Commercial buildings	≤ 240	≤ 180	E-value$_{new}$ ≤ 0.7 x E-value$_{old}$
5) Accommodation buildings	≤ 240	≤ 180	E-value$_{new}$ ≤ 0.7 x E-value$_{old}$
6) Educational or day-care buildings	≤ 170	≤ 150	E-value$_{new}$ ≤ 0.8 x E-value$_{old}$
7) Sports halls	≤ 170	≤ 170	E-value$_{new}$ ≤ 0.8 x E-value$_{old}$
8) Hospitals	≤ 450	≤ 370	E-value$_{new}$ ≤ 0.8 x E-value$_{old}$

Sekki et al. [16] have assessed and compared a number of indicators for (educational) building energy efficiency. They conclude that annual energy use expressed in kWh/m^2 is not always the most suitable indicator for the overall efficiency of the building usage. When building energy efficiency is assessed by the annual energy use per area or per volume, the building often seems the more energy-efficient, the less it is occupied. This is clearly a misleading metric for the overall energy efficiency, especially as the trend for the public buildings is to be utilized more, and for more diverse purposes. From the energy system point of view, it is not energy efficient to let public buildings stand empty for a large portion of the time; high building utilization rate is also a manner of efficiency. [16]

The building E-value indicator does not suffer from the occupancy problem outlined above. E-value is a specific tool for comparing buildings or building technology solutions with each other, independently from actual occupancy levels. For this reason, E-value is always calculated assuming a standard building usage, defined by the national building code. The E-value is suitable for comparisons between the buildings, but because it is calculated assuming standard behaviour, it also cannot indicate whether a given building is occupied and operated in an energy-efficient manner. Sekki et al. suggest that for service buildings such as educational buildings, a more relevant energy efficiency indicator would be energy consumption adjusted for the building usage (person hours). [16] This is an especially valuable metric when attempting to lower the energy costs from the building operational stage [17].

Other possible indicators for a building's overall performance are e.g. life-cycle carbon footprint, operational carbon footprint, life-cycle cost, indoor air class and user satisfaction [18]. All are relevant for municipal service buildings, but only the energy performance indicators are considered in this work.

2.3 Energy use in municipal service buildings

It is estimated that the public sector consumes 4% of Finland's end use energy, amounting to 12–13 TWh annually. A large portion of this demand results from the municipal (service) building energy use. [19] When improving energy efficiency of the public sector, municipal building energy use deserves much attention, but extensive and useful data on municipal service buildings is not easily available. For example, Statistics Finland (the state of Finland's statistical bureau) does not offer readily available statistics for municipal service building energy use in its own category. Where data on municipal building energy use is available, it can be given in the form of various indicators: for example, calculated either per area or per volume. When energy use is given per area, it is not always clear which area is considered. Sometimes the data is normalized according to the weather, and sometimes not. Different energy indicators and normalization factors can render comparisons difficult. (E.g. [19].)

One useful source of data is Finland's Energy Audit Programme (EAP), run by Motiva, a state-owned energy expertise company. At the end of the year 2014, 72% of the municipal public buildings have been audited in the EAP programme (88 million m^3 out of 123 million m^3), making the audit programme extensive and its results well generalizable. Educational buildings are especially well surveyed: they comprise 20% of the energy audited buildings, and are the single most comprehensively audited building class. The audit data covers only public, industry and energy generation buildings, not e.g. residential homes. [20]

Table 2 shows the median heat and electricity consumptions for Finnish school buildings, day-care buildings and old people's homes, based on EAP data collected in years 2009–2014. One conclusion from the audit data is that for all these buildings, heat consumption currently has greater energy saving potential than electricity consumption. For the entire municipal building sector audited in EAP, the estimated electricity saving potential is 3% and the estimated heat saving potential is 16%. For the service building sector (both municipal and private service buildings), it is estimated that approximately 60% of the energy saving potential is realized after the auditing has taken place, and 40% remains. [20]

Table 2. Median energy consumptions and energy saving potential of service buildings audited in Finland's Energy Audit Programme (EAP) during years 2009–2014.

Building class	Number of buildings audited in 2009–2014	Median electricity consumption [kWh/m^{3}a]	Median heat consumption [kWh/m^{3}a]	Energy saving potential estimated by EAP, electricity	Energy saving potential estimated by EAP, heat
Day-care buiding	216	21,7	58,5	1%	15%
Comprehensive and high school building	253	14,8	45,2	5%	16%
Old people's home	33	57,5	26,6	7%	13%

More detailed studies exist on the building energy consumption in specific locations, and also according to the building age. Sekki et al. [21] have surveyed the energy consumption of educational buildings (day-care centres, schools and university buildings) in the city of Espoo, in Southern Finland. Their survey extended to 82% of the schools and 62% of the day-care buildings of the city. The findings for day-care and school buildings are shown in Table 3. It was found that variations in both heating and electricity consumption were large among the surveyed buildings. University buildings do not belong to the class of municipal service buildings, so the findings for them are omitted here.

Table 3. Energy consumption of day-care and school buildings in Espoo [21].

Buidling class	Median energy consumption [kWh/m^{2}a]	Range of electricity consumption [kWh/m^{2}a]	Range of heat consumption [kWh/m^{2}a]
Day-care building	251	37…372	61…551
School building	214	10…125	45…383

Sekki et al. [21] also categorized the surveyed buildings according to their age. The buildings originated from 1950s to 2000s, and trends in the energy consumption were detected according to the building age. Heating consumption portrays a clear decreasing trend: newer educational buildings consume less heat. Day-care buildings erected in the 2000s were found to consume on average 14% less heat than all the surveyed day-cares, and schools erected after 2004 consumed on average 22% less heat than all the surveyed schools. This trend is also reflected in the total primary energy consumption.

However, for electricity consumption, a slightly rising trend was observed. This is consistent with the electricity consumption trend for both residential and service buildings shown in [9]. Sekki et al. [16] propose that the growing trend in electricity consumption results from the increased occupancy of the newer educational buildings. Perhaps the newer buildings are designed to accommodate more evening and weekend activities, which in itself is a positive trend. This underlines the dilemma mentioned in Chapter 2.2: measuring the building annual energy use does not necessarily reveal the overall energy efficiency of the building, unless the occupancy hours are considered as well.

The trends of declining heating energy use and increasing electricity use in educational buildings are also observed in the COMBI project. Ruusala [22] categorized 278 day-care buildings and 280 school buildings in Tampere and Helsinki, arranging them into cohorts according to the construction year. The buildings originated from 1960s to 2010s. It was found that the buildings constructed in 1975–1984 had the largest total energy consumption (heat + electricity). After that time period, newer school and day-care buildings tend to consume less heating energy and more electricity than the older buildings. Ruusala's data does not yield specific explanations as to why the electricity consumption of educational buildings has increased. [22]

Whichever is the underlying reason behind the larger electricity use in the newer educational buildings, one key conclusion is this: the importance of electricity consumption is on the rise. Finland has a cold climate, and often heating is considered the most pressing issue. However, in the surveyed educational buildings constructed in the 2000s, primary electricity consumption has already surpassed primary heating consumption [21]. At the same time, general findings from the EAP suggest that in the existing buildings, it is easier to economize on the heating consumption by adjusting building systems etc. than to cut down the building electricity consumption (see Table 2). This stresses the importance of careful building design: to lower the delivered energy consumption of the new service buildings, special attention should be paid to electricity consumption from the start. Installing own electricity generation, for example solar PV, is one of the possible solutions for tackling this challenge.

Note that in the Espoo educational building survey, all new day-care and school buildings received their heat from the district heating network. In case heat pump solutions start replacing district heating in the municipal service buildings, the importance of electricity becomes even more pronounced.

Some case studies exist on the energy consumption of Finnish old people's homes, usually in the form of a thesis or a final project. For example, Räikkälä [23] surveyed the energy usage for an old people's home in Karvia, Western Finland (built 1957, renovated 1999). The electricity consumption of the old people's home (cooling excluded) was 32,9 kWh/m^{3}a, and the heating consumption was 68,8 kWh/m^{3}a. Kohvakka [24] surveyed the energy use in an old people's home in Espoo, Southern Finland (built 1966, renovated in 1987 and 2002). For this building, the electricity consumption was 23,4 kWh/m^{3}a, and the heat consumption was 64 kWh/m^{3}a. Much cannot be generalized from such results; typical values for old people's homes are already indicated by the EAP survey data (see Table 2). Extensive studies on the Finnish old people's home energy consumption long-time trends are not available.

For old people's homes, the question of assessing the building occupancy hours is less pressing than for the educational buildings. Old people's homes are usually inhabited throughout the day and around the year, making it easier to estimate the occupancy profiles. Räikkälä [23] compared the standardized heating energy consumption (calculated with the occupancy profiles specified by the national building code) with the measured heat consumption of an old people's home, and found that they largely coincide, mostly because the building occupancy is easy to predict. Of course, the occupancy of the staff may vary, and old people's homes can offer more diverse services for the nearby community than just sheltered housing. For example, hall spaces in old people's home can be rented for clubs or for local meetings. If such functions become more common in the future, they will also have an impact on the building usage profile, and therefore also on the overall building energy consumption.

Finally, it must be remarked that the energy usage in the municipal service buildings is not entirely determined by the combination of building technical solutions and building occupancy times. Building user energy consumption behaviours also matter, and this has been a subject of much research. Traditionally many research approaches have seen the building users as individuals that would more or less automatically act in energy efficient manner, had they sufficient knowledge or sufficient motivation (e.g. a financial incentive, positive feedback) to do so [25]. Recent studies have questioned this approach: when the building users' actual energy behaviours are surveyed and monitored, they are found to be highly context-dependent and subject to various complexities, especially in the case of the workplace energy behaviour. In municipal service buildings, work-place cultures and social norms play a large role, as was found by e.g. Bull et al. in the UK [26].

More detailed remarks on municipal service building users and their energy behaviours are outside the scope of this thesis. The matter is worth mentioning, because even with mostly automatized building systems, building users still have ways to affect the building energy consumption. When recommendations are given on e.g. how to lower the building energy consumption, it should be kept in mind that these recommendations may overlook important aspects of actual building usage and user energy behaviours. These actual building usages should be surveyed, too, if possible.

3 Defining nearly Zero Energy Buildings: methodologies and legislation

3.1 Energy efficient buildings: terminology

This sub-chapter introduces some of the terminology and the acronyms used for different types of energy efficient buildings. The summary presented here is based on the reviews given in [27], [28], [29] and [2], and other sources indicated in the text when appropriate. The acronyms presented below are chosen according to the most common usage in the literature: not every source uses these acronyms in precisely the same manner. For example, REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations) applies the acronym nZEB for Net Zero Energy Buildings and nnZEB for Near Zero Energy Buildings [30].

Zero Energy Building (ZEB)

Zero Energy Building can be broadly described as *"a residential of commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied by renewable technologies"* [31]. Currently there is no internationally agreed standard for Zero Energy Buildings, and several methodologies have been suggested for calculating their energy balance. Sometimes the acronym ZEB is used to refer to Zero Emissions Building instead of Zero Energy Building.

Off-grid Zero Energy Building (Off-grid ZEB)

Off-grid Zero Energy Building is not connected to energy distribution networks such as electrical grid, gas pipeline, district heating or district cooling. All the energy the building requires must be produced on site. Such buildings are also called autonomous, stand-alone, or self-sufficient Zero Energy Buildings.

Net Zero Energy Building (NZEB, Net ZEB)

Net Zero Energy Building refers to a ZEB that is connected to one or several energy distribution networks. The building can purchase energy from the distribution networks when required, and at other times it will produce excess energy and feed it back to the network. In this way, their net energy balance is zero over the chosen calculation period (usually one year). In most cases Zero Energy Buildings are connected at least to the electrical grid, so the acronyms ZEB and NZEB are used almost synonymously.

Nearly Zero Energy Building (nZEB)

There is no agreed common standard for a Zero Energy Building, and the same is true for nearly Zero Energy Buildings. The EU directive 2010/3 on the energy performance of buildings (EPBD recast) describes nZEB as "*a building that has a very high energy performance [...]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" [3]. Existing and forthcoming national definitions and methodologies of nZEBs are discussed in Chapter 3.3. The national definitions of nZEBs are of great interest especially in the EU, because all the new municipal buildings in EU should be nZEBs from the year 2019 onwards, and all new buildings in EU should be nZEBs from the year 2021 onwards.

Energy Plus Building (+ZEB)

Energy Plus Building generates more energy from renewable sources than it draws from the supply networks, over the balancing period. The period typically suggested for the energy balance is one year. In many countries it is not possible for a building to have an official +ZEB status, because the national building code does not accept energy sold to the distribution networks to be included in the building energy balance.

Low Energy Building

A concept of Low Energy Building is also applied in many countries, and has differing national definitions. In Finland a Low Energy Building commonly refers to a building with requires only half of the heating needs specified in the current building standards (e.g. [32]). In practice, the values for Low Energy Buidings and currently suggested values for nZEBs are within the same region. The term "Low Energy Building" may become obsolete, as the current focus is in defining and implementing nZEBs / ZEBs.

Passive house (*Passivhaus*)

A passive house is a concept originating from Germany. It refers to a building with very good thermal insulation, and thereby very small heating and cooling needs. According to the international definition, a passive house typically has a peak daily average heating and cooling load below 10 W/m^2, and its annual useful heating energy demand is typically below 15 kWh/m^2a. Here usual heating energy refers to the theoretical amount of heating energy the building requires, without considering the efficiency of the heating system. The definition of a passive house can be adapted for different climates. Although a passive house has quantitative criteria, it is not meant to serve as a rigid standard, but rather a voluntary approach to building energy efficiency. (E.g. [8], [33], [34].)

3.2 Zero / nearly Zero Energy Buildings: methodologies

No internationally agreed definition for a Zero Energy Building has been established so far. Even the acronym ZEB is ambiguous: it sometimes refers to a Zero Emissions Buildings, instead of Zero Energy Building (e.g. [27], [28], [35]). In this work, the abbreviation ZEB always refers to a Zero Energy Building, if not explicitly stated otherwise.

Different national standards regarding ZEBs have been introduced, or are currently being shaped. These are discussed e.g. in [27] and [28]. Because the EU directive on the Energy Performance of Buildings (EPBD) recast sets nearly Zero Energy Buildings as the EU target, the focus of the European research and legislative processes has shifted into creating national definitions for nZEBs. The current state of these processes is reviewed in [2] and discussed more closely in Chapter 3.3.

Before either ZEB or nZEB target can be implemented in the national building codes, at least the following aspects of the energy balance calculation should be considered [28]:

Metric of the energy balance: Primary energy, end-use energy or some other parameter defined by the national energy policy?

Balancing period: Entire life-time of the building, operational lifetime of the building, or a shorter period (year, season, month)?

Types of energy included in the balance: Heating, cooling, electricity, embodied energy?

Renewable energy (RE) generation options: On-site or off-site? Should the building operator actively participate in the RE generation, or is it enough just to purchase renewable energy?

Possible special requirements for the energy efficiency or the indoor climate of the ZEB?

Possible special requirements for the building-grid interaction of the ZEB?

It is immediately evident that different selection of variables, or emphasis on different factors, gives rise to widely different calculation methodologies. A number of proposed methodologies are discussed in [28].

One key question to answer is the allowed (or preferred) location of the renewable energy generation. Most existing or proposed ZEBs and nZEBs are connected to the energy supply networks, and thus they are not physically required to generate all their energy on-site. Could a building be defined ZEB or nZEB, merely because it purchases renewable energy from the energy distribution network?

National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy has suggested the following categories for ZEBs (or NZEBs, according to their terminology) [36]:

NZEB:A	A footprint renewables Net Zero Energy Building, where renewable energy is generated within the building itself
NZEB:B	A site renewables Net Zero Energy Building, where renewable energy is generated within the building site boundary
NZEB:C	An imported renewables Net Zero Energy Building, where renewable fuel (e.g. wood pellets, biodiesel) is transported into the building site to generate renewable energy
NZEB:D	An off-site purchased renewables Net Zero Energy Building, where renewable energy is either installed off-site or at least purchased from an off-site installation

The classes from A to D establish a hierarchy, where (according to NREL) A is the most preferable and D the least preferable option. Marzal et al [35] have illustrated these generation options in their review of ZEB calculation methodologies, and the illustration is re-printed here as Figure 4. Unlike NREL, Marzal et al. do not suggest a hierarchy among the generation options I-V. They note that this is a matter of much international debate, and that various parties and organizations have their own preferences.

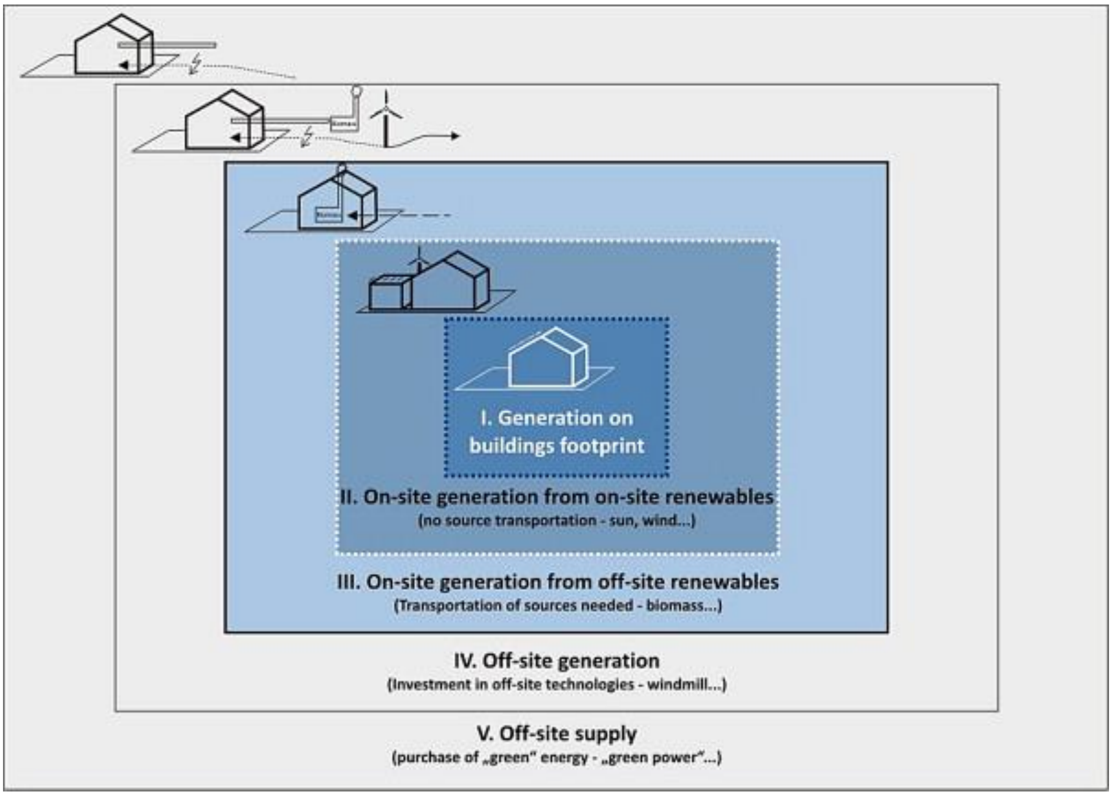

Figure 4. Possible renewable energy options on-site and off-site, re-printed from [35].

There are certain advantages in the energy generation happening as close to the building as possible. When generation systems are mounted on the building itself, there is a stronger likelihood that the energy harvesting area will stay available throughout the lifetime of the building. In case renewable energy is generated within the property, but not within the building itself (e.g. solar panels in the parking lot), there is the risk of the area being claimed for other uses in the future. Generating renewable energy with transported fuels, instead of harvesting the energy on-site, is subject to disruptions in the fuel distribution chain. Finally, renewable energy power plants entirely outside the building site boundary cannot be guaranteed to function throughout the building life-time. From this point of view, solutions mounted on the building appear as preferable; they give more control to the building owner / operator.

However, there may be a trade-offs between distributed generation and system-level energy efficiency. A ZEB / nZEB building is usually connected to one or more energy distribution networks, joining the building into the ambient energy system. It can be argued that the climate does not care whether emission reductions happen on a building level or on a regional level, as long as they happen. From this point of view, it may be more energy efficient, and perhaps also more cost efficient, to generate some of the renewable energy required by a ZEB / nZEB building off-site. These are energy system considerations and legislation aspects to be weighed by each country while crafting a national ZEB / nZEB definition. These considerations are also addressed in the COMBI project, in work package T4.5: *"Societal and legal aspects of renewable energy production off-site"*.

3.3 EU nZEB targets and national definitions

The EPBD 2010 recast sets the nZEB targets for all EU member states: new municipal buildings should be nZEBs from 1.1.2019, and all new buildings should be nZEBs from 1.1.2021. The directive itself does not define nearly Zero Energy Buildings quantitatively. According to EPBD, nZEBs should have a "very high energy efficiency", require a "low amount of energy", and produce this energy "to a very significant extent" by renewable energy sources "on-site or nearby" [3]. As Pikas et al. [37] point out, the EPBD recast in fact requires the nZEB solutions to be cost-optimal. It is not enough to erect nZEB buildings: the life-cycle costs of different energy-saving alternatives must be considered and compared. The COMBI project, as well as the specific study at hand, contribute to this field of inquiry.

It is the task of all member states to implement the nZEB targets into their national legislation. In the absence of an EU-wide definition, the first step in each individual member state is to develop a nationally appropriate definition of a nZEB. In 2015, only four member states already had the nZEB defined and the nZEB target fully implemented into their national building codes. Six member states had the definition ready and were in the process of implementing it as a target. The rest of the member states were either still developing the national nZEB definition in 2015, or did not provide sufficient information for their progress to be evaluated. [2]

Although the process of nZEB definition and implementation on the national level is still underway, some preferred methodological choices are emerging. Principal energy uses included in the balance are heating, domestic hot water (DHW), ventilation, cooling, air conditioning and lighting. Several countries also include energy use from equipment and central services. On-site, nearby and external generation all feature in the various national nZEB definitions; the most common choice is to consider both on-site and nearby generation, but not allow external generation. The most frequently used balancing period is one year, and the prevailing normalization factor is the conditioned area of the building. [2]

In the year 2015, only a minority of the EU member states had provided numerical criteria for a building nZEB performance level. The criteria typically refer to primary energy consumption, and therefore nationally accepted energy carrier factors for different primary energy forms must be defined as well. For the member states that have defined nZEB criteria based on primary energy use, the value of this indicator varies from 20 to 270 kWh/m^{2}a, depending on the member state and the building type. [2]

Even within the same building type there is very considerable variance of the nZEB target levels between the countries. For example, Cyprus suggests an energy use limit of 180 kWh/m^{2}a for a nZEB residential house, whereas in Denmark the limit is 20 kWh/m^{2}a. [2] However, the types of energy use and energy carrier factors vary between the member states, and this affects the indicator values in each country. Just by looking at the indicator value, it cannot be concluded that Cyprus allows the nZEB residential houses to use nine times the amount of energy that is allowed in Denmark.

Clearly the lack of an EU-wide definition allows for widely differing national definitions of a nZEB. In several member states, information provided on the methodological choices is also unclear or missing. Much work remains before the national nZEB criteria and evaluation methodologies are implemented in all EU member states.

3.4 Finnish nZEB definition: a work in progress

14.3.2016 the Finnish Ministry of the Environment published the draft for the new building energy efficiency legislation. Drafts of the more specific regulations, such as E-value limits for nZEB buildings and the new energy carrier factors, were published on 7.10.2016. The revision of the national building code and the new regulations will implement the EU EPBD into the Finnish national building code.

Comments on the legislation draft published in March 2016 were solicited from various stakeholders and concerned bodies (e.g. other ministries and government offices, research institutions, city councils, construction companies and non-profit organizations). The time period reserved for comments closed ended 13.5.2016. Another round for comments was issued for the regulation drafts, ending 7.11.2016.

During the initial review period, the nZEB legislation draft received a total of 75 comments from the various stakeholders [38]. According to the schedule, the legislation will be brought to parliament during autumn 2016.

In the regulation draft, the building E-value is calculated in the following manner:

$$E = \frac{f_{dist.\ heating} Q_{dist.\ heating} + f_{dist.\ cooling} Q_{dist.\ cooling} + \sum_i f_{fuel,i} Q_{fuel,i} + \sum + f_{elec.} W_{elec.}}{A_{net}} \qquad [1]$$

where

E has a unit of kWh/m^{2}a,

$Q_{\text{dist. heating}}$ is the annual district heating consumption [kWh/a],

$Q_{\text{dist. cooling}}$ is the annual district cooling consumption [kWh/a],

$Q_{\text{fuel,i}}$ is the annual consumption of fuel i [kWh/a],

$W_{\text{elec.}}$ is the annual consumption of purchased electricity from the grid [kWh/a],

$f_{\text{dist. heating}}$ is the energy carrier factor for district heating,

$f_{\text{dist. cooling}}$ is the energy carrier factor for district heating,

$f_{\text{fuel,i}}$ is the energy carrier factor for fuel I,

$f_{\text{elec.}}$ is the energy carrier factor for grid electricity,

A_{net} is the building heated net area.

Own renewable energy generated on the building or on the property, such as solar PV generation, is only implicitly present in the E-value calculation: if own generation is able to meet some of the demand, it can lower the need for purchased energy. The regulation draft suggests that selling excess renewable energy into the grid has no effect on the building E-value. [39]

The regulation draft suggests upper limits for the building E-values These are listed in Table 4. The draft for the new regulation also specifies a heat loss upper limit for the whole building. To ensure the overall energy efficiency of the building, both the E-value limit and the heat loss upper limit must be met. For the E-value requirement, some mitigations are granted e.g. for buildings with a massive wood structure. [40]

The current upper limits for the building E-values for different building classes were listed in Table 1. A direct comparison between the current and the suggested E-value requirements is not possible, because the draft for the new regulations also includes alterations to the energy carrier factors ([41], [42]). The current numeric values for the energy carrier factors, as well as the suggested new values, are listed in Table 5.

One important element of the suggested legislation is the site of the own renewable generation. According to the draft, using local generation to lower the building E-value is only possible, when the generation is situated within the same property as the building itself. Thus two buildings on the same property can share an generation facility, and both will benefit, even when the generation is physically situated on just one of the buildings. However, two buildings on neighbouring properties cannot share energy generation in this manner: the energy generated can only be utilized within the property limits. [43]

Table 4: Suggested E-value requirements by building type, according to regulation draft given 7.10.2016 [40].

Building type	E-value [kWh/(m^{2}a)]
Class 1: Single-family houses and terraced / attached houses (several sub-classes)	Depends on building size and sub-class: the strictest upper limit is 92 (for detached or terraced buildings larger than 600 m^2)
Class 2: Blocks of flats	≤90
Class 3: Office buildings, health care centres	≤100
Class 4: Commercial buildings, shopping centres, libraries, theatres, concert- and congress buildings, cinemas, museums, galleries etc.	≤135
Class 5: Accommodation buildings, hotels, dormitories, care buildings, old people's homes	≤160
Class 6: Educational and day care buildings	≤100
Class 7: Sports halls	≤100
Class 8: Hospitals	≤320
Class 9: Other buildings	No upper limit specified

Table 5. Current and suggested numerical values for energy carrier factors used in Finland ([41], [42]).

Energy form	Current energy carrier factor	Suggested energy carrier factor
Electricity	1,70	1,20
District heating	0,70	0,50
District cooling	0,40	0,28
Fossil fuels	1,00	1,00
Renewable fuels utilized on-site	0,50	0,50

During the first period of review, the Ministry of Environment received a variety of comments on the nZEB legislation draft [38]. Both positive and critical statements were issued, and in many cases, the feedback from different stakeholders has been conflicting. The system balance boundary has been subject to many comments: the suggestion to disallow RE production outside of the property limit has received both approval and disapproval.

The estimated GHG emission savings from the suggested legislation are modest. Finnish Environmental Institute has assessed the environmental impact from the E-value limits that were earlier suggested by a collaboration between the ministry and representatives of Finnish building industries (FinZEB project). It was estimated that the (previously) suggested E-value limits would have resulted in 18% decrease in building CO_2 emissions for the new buildings. [44] In the regulation draft issued for comments in October 2016, the E-value limits were revised considerably upwards from the values suggested by the FinZEB pjoject. This means that the emission reduction estimate of 18% is also revised downwards. Compared with the EU target of reducing overall GHG emissions 80% by 2050, which in itself may need to be revised to meet the targets of the Paris climate agreement, the suggested new E-value limits do not appear to be ambitious enough.

4 Nearly Zero Energy service buildings: pilot projects

4.1 Pilot nZEB service buildings in Finland

Although there is no international standard for a ZEB, and national standards for ZEBs and nZEBs are in most cases still under preparation, the building industry, expertise organizations and several other stakeholders are already applying the terms "Zero Energy Building" and "nearly Zero Energy Building". Energy efficient service buildings are also erected, both in Finland and elsewhere, and some examples of such building projects are given in this chapter. However, in most cases, data of continued usage is still missing or unpublished, so it is difficult to assess the general success in reaching the energy targets.

Järvenpään Mestariasunnot – a construction company from Järvenpää, Finland – undertook Finland's first large-scale service-sector ZEB pilot project. The company erected two buildings in 2011, both intended to produce as much renewable energy on-site as they purchase from the grid. Both buildings are multi-storey service buildings: the Kuopio building ("Asuntola Puuseppä") is an apartment block for disabled students, and the Järvenpää building ("Jamppa") is an old people's home (Figure 5). Both have individual apartments as well as communal spaces providing various services for the residents.

In 2015, after some years of operation and monitoring, a press release announced that the Jamppa building in Järvenpää had surpassed its zero energy target. On a yearly level, the building has produced more electricity than it consumed from the grid. [45] Renewable energy production within the building includes PV and solar thermal harvesting. Ventilation system has a heat recovery unit, and the braking energy of the elevator is also recovered. The building has won several awards and enjoyed some international reputation. The low-energy student dormitory in Kuopio also won an award for energy efficiency, but no extensive data is provided on its energy performance.

Figure 5. "Jamppa" ZEB / +ZEB in Järvenpää attracts international visitors. Photo: Mestariasunnot oy.

Another Finnish pilot example of an energy-effective service building is the "Onnelanpolku" old people's home in Lahti (Figure 6). The building was erected in 2014, and designed "according to the nearly Zero Energy concept". A key difference between this building and the two service buildings introduced before (Jamppa / Puuseppä) is that Onnelanpolku does not have a ground heat pump as the base heating solution. Instead, it is connected to district heating network, and uses solar thermal collectors as a heat supplement. The building also has solar PV production to supplement the electricity bought from the grid. According to the simulations, Onnelanpolku consumes 26 kWh/m^2 of electricity and 18 kWh/m^2 of heat in a year. Actual usage data from the operational phase is not yet published. [46]

Figure 6. Onnelanpolku old people's home in Lahti. Photo: Henttonen oy.

The service buildings presented in this chapter – Jamppa, Puuseppä and Onnelanpolku – have inhabitants with special needs. Indeed, this is often the case with service buildings, and especially old people's homes. Careful attention must be paid to e.g. accessibility, indoor air quality and the functionality of the common areas. If these multi-storey buildings have achieved or even surpassed their energy efficiency targets, they show it is possible to design and implement multi-storey, special-needs accommodating, nearly Zero Energy service buildings in the Finnish climate. However, further research should be performed on these and other energy efficient buildings in continuous operation, to verify their performance.

The above examples of energy efficient service buildings are old people's homes or assisted housing. A pilot example of a Finnish nearly Zero Energy educational building is Aurora school in Espoo, inaugurated in autumn 2016. The building houses an elementary school, day care and a family health care unit. Energy efficiency is implemented via passive-grade building envelope, energy efficient ventilation system with heat recovery, use of daylight and energy efficient lighting solutions. The E-value target is 80 kWh/m^{2}a (net floor area) [47]. Solar panels are also installed on the roof [48]. If the energy targets are reached in operational use, Aurora school may be the first nearly Zero Energy school operating in Finland. Vehmainen school in Tampere, one of the case studies in this research, is also designed as an energy efficient school building- but its E-value target is less ambitious (120 kWh/m^{2}a, gross area).

4.2 Pilot nZEB service buildings in Europe

Innovative and extremely energy-efficient buildings are erected worldwide, many of them utilizing renewable generation on-site. Reviewing the state-of-the-art of such low energy buildings globally, or even within EU, is outside the scope of this work; a short review can be found e.g. in [49]. This chapter is limited to reviewing some pilot examples of nearly Zero Energy, Zero Energy or Plus Energy service buildings in Europe. Peer-reviewed published articles on the subject are scarce, perhaps because many of the newly erected energy efficient buildings have not been in operation long enough to gather the necessary data. Current information on nearly Zero Energy pilot buildings in Europe is best found in conference publications and reports from various EU-funded projects.

In order to facilitate the implementation of the EPBD, the EU commission and the EU member states (plus Norway) have set up a joint initiative The Concerted Action EPBD (or EPBD CA). The consortium publishes reports on the outcomes of the EPBD in participating countries, and they have also reviewed state-of-the-art energy efficient construction and renovation projects in Europe [50]. As discussed in Chapter 3.3, most EU member states have not yet implemented the nearly Zero Energy Building requirements into their national building codes, so it is not yet possible to state with certainty that the reviewed pilot buildings will fulfil the forthcoming national nZEB criteria. The Concerted Action EPBD has considered this, and chosen to review buildings that "most probably fulfil the envisaged nZEB requirements or surpass them".

Of the state-of-the-art energy efficient buildings presented by the EPBD CA, the majority are either residential buildings or office buildings. The only old people's home included in the review is the "Jamppa" old people's home in Järvenpää, Finland, which was discussed in the previous chapter. Two public primary schools have made the EPBD CA report as likely candidates for nZEB schools: Coláiste Choilm post-primary school (a new construction) in Tullamore, Ireland and Hauptschule Schrobenhausen (a renovated school) in Schrobenhausen, Germany [50].

The Coláiste Choilm school (Figure 7) has a biomass boiler for heating, a gas-fired CHP system for both power and heat, as well as solar panels for electricity. It also utilizes other sustainable practices such as rainwater recycling and waterless urinals. The Schrobenhausen school is connected to a district heating system and has PV production on-site. Both schools utilize improved insulation and energy efficient ventilation. The calculated final energy use for Coláiste Choilm is 53 kWh/m^{2}a, corresponding to a primary energy use of 82 kWh/m^{2}a. The Schrobenhausen school building reaches a calculated final energy use of 69 kWh/m^{2}a, corresponding to primary energy use of 105 kWh/m^2 a. No data is yet provided to verify whether the energy use targets have been reached in operation. [50]

Another EU-funded research consortium, "School of the Future", investigates solely renovations and energy retrofitting of existing school buildings. The research partners are from Germany, Italy, Denmark and Norway, and the case studies are selected from these countries, as well as from France. The project reviews a variety of schools that – calculation method allowing – have reached Plus Energy status after a retrofit. As the consortium points out, in some cases this Plus Energy status is fictional, or at least not official, because according to the national building code the energy sold into the grid is not allowed to lower the building energy efficiency. For some of the schools the estimated energy balance has already been verified by measurements; for others, the monitoring is still on-going. [51]

Figure 7. Coláiste Choilm post-primary school in Tullamore, Ireland. Photo: Donal Murphy.

The methodologies of energy balance calculation vary between countries, and it is not often possible to directly compare building performances across EU member states. In any case, a wide variety of solutions exists for school building energy retrofits, and can be applied in buildings of varying ages, even historical ones. One common factor is that in the "School of the Future" project, all case schools except one utilize solar PV on-site. Own energy generation also takes place with CHP systems, solar thermal harvesting, and (in two German schools) wind power production. [51]

A valuable lesson was learned in Drammen, Norway, where the Brandengen school building (Figure 8) from 1914 was renovated. The old oil-based central heating system was designed for a supply water temperature of 80 °C. The new heating solution was based on a ground source heat pump, with an electric boiler as a back-up system. Even after the renovation, supply water temperatures above 60 °C were required for the building. Using a standard commercial heat pump solution would have led to low COP and poor heat pump performance. [52]

A new heat pump solution was designed especially for Brandengen school, allowing for the higher supply water temperatures. The design proved successful in the Brandengen case, and as a result, several heat pump manufacturers in Norway now deliver this type of heat pump solution for similar projects. In this case, a pilot project of retrofitting a public building yielded a new product on the market. Using the readily available solutions might have led to poorer energy performance, as well as a missed business opportunity. [52]

Drammen municipality in Norway has another successfully designed low-energy school building. Marienlyst school was built in 2010 and it was the first passive-grade school in Norway. As a new building, Marienlyst is not a part of the School of the Future project. After Marienlyst school began operation, its energy performance was monitored for one year. The simulated net energy use (not primary energy) was 63 kWh/m^{2}a, and after the monitoring period, the actual energy use was found to be 61 kWh/m^{2}a. It is not easy to find very exact information on many schools where the energy performance has been both simulated and verified over a period of time; Marienlyst school is one of those happy instances. [53]

Figure 8. Brandengen school in Drammen, Norway. Photo: www.veidekke.no

Examples of energy effective old people's homes are harder to find than examples of energy effective schools. One example is found in another EU-funded energy retrofit research project: Bringing Retrofit Innovation to Application in Public Buildings (BRITA in PuBs). One case study in this project is Filderhof nursing home near Stuttgart, Germany. The building dates back to 1890 and its exterior has historical elements worth preserving (e.g. balconies, door frames). A new extension was joined to the old building, and the old building was renovated in a manner that preserved its historical features. Solar PV and solar thermal collectors were installed on the roof, although these are a modern technology. [54]

The primary energy use of the Filderhof nursing home had been 397 kWh/m^{2}a before the renovation, and it was calculated to drop to 177 kWh/m^{2}a after the renovation. The renovation was even more successful than predicted: based on monitoring the renovated building usage for one year, the primary energy use was only 97 kWh/m^{2}a. The result was reached, even though excess energy sold to the grid was not allowed to affect the primary energy use calculation. During the monitoring phase of one year, Filderhof nursing home in fact produced both heat (solar thermal, CHP) and power (solar panels, CHP) more than it consumed. If the method allowed, it could be considered a Plus Energy building. [54]

In conclusion, pilot projects of ZEB or nZEB public service buildings exist in many European countries, both as new constructions and renovations. In many instances the reported energy performance of the building is based on simulations, and data is not yet available from long-term usage. In those cases where measured energy consumption is available at least for one year, the results are encouraging: buildings have attained or even surpassed their energy targets. Of course it can be asked, whether the successful projects are reported more readily and more widely than the less successful ones. Also the EU- or Europe-wide comparison between projects is difficult, because the energy balance calculation methods vary from one instance to another. Extensive comparative studies on the performance of energy effective service buildings across Europe are still lacking, and should provide a fruitful area of research.

5 Solar photovoltaics (PV) in buildings

The rate of solar photovoltaic installations is so rapid that any current statistics are soon out of date. At the end of 2014, the global installed solar capacity was 175 GW; at the end of the year 2015, it was 222 GW [55]. This represents a growth of 27%, an impressive figure for annual increase. At the end of 2015, Europe still held the largest share of installed solar capacity (43%), but the majority of the new capacity was added in Asia [56].

Despite its northern location, Finland is also suitable for PV generation. In Finland the solar photovoltaic capacity saw an increase of 50% in the year 2015. From a modest 5 MW at the end of 2014, the capacity grew to 10 MW at the end of 2015. Forecasting growth in such a rapidly changing field is difficult, but the projections for the coming years are very optimistic. An addition of more than 10 MW is predicted for the year 2016, and an addition of more than 20 MW for the year 2017 [57].

It can be said that Finland is now on the verge of photovoltaic breakthrough on the industrial level. Currently the majority of the capacity is still mid-scale (5–100 kW_p) building PV systems [58]. Such mid-scale systems, installed in public service buildings, are also the subject of this study. It is noteworthy that solar photovoltaic generation plays a role in practically all of the ZEB or nZEB service buildings described in Chapter 4, both in Finland and elsewhere in Europe. Although the nZEB criteria are not yet established in all EU member states, it already seems likely that solar PV will be a widely used method to lower the building delivered energy use across Europe.

In Southern Finland the annual solar irradiation is similar to the annual solar irradiation in northern parts of Germany. However, in Finland the large majority of the solar irradiation arrives in the summer season, so there is a greater seasonal variability than in southern parts of Europe (e.g. [59]). This introduces challenges in matching the produced and the consumed power. On the system level this is not an immediate problem during the summer season: in a typical summer day, the solar PV peak hours coincide with the electricity demand peak hours [60]. From the municipality point of view, the matching challenge occurs on the building level: some service buildings (schools, the majority of day-care centres) are closed during a large part of the summer, when solar PV production is the highest. In case of service buildings with year-round inhabitants, such as old people's homes and other forms of assisted or sheltered housing, the matching is easier.

In general, the usefulness of the solar PV for improving the building energy performance depends on the following aspects:

1. **Physical conditions**: how much solar irradiation is available at a given latitude and in the prevailing climate?
2. **Technology status**: how large portion of the solar energy can be harvested with current technologies?
3. **Building architecture**: how much of the suitable building area is available for electricity generation?
4. **Building occupation profile**: how well do the on-site PV production and electricity consumption match?
5. **Legislation**: is the excess electricity (i.e. electricity sold into the grid) allowed to lower the building E-value?

In the EU legislative framework the energy efficiency solutions should be chosen in a cost-optimal manner [3]. This presents yet another consideration:

6. **Financial constraints**: what is the cost-optimal way to lower the building E-value in a given setting (installation costs, electricity buying and selling prices)?

This study is mainly concerned with questions 4 and 6, although all of the considerations must necessarily form some part of the problem setting. Physical conditions such as solar irradiance and weather (1.) are taken into account in the building energy simulations. Solar PV technology (2.) considered in this research is not state-of-the-art variety, because the aim is not to research the newest and highest performing systems. Off-the-shelf technologies give the best idea of currently prevailing installation prices and panel performances.

The architecture of each study case (3.) must be considered, because it yields another boundary condition for the optimization problem: what is the availability of roof space for solar PV installation? However, exploring other possible building architecture options and their suitability does not form part of the research problem.

Question number 5 about the legislation is highly topical, because the new national building code is under preparation in the Ministry of the Environment. The current draft for the nZEB criteria suggests that excess electricity sold into the grid cannot lower the building E-value. In this study, it is assumed that this will also be the case with the new legislation, once it is passed. Because none of the excess electricity is beneficial from the building E-value point of view, the matching of the own production and consumption (4.) becomes the key issue.

6 Methods and data

6.1 IDA ICE building simulation tool

In order to perform the simulation-based optimization tasks, the energy consumptions of the case study buildings were simulated. The simulations for the annual building energy use were performed with a dynamic building simulation programme IDA Indoor Climate and Energy (abbreviated IDA ICE), created and maintained by EQUA Simulation AB [61]. IDA ICE can be used to simulate the annual delivered energy usage of a building, and is well suited to simulation-based optimization tasks.

Within IDA ICE, a building is divided into zones with specified heating, cooling and ventilation needs. This is important for service buildings, which can have zones in very different usages (e.g. kitchens, laundries, sport halls, classrooms, workshops). Solar illumination and shading of the building is considered, as well as wind and temperature-driven air flow. Existing weather data can be used for the simulations, making the result more realistic in terms of heating / cooling needs and PV production. A variety of pre-defined building components exist at the user's disposal, and a feature called Early Stage Building Optimization tool (ESBO) can introduce one or several renewable energy generation systems into the building simulation.

Various IDA ICE models of the three case study buildings were already created and utilized by Nyman [5], for the COMBI project task 4.1. Nyman used IDA ICE version 4.62 to find the optimal heating and cooling solutions for the three case study buildings. The heating solutions incorporated in the models were district heating (DH), ground source heat pump (GSHP), air-to-water heat pump (A2WHP) and pellet boiler (PB). Flat plate solar heat collectors were included in some of the designs to create auxiliary heat. The modelled cooling solutions for the buildings were district cooling, free cooling provided by the ground source (boreholes) and air- or water-cooled condenser chillers. Heating and cooling systems were dimensioned by simulating the energy use and living conditions with the help of climate data over a reference year. In this case the climate data used by IDA ICE was a Helsinki-Vantaa test reference year 2012 [62].

In this study, the original building simulations were modified to better suit the optimization task. The modified building simulations were performed with the current version of the programme, IDA ICE 4.7, although the simulations in the previous project task were performed with IDA ICE 4.62. The new version was used in the current work, because it has a more advanced handling of solar PV matching with the building energy consumption. The building model compatibility between IDA ICE versions 4.62 and 4.7 was checked to find out whether the switch between the models introduced changes into the simulation results. It was found that for the total energy consumption, the difference between the model results was 2–3%, due to e.g. slightly altered model for the ground source heat pump system. The deviation of 2–3% was deemed acceptable, and the remainder of the research was carried on in the IDA ICE version 4.7.

6.2 Multi-objective optimization and the Multi-objective Building Optimization tool (MOBO)

Optimization is the process of finding out the most desirable solution to a given problem. The problems than can be solved by optimization occur e.g. in technology design, resource allocation, taxation or policy measures. The outcome of a given design (or resource allocation, policy etc.) is described by an objective function, which is dependent on one or more variables. These variables are called decision variables. Optimization problem is solved by altering the values of the decision variables in some algorithmic manner, and finding a set of values that a) satisfy the boundary conditions, and b) minimize/maximise the value of the objective function. (E.g. [63], [64], [65], [66].)

In the research area of building performance, the desired target can be e.g. to minimize heat loss through the building envelope, to minimize the building operation costs, or to maximize thermal comfort. Constraints can be e.g. maximum initial investment, or maximum amount of emissions allowed in a time period. The optimization algorithm is designed to reveal the combinations of decision variables that best satisfy the objective function(s). The optimization algorithm must be chosen according to the type of problem, because no algorithm is efficient with every class of optimization problems. (E.g. [63].)

In building design, or building energy systems design, there is usually more than one objective function to be considered. When the minimization of costs is the only objective, the cost-optimal solution is often poor in quality. Minimizing the emissions or energy usage, and considering no other objectives, may lead to impractical solutions such as unnecessarily thick walls. In most practical optimization problems, several objectives are taken into account simultaneously. This practice is termed multi-objective optimization.

The multiple optimal solutions to a multi-objective optimization problem are called Pareto-optimal solutions, and they form a so-called Pareto front. Once obtained, the Pareto front yields quantitative information about the trade-offs inherent in a given problem. It may be intuitively apparent that, for example, higher price can purchase more efficient solutions: but how much more efficient, at which price? The Pareto front does not suggest a single “winning” solution, but rather gives a set of solutions where no solution dominates over the others. In the end, the decision-maker must decide between the Pareto-optimal solutions, based on individual judgment, company policy, or some other deciding factor. (E.g. [63].)

For complex systems, optimization problems can be carried out with the help of simulations. Buildings are a good example of such complex systems: they have zones with different intended uses and occupation profiles, they incorporate an assortment of building technologies, and they are subject to varying weather conditions. In a simulation-based optimization problem, decision variables are passed on to the building simulation software, which performs the building simulation. In the field of building energy research, the parameter of greatest interest is often the building (delivered or primary) energy consumption over the desired time period. After the simulation is performed, the simulation results are passed on to the optimization algorithm, which determines new candidates for the decision variables. A review of simulation-based optimization methods in building performance analysis is given in [66].

Multi-Objective Building Optimization tool, MOBO, is a free software developed for solving both single- and multi-objective optimization problems in the field of building performance research. The software was developed in cooperation between Aalto University and Technical Research Centre of Finland. MOBO can be coupled with several different kinds of building simulation programmes to solve simulation-based optimization problems. In this work MOBO is coupled with IDA ICE (see Chapter 6.4). MOBO can handle both continuous and discrete variables and constraint functions, and it has a library of optimization algorithms, including NSGA-II algorithm used in this work, and introduced in the next sub-chapter. The user can also add more algorithms, if necessary. The handling of the programme, as well as the interaction with the simulation software, is made simple with a graphical user interface (GUI), where the optimization problem is formulated. [67]

6.3 NSGA-II algorithm

The algorithm chosen for this study is NSGA-II, short for Non-dominated Sorting Genetic Algorithm II. NSGA-II was developed by Deb et al. [68], and it is shown to be well suited to solve non-linear, multi-objective optimization problem with constraints. The optimization problem of this study falls precisely within this class, and requires fast calculation times, also provided by NSGA-II. The algorithm is fully described in [68]. Its main characteristics are:

- Genetic algorithm NSGA-II is an **evolutionary algorithm**. In this class of algorithms, an initial population of solutions is tested against the objective function, after which the members of the population undergo various operations that often mimic a natural process: selecting "survivors", combining or "mating" solutions with each other, and slightly altering or "mutating" individual solutions. As a result, a new population of solutions emerges. Generations of improved solutions replace each other, and the best solutions survive to continue their existence and to "mate" with other candidates. The longest-surviving solutions in the final generation reveal the Pareto front.
- NSGA-II is an **elitist algorithm**: strong population members are good candidates for appearing in the final Pareto front, and they are not necessary recombined with other population members. Elitism in this context means that such strong candidates can "survive" into the next generation unaltered.
- NSGA-II applies **non-dominated sorting** as the process that ranks the solution into "survivors" and those that are discarded. The ranking process first selects the solutions not dominated by any other solutions. Domination in this context means that no other solution in the whole set is better than the non-dominated solution. After the non-dominated solutions are chosen, they are taken out of the population pool, which now contains a new set of non-dominated solutions. These are identified next, and taken out of the pool. The process continues, until a desired number of population members are passed on to the next population.
- **Constraints** are handled by the selection process, and by extending the definition of domination: solutions that do not violate any constraints dominate over those solutions that do violate constraints.

Tested on multi-objective, multi-constraint optimization problems, NSGA-II is a computationally fast algorithm, and able to find solutions well dispersed on the Pareto front [68]. NSGA-II has been used to solve simulation-based building energy optimization problems in e.g. [69], [70] and [71].

6.4 Simulation-based optimization: coupling MOBO with IDA ICE

Utilizing both an optimization and a simulation software, such as MOBO and IDA ICE, enables simulation-based optimization (SBO) tasks. In such an optimization task, the optimization software varies the decision variables according to the chosen optimization algorithm, and passes the variable values to the simulation software. The simulation software performs the building simulations, and passes the results back to the optimization software. The optimization software processes the results according to the optimization algorithm, and then chooses new decision variable values to be passed on to the simulation software. This is repeated until the optimization algorithm has run its course, e.g. when a desired number of generations has been processed.

Figure 9 visualizes how this process is handled with MOBO and IDA ICE (figure is based on [72] and [73]).

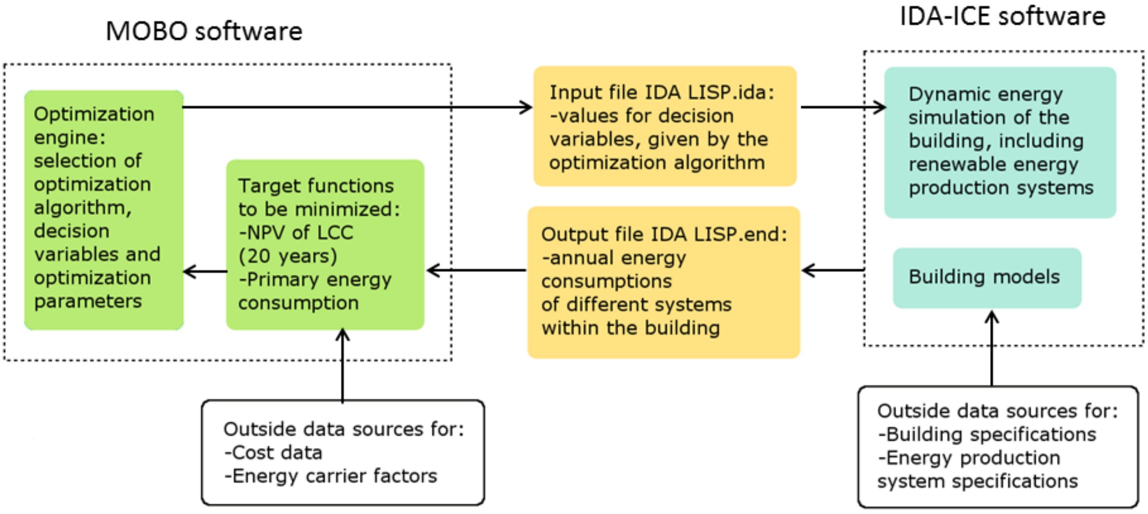

Figure 9. Communication between MOBO and IDA ICE softwares. Modified from [73].

Simulation-based optimization is a technique well suited to studying building performance. First experiments on using simulation-based optimization in building performance analysis were carried out already in the 1980s, and the technique was employed in a small number of studies in the 1990s. In the 2000s simulation-based optimization became a tool regularly used in the building performance analysis. This progress has been reviewed in [66].

More recent examples of simulation-based optimization in the field of building energy performance include a study by Delgarm et al. [71], who studied the energy performance of an office building in the climate of Iran. In this research, NSGA-II algorithm was executed in the MATLAB environment, and the building simulations were performed by EnergyPlus. Both single and multi-objective optimization tasks were performed to model and assess the energy performance of the case-study building.

Niemelä et al. [72] applied simulation-based multi-objective optimization to investigate the energy performance of an educational building in the climate of Finland. In this investigation MOBO was coupled with IDA ICE, in a manner similar to the study at hand. Niemelä et al. also considered the future Finnish nZEB regulations, and assessed various technologies and solutions that may be needed to fulfil the target. One of their findings was that own generation of solar PV is likely a cost-effective solution for improving the building energy performance, at least in cases where considerable base demand exists for electricity.

6.5 Life-cycle cost (LCC) analysis and financial data

6.5.1 Life-cycle cost calculation

A roof-top solar PV system is most often installed to generate energy for the building's own consumption. Such a system may bring in profit, but profit is not necessarily the only purpose for installing solar PV. As the EPBD directive will require new buildings to be nZEB buildings, own energy generation helps to offset some of the energy purchased from the grid. Even in that case, it is desirable to know how to install own energy production in a cost-effective manner, and life-cycle cost (LCC) analysis can be used to investigate this.

In general, the profitability of an energy production facility can be calculated with the following life-cycle cost formula (e.g. [5], [72], [73])

$$LCC = \sum I_{0,tot} + \sum M_{tot} + \sum R_{tot} + \sum E_{purchased,tot} - \sum Res_{tot} - \sum E_{sold,tot} \qquad [1]$$

where

$\sum I_{0,tot}$	Total initial investment cost for the system [€]
$\sum M_{tot}$	Total maintenance costs of the system [€]
$\sum R_{tot}$	Total replacement costs of the system [€]
$\sum E_{purchased,\ tot}$	Energy costs for running the system (e.g. fuel) [€]
$\sum Res_{tot}$	Residual value of the system after a lifetime of 20 years [€]
$\sum E_{sold,tot}$	Profit from selling the energy [€].

All values are considered over the designated life-time of the studied system, and discounted back to the present-day value.

Equation 1 can be modified for the purpose of own solar PV generation. In the COMBI project all life-cycle calculations are done for 20 years. This is a reasonable life-time for a solar panel, and therefore no panel replacement is considered. The inverter is considered in need of replacement after 15 years, and the term $\sum R_{tot}$ will describe the costs from the inverter replacement. Since solar panels in operation are almost maintenance free, there are no yearly maintenance costs are budgeted for the system, and the term $\sum M_{tot}$ becomes zero. In case some physical maintenance work (such as snow removal) should be required, this is expected to take place within the existing building maintenance arrangement. Running the system requires no fuel or other extra energy costs, and therefore the term $\sum E_{purchased,\ tot}$ can also be left out of the calculation. Note that this is just a description how Equation 1 is modified: the terms themselves, and justifications for their chosen values, are presented in the next sub-chapter.

On the profit side, the value of the energy consumed on-site must be taken into account. In case part of the own consumption was not covered by on-site solar PV, this electricity would be purchased from the grid. Normally the energy purchasing price from the grid is considerably higher than the profit from selling the same amount of energy into the grid, so this is an important term to consider.

With the above considerations, and for a life-time of 20 years, the generic Equation 1 becomes

$$LCC_{20a} = \sum I_{0,tot} + \sum R_{tot} - \sum Res_{tot} - \sum E_{used,tot} - \sum E_{sold,tot} \quad [2]$$

where

$\sum E_{used,tot}$ Purchase value of energy generated and consumed on-site [€].

All values in Equation 2 must be expressed in present-day values. For discounting future gains or profits into present-day value, a real interest rate r must be chosen. For a single transaction happening at t=k years from the initial investment (t=0), the present value factor can be derived as

$$a_k = \frac{1}{(1+r)^k} \quad [3]$$

For an annual cost, for example a yearly occurring maintenance cost, the present value factor is

$$a'_n = \frac{1-(1+r)^{-n}}{r} \quad [4]$$

The exception is yearly energy costs, for which the discounting rate must take into account both the real interest rate (r) and the energy price escalation rate (e). The resulting escalated real interest rate r_e is

$$r_e = \frac{r-e}{1+e} \quad [5]$$

The annual energy costs or energy profits are discounted to present-day value with the following present value factor

$$a''_n = \frac{1-(1+r_e)^{-n}}{r_e} \quad [6]$$

Real interest rate r and energy price escalation e are specified in the COMBI project, to make the results more easily comparable between project work packages. For the base case, real interest rate is chosen as 3%, and energy price escalation as 2%. In this work the cost of heating energy is not considered explicitly, because the self-generated solar electricity replaces only purchased electricity, and not purchased heat (e.g. district heating). Therefore in this work the energy price escalation e is the same as electricity price escalation.

The escalated real interest value is calculated according to Equation 5, and present value factors are calculated according to Equations 3, 4 and 6. The resulting LCC calculation parameters are summarized in Table 6.

Table 6: Financial parameters for the LCC calculation.

Real interest rate r	3%[1]
Energy price escalation	2%[1]
Escalated real interest rate	1%
Time period of analysis	20 a[1]
Time of inverter interval	15 a[2]
Present value factor for energy costs / profits	18,08
Present value factor for single transaction at t=15 a	0,64
Present value factor for single transaction at t=20 a	0,55

[1] Value agreed in the COMBI project.

[2] Commonly used value for inverter life-time; see next sub-chapter on “Replacement cost”.

6.5.2 Cost data for LCC calculation

Initial investment cost $I_{0,tot}$

Initial investment cost is the cost for installing the complete solar PV system, including solar panels, inverter, mountings etc. as well as the labour cost and overhead costs. In the life-cycle cost calculation this initial cost is calculated to happen at year zero, and the system life-time begins from the installation. The complete investment costs are also referred to as turn-key prices, signifying that the cost buys a system that is finalized and ready for use.

Investment costs for rooftop solar PV systems installed in Finland have recently been surveyed by Ahola [74]. During 2015, grid-connected rooftop systems installed for commercial and public buildings in the range of 10 to 250 kW$_p$ had turn-key prices ranging from 1,15 to 1,4 €/W$_p$. In a recent German survey, the installation costs of rooftop solar PV were estimated at 1,27 €/W$_p$ at the end of the year 2015 [75]. The price depends on e.g. the type of mounting, the desired panel inclination and the chosen panel model.

To construct a realistic optimization case, panel price quotes for different system sizes were obtained from a Finnish solar panel provider, using typical off-the-shelf panels. Several panel providers were consulted, and a price quote was chosen from a panel provider that was able to estimate the investment costs also for large systems (up to 1500 m^2 of panel area). According to the wishes of the panel provider, the model of the solar panel used for the quote is not disclosed here. The specifications of the solar panel used for the price quote and also for the simulations are given in Table 7.

Quoted turn-key installation costs for the solar panel system, with inverters, mounting etc. included, ranged from 1,75 €/W$_p$ to 1,11 €/W$_p$, for systems in the range of 5 kW$_p$ to 500 kW$_p$, larger systems being relatively cheaper to install (see Figure 10). For the largest part of the system size range (50–400 kW$_p$), the installation price was 1,2 €/W$_p$. This agrees well with the surveyed solar panel installation prices in Finland and in Germany at the end of 2015. Another Finnish solar panel system provider quoted (again with details kept confidential) a price of 1,16 €/W_p for a system of 100 kW_p, which further confirms that the price range used in this study is realistic.

Table 7. Technical specifications for the solar panel used in the building energy simulations.

Maximum power	280,1–285 W_p
Rated voltage	32,64 V
Rated current	8,71 A
Open circuit voltage	38,4 V
Short circuit current	9,21 A
Efficiency at standard test conditions	17,21%
Panel area	1,63 m^2
Number of cells	6 x 10
Operating temperature	-40 °C…+85 °C
Maximum wind load	2400 Pa
Maximum snow load	5400 Pa
Turn-key installation cost (5–500 kW_p)	1,75–1,11 €/W_p

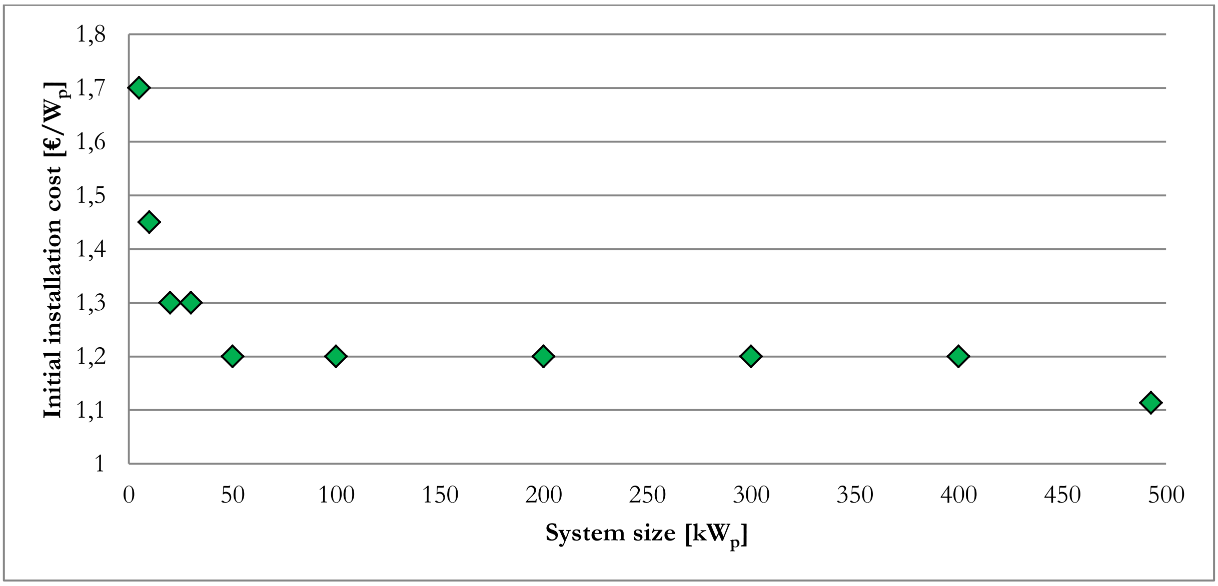

Figure 10: Solar panel initial installation cost information used for the LCC estimate of solar PV system. Initial installation cost [€/W_p] vs. system size [kW_p].

Replacement cost, R_{tot}

A maintenance cost typically assigned for solar PV systems is the replacement of the inverter, which is calculated to happen at year 15, counting from the time of installation. The cost of replacing the inverter can be estimated as 8–10% of the initial investment. Both estimates are commonly used in solar PV profitability calculations, e.g. by the FinSolar project researching the market conditions of solar energy production in Finland. [76] The estimate is backed up by recent data from the German

Fraunhofer Institute, who surveyed the installation costs of solar PV systems and inverters. At the end of 2015, the costs of the most typical inverter were approximately 0,1 €/kW$_p$, whereas the installation costs of solar PV were estimated at 1,27 €/kW$_p$ [75]. This also places inverter replacement costs at approximately 8% of the total system costs.

In this study, inverter is also assumed to be replaced at year 15, at the cost of 8% of the initial investment. No replacement of the panels themselves is considered. Because the inverter replacement occurs at year 15, the one-time investment must be discounted back to present-day value with a discounting factor of 0,64 (see Table 6).

Panel residual value, Res$_{tot}$

After 20 years of use, the solar panels themselves likely have some residual value, especially as inverter replacement at year 15 has been considered. Solar panels have some tendency to degrade and lose their efficiency over time, although the magnitude of this degradation is small for the most commonly sold panels. For monocrystalline and multicrystalline silicon solar panels, the measured degradation is in the realm of 0,1 % annually. Long-term data for degradation of more modern type of solar cells, such as thin-film based cells, is not yet available. [77] A value of 0,5 % annually is often used in profitability calculations (e.g. [76]).

A residual value for a solar panel system at the end of 20-year lifetime should take into account both the general price development of solar PV and the physical degradation of the solar cells. In Finland solar PV is just breaking through, so not enough long-term data is available, but data collected from Germany by the Fraunhofer Institute helps to assess these factors. In the past 25 years, the annual average price reduction for roof-top solar PV systems sold in Germany has been 9% [75]. According to the same source, in 2015 the installation cost of roof-top solar PV systems (ranging from 10 to 100 kW$_p$) comprised 48% panel costs and 52% other costs (e.g. inverter, mounting, labour).

Accepting a module price drop of 9% annually, panel degradation of 0,5% annually, and lastly a 48% share of the panels in the initial investment price, the residual value left after 20 years can be estimated as

$$Res_{tot} = I_0 * 0{,}91^{20} * 0{,}995^{20} * 0{,}48 \approx 0{,}066 I_0 \qquad [7]$$

Residual value of 6,6% of the original initial investment cost is assumed for the panels at the end of 20 years. In order to keep the residual value estimate on the conservative side, residual value of the inverter is not considered. The panel residual value is realized at the end of 20 years, and for the life-cycle cost calculation it should also be discounted back to present-day with a discount factor of 0,55 (see Table 6).

Purchase value of used electricity, E$_{used,tot}$

The cost of electricity and electricity transmission are key factors affecting the feasibility of own generation: with more expensive electricity and transmission, own generation becomes more attractive. Normally a client can select the energy company freely, from companies offering different electricity tariffs. This complicates the issue of solar PV optimization: which electricity price should form the basis of comparison?

In the COMBI project, the case studies are actual municipal service buildings situated in Tampere. They buy their electricity from Tampereen Sähkölaitos, which is the municipal energy company in

Tampere. It has been agreed in the project that the electricity purchase prices used in the calculations are the actual prices for the service buildings in question. For a municipal service building, the prices are without value-added tax (VAT). For the smallest case study building (Luhtaa day-care centre), the electricity price (electricity + transmission) for the year 2016 is 92,20 €/MWh, and for the two larger buildings (Jukola old people's home and Vehmainen school) the price is 81,20 €/MWh. The buildings have a different transmission fee, which accounts for the price difference. [5]

Profit from sold electricity, $E_{sold,tot}$

The selling price for electricity sold into the grid must also be considered for the life-cycle cost calculation. As for the buying price of electricity, it is not easy to determine how to form the exact reference price. A building operator can choose to sell the produced electricity for one of several energy companies, having perhaps slightly different pricing. Normally the electricity is bought and sold to the same energy company, and in this case it is assumed that the excess solar electricity is sold to Tampereen Sähkölaitos. The selling price (again without VAT) is chosen in this work as 24,1 €/MWh, based on sold electricity pricing in Tampereen Sähkölaitos, which is in turn based on the NordPool spot pricing (minus a small commission fee). In addition the electricity company pays a one-time lump sum of 30–130€ for customers setting up their own small-scale distributed generation, but this small sum is disregarded in the calculations.

Luhtaa day-care centre already has solar PV generation with some excess electricity generated during the summer. Currently the electricity company does not pay for the excess electricity fed into the grid from Luhtaa, but it may do so in the future (personal communication with Pekka Leinonen, Tampereen Sähkölaitos).

7 Case study buildings and their simulation models

This chapter introduces the selected case-study buildings: Luhtaa day-care centre, Jukola old people's home and Vehmainen school. All the buildings are situated in Tampere, within 10 km of the city centre (61°30'N, 23°44'E). They represent different types of challenges in low-energy construction within the municipal building sector. Jukola is a renovated care building dating from 1955. Luhtaa day-care centre and Vehmainen school are new buildings: Luhtaa day-care centre has been in use since 2012, and Vehmainen school was inaugurated in autumn 2016.

In COMBI work package 4.1, IDA ICE building simulation models were utilized to find the optimal heating and cooling solutions for the case study buildings. This chapter gives an overview of the building models. The buildings and their original simulation are thoroughly reviewed in [5], so the detailed descriptions are not repeated here. The simulated building and HVAC systems were simplified and otherwise modified for the purposes of this study, and these alterations are described in detail in Chapter 7.4.

7.1 Luhtaa day-care centre

Luhtaa day-care centre, approximately 6 km from central Tampere, is the first passive-grade day-care building in Finland. The decision on building Luhtaa day-care centre was made in 2007, and the project plan was formulated in 2010. The building was inaugurated in early 2012, and now provides day-care and pre-school education for approximately 120 children. Luhtaa day-care centre has a net floor area of 1438 m^2. [78] Figure 11 shows a design drawing of the building.

Figure 11. Axonometric drawing of Luhtaa day-care centre. Image from BST-Arkkitehdit Oy [78].

Luhtaa day-care centre is one of Tampere city's low energy building pilot projects. According to the design-phase simulations, the building was to reach energy class A, and also to fulfil the passive-grade building requirements, with annual primary energy use of 135 kWh/brm^2 or less. According to design phase simulations the building consumed 84 kWh/brm^{2}a, and calculated with German energy carrier factors this resulted in primary energy use 156 kWh/brm^{2}a. This was more than the targeted passive grade primary energy consumption, so own renewable generation was installed to produce some of the required energy on-site. [78]

Both solar thermal and solar PV technologies were considered in the planning phase, and solar PV was decided to be the more efficient way to improve the building energy performance [78]. The building was equipped with 56 TopSun TS-S390 solar panels, each with a nominal power of 390 W_p. The total area of the panels is 143 m^2. The panels face south-west and are placed in a 23° angle to the horizon (see Figure 12). The total nominal power of the system is 21,8 kW_p. [79]

Figure 12. Luhtaa day-care centre photographed 9.4.2016. Photo: Paula Sankelo.

Several other methods, both passive and active, were applied in Luhtaa to reach the energy target. The day-care building has a wood frame construction. The total thickness of the walls is 500 mm, with 400 mm of insulation. All building elements, including doors and windows, have a low U-value, and passive methods are applied for solar shading. Temperature efficiency of heat recovery varies between 60% and 80% depending on the air handling unit (AHU). [78]

In the work package 4.1, it was found that the optimal heating solution for Luhtaa would be GSHP, having both lowest costs and lowest primary energy use. The actual heating system in Luhtaa is district heating, with the connection dimensioned at 1,8 m^3/h. The heating set-point temperature is 21 °C. Heat is distributed via water-based floor heating on the ground floor, and water-based radiators in the basement and ventilation system. Dimensioning of floor heating and radiator heating capacities are performed in IDA ICE for Tampere design temperature of -29 °C. [5]

The basement houses three centralized air-handling units, all equipped with heat recovery. One of the AHUs is designated for the kitchen only, and provides also cooling for the kitchen. In reality, only the kitchen space is cooled. A cooling setpoint of 25 °C was utilized in the simulation model for this study, and it was found that the simulated indoor temperatures violated the target of 25 °C, which is the target maximum indoor temperature recommended by the national building code [13]. To prevent the violation of the target, the simulated AHUs were all equipped with supply air cooling. [5]

The building usage profiles for the Luhtaa building model, as well as for the other case-study building models, are based on 1) profiles defined by the The Finnish Association of HVAC Societies (FINVAC), 2) building user interviews and 3) measured data. FINVAC suggests standard building occupancy profiles (available at http://www.finvac.org), and in these models, the standard profiles have been modified somewhat (but not extensively) according to the interviews with the building users. Domestic hot water (DHW) consumption is modelled with the help of measured data. The resulting occupancy profiles for all three case study buildings have been explained in detail in [5], and they are not repeated here. Luhtaa day-care building is assumed unoccupied during weekends and holidays.

Figure 13 shows the 3D visualization of the Luhtaa day-care centre in the original IDA ICE model, without the existing solar PV incorporated into the model. In the 3D view the model is shown in the original form, because it gives a more realistic view of the doors and the windows, and therefore shows a more correct outside appearance of the building. Luhtaa has roof planes facing south-east, south-west and west. By design, it is well suited for solar PV production. A rough estimate of the best suited roof area available for panel installation is 600 m^2, and this has been set as the maximum panel area in the optimization runs.

Figure 13. IDA-ICE model showing the building envelope of Luhtaa day-care centre, without the existing solar panels.

Virhe. Viitteen lähdettä ei löytynyt. shows the floor plan for the ground floor. This time the view is of the modified model, already simplified for the optimization purposes e.g. by combining some building zones together. The simplification process is explained in Chapter 7.4. The detailed zone divisions in the original, un-simplified models are shown in [5], where the original building model is documented in detail.

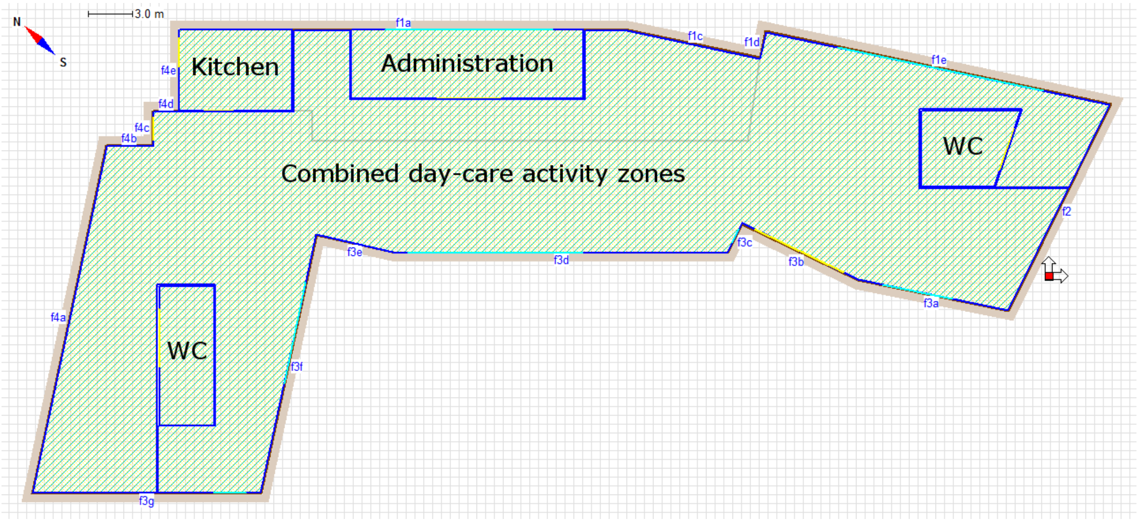

Figure 14. Floor plan of Luhtaa modified IDA ICE building model, with simplified zone division, ground level. The building also has a basement space.

7.2 Jukola in Koukkuniemi old people's home

Jukola is a sheltered residence for elderly people, 2 km away from Tampere city centre. Jukola building belongs to Koukkuniemi old people's housing complex, which has been residing in the location for more than 125 years. The oldest hospital or care buildings in Koukkuniemi were demolished in the 1950, and new buildings were erected. One of these new buildings erected in the 1950s was Jukola, originally built to house 208 residents. [80]

Finished in 1955, Jukola is a concrete building with 5 floors and a floor area of 4709 m^2. It has a brick exterior finished with plastering, and a hip roof made of clay tiles. Jukola functioned as old people's home until 2009, when it was deemed to be in poor condition and badly suited for modern care housing. Some day-time activities took place in Jukola until 2010, when they too were ceased. The building was then in near-original condition, having undergone only small reparations and alterations during 55 years of operation. [80]

It was decided that Jukola should undergo a complete modernization, and a new extension called Impivaara was to be attached into Jukola (see Figure 15). The renovated Jukola was designed to provide sheltered housing in 67 apartments, organized into five group homes, one on each floor. The new extension Impivaara was designed for intensified sheltered housing, with care available 24/7. [80]

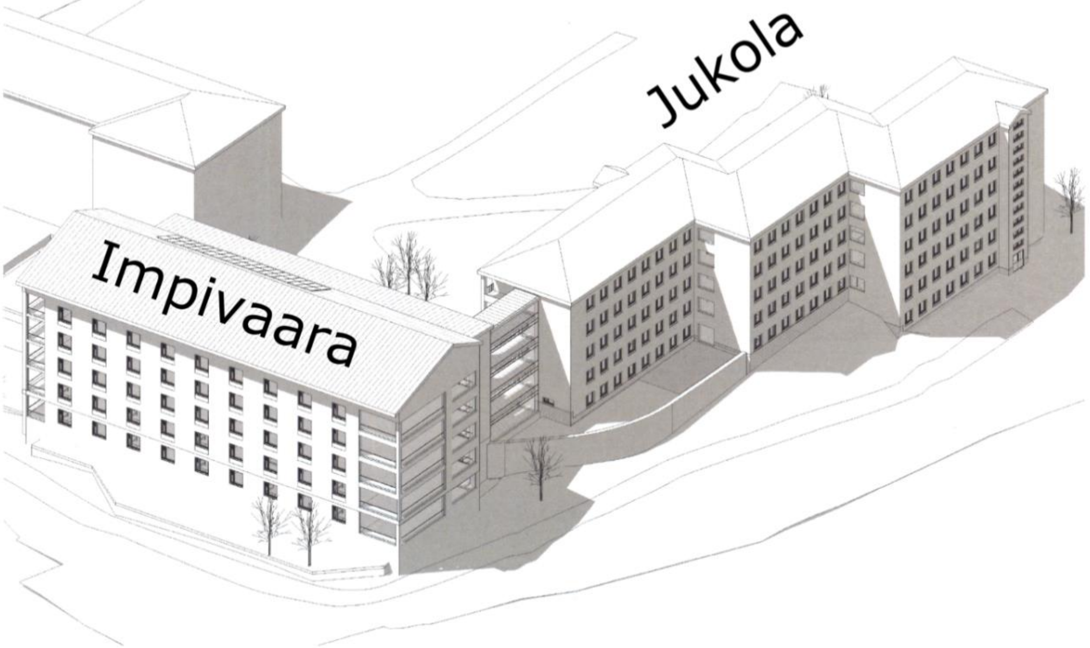

Figure 15. Conceptual drawing of modernized Jukola wing, with the new building Impivaara attached (in the foreground). Image based on BST Arkkitehdit Oy [80].

The renovation aim for Jukola was to provide sheltered living with an energy efficient manner. The new extension Impivaara was planned to reach energy class A for care buildings (<160 kWh/m^{2}a), and the renovated Jukola was to reach energy class C (201–260 kWh/m^{2}a). Passive methods were emphasized: heat losses through walls were minimized, and shading was installed to prevent overheating. Active methods to improve energy efficiency included energy efficient lighting, exhaust air heat recovery and utilizing the nearby lake water in cooling the ventilation supply air in summertime. [80] The original renovation plan was to utilize the lake water also for heating the incoming air in winter. The arrangement was tested in winter 2014–2015 and it was deemed unprofitable, so the practice was discontinued [81].

The optimal heating system for Jukola, defined in the previous project task [5], is air-to-water heat pump (A2WHP). The actual heating system in Jukola is district heating, with the connection to the municipal district heating network dimensioned at 5,2 m^3/h. Heat is distributed via water-based radiators and the heating set-point temperature is 22 °C. The design supply and return water temperatures on the actual radiators are (65/35°) at the design outdoor temperature of Tampere (-29°C). When heat pump solutions were considered in the models, low temperature radiators (45/35°C) were incorporated into the models as needed. This is more closely explained in [5].

Jukola has three separate "wings", and each wing is assigned its own air-handling unit. A fourth AHU is assigned for the basement. All AHUs are equipped with heat recovery units with 60% temperature efficiency. The AHUs are always on, but can be operated at either slow of fast speed, according to the schedule of each unit. The Jukola basement houses a water-to-air chiller, providing cooling that can be distributed by the AHUs. In the building simulations, each AHU was provided with supply air cooling, and 25 °C was chosen as the cooling set-point. This is also the target value specified by the national building code [13]. In some cases the zone temperatures in the building simulation violated the target maximum indoor temperature of 25 °C, and in those instances additional space cooling was introduced to the zone. [5]

Similar to Luhtaa day-care centre, the Jukola building occupancy profiles are based on 1) profiles defined by the The Finnish Association of HVAC Societies (FINVAC), 2) building user interviews and 3) measured data. The resulting occupancy profiles for all three case study buildings have been explained in detail in [5], and they are not repeated here.

Figure 16 shows the 3D visualization of the original IDA ICE model for Jukola. In the model the floors 2–4 are identical with floor 1, and the visualization does now show them separately. In reality some differences exist between these floors (minor variations in balconies, terraces and apartment division), but these can be ignored for the energy modelling purposes [5]. Again the 3D view is of the original model, but Figure 17 shows the floor plan of the downstairs levels in the simplified version, modified for the optimization purposes. The more detailed zone division of the original model is documented in [5].

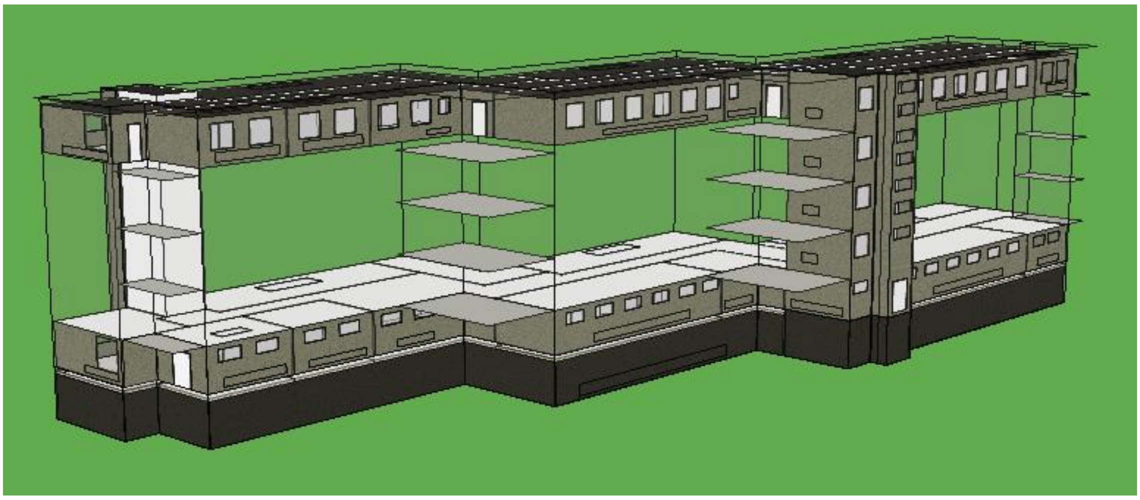

Figure 16. IDA ICE model showing the envelope of the modelled Jukola building. Floors 2–4 are identical to floor 1, and therefore they are not separately shown in this visualization.

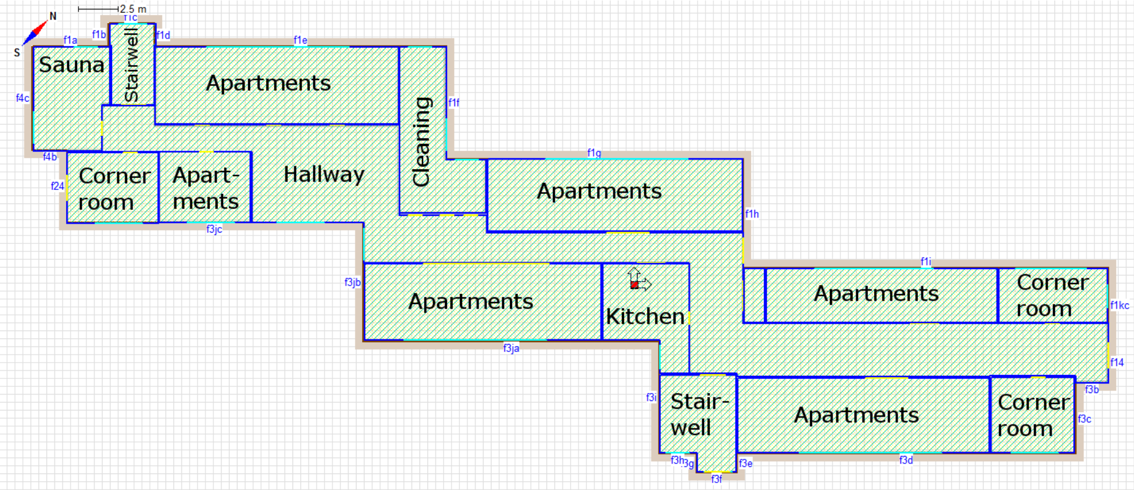

Figure 17. Floor plan of Jukola modified IDA ICE building model, with simplified zone division, levels 1–4. Level 5 is very similar to levels 1–4. WC and and shower spaces are situated in the apartments.

As illustrated by Figure 18, Jukola does not have abundant roof space for solar panel installation. One of the long façades of the building faces south-west, which is a suitable direction. From the technical drawings, a rough estimate was made of 200 m² available for solar panel installation. In the end, the optimization runs were made for even larger solar PV systems (this is explained in Chapter 9).

Figure 18. Jukola building photographed 9.4.2016. Photo: Paula Sankelo.

7.3 Vehmainen elementary school and day-care

Vehmainen school is the newest of the case-study buildings, located 10 km away from Tampere city centre. Use of the previous school building, dating from 1968, was discontinued in 2013 due to extensive indoor air quality problems and poor accessibility. The decision on the new building was made in 2013, the project plans were drawn in 2014, and the construction was undertaken in 2015–2016. [82] Vehmainen school was inaugurated in August 2016. Day-care groups and pre-school education classes are also incorporated into the new school building. Figure 19 shows a conceptual drawing of the school.

Figure 19. Conceptual drawing of Vehmainen school. Image from Arkkitehtitoimisto Perko Oy

The new school building accommodates 410 children in school / pre-school and 160 children in day-care. It has net floor area of 6379 m^2, on two floors. Just like in the case of Luhtaa day-care centre, Vehmainen school is designed to allow evening usage "as extensively as possible". This may have an effect on the future energy consumption of the building. [82]

The minimum energy class target for the building was energy class C, but the aim was to reach energy class A (< 120 kWh/br-m^2) if economically feasible. The methods for lowering the energy consumption are e.g. energy-efficient HVAC technology, including exhaust air heat recovery with a temperature efficiency of 50-75% depending on the AHU. Lighting is also energy efficient, equipped with motion detectors. Structural solutions are designed to protect the building from overheating. [82]

Vehmainen school is a concrete building, with extensive glazed wall areas facing west and east. These are realized as solar shading windows. Daylight penetrates further into the building with the help of indoor windows. [5] The roof has a large plane facing south, and provides ample space for solar PV installation. For the purposes of the modelling, the available roof space for solar PV is roughly estimated at 1500 m^2.

Figure 20 shows the 3D view of the original building modelled with IDA ICE, and Figure 21 shows the modified plan of the 1st floor, with the simplified zone division in its main characteristics. The original zone division is documented in [5]. Some of the solar shading windows are visible in Figure 22, which was taken in April 2016, during the construction of the building.

Similar to Luhtaa day-care centre, the optimal heating system for the building was found to be GSHP [5]. The actual heating system in Vehmainen is district heating, with a connection of 10 m^3/h. The heating set-point temperature is 21 °C. Heating is distributed via water-based floor heating in the day-care areas and dressing rooms, and via water-based radiators in all other spaces. Dimensioning of floor heating and radiator capacities is realized in IDA ICE at Tampere design temperature of -29 °C. [5]

The building is served by 12 centralized AHUs. Cooling is applied via AHUs with cooling circuits, or with air condensing units. In the actual building, cooling is provided in the kitchen, library and administration rooms, as well as some classrooms (computing, acting, music). Additional cooling units may be installed into the building in the future, if they turn out to be necessary. [5]

In this study, a cooling set point of 25 °C was again utilized. Similarly to Luhtaa and Jukola cases, some zones of the building experienced indoor temperatures greater than the target value of 25 °C. In the simulations all AHUs are equipped with supply air cooling, and space cooling is also provided into the critical zones. [5]

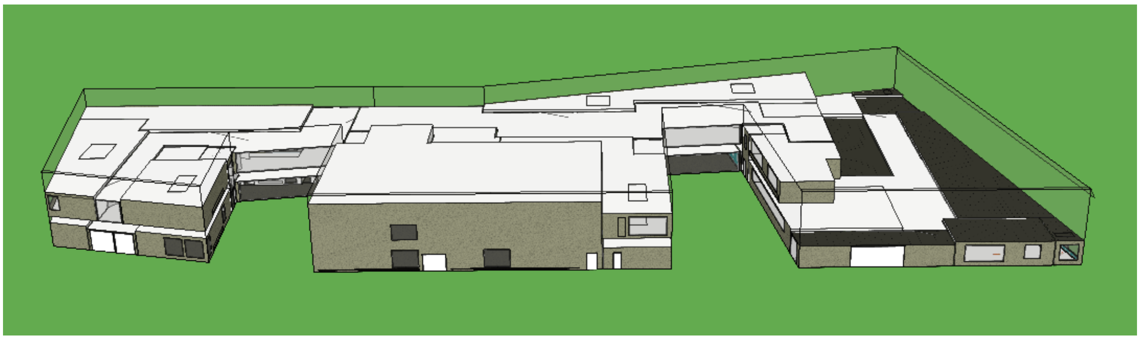

Figure 20. IDA ICE model showing the building envelope of Vehmainen school.

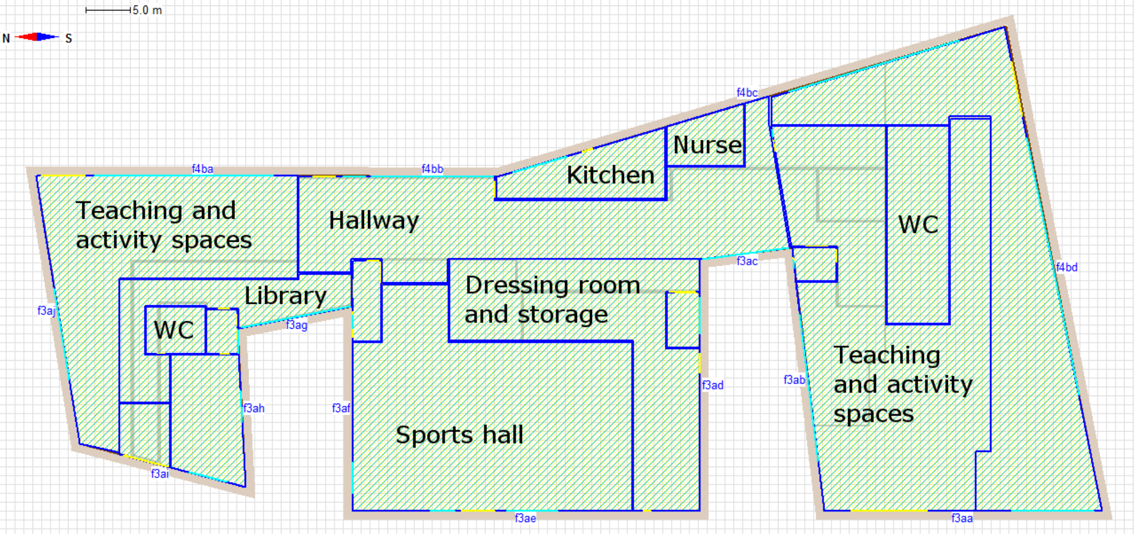

Figure 21. Floor plan of Vehmainen modified IDA ICE building model, with simplified zone division, ground floor. The school also has a 2nd floor.

Building usage profiles are once again based on the FINVAC profiles, with some modifications. The building has two vacation schedules: one for the day-care and one for the school. School staff and pupils have an additional holiday in spring and autumn, as well as longer summer and Christmas holidays. Occupancy during evenings and weekends was assumed to be always zero, which may not be the case in the future, in case the school premises are being used for hobbies and other extra activities. Building occupancy profiles and operation schedules, as well as the building technology, are discussed in more detail in [5].

Figure 22. Vehmainen school and day-care centre construction site photographed 9.4.2016. Photo: Paula Sankelo

7.4 Processing and running the building simulation models

In order to perform the optimization tasks, the original detailed building models [5] were simplified to reduce the simulation times. Simulations with the original building models were cumbersome: simulation times varied from 34 minutes to more than 6 hours (see Table 8). The original building models were thus impractical to use for optimization problems that called for several hundreds of simulation rounds. Because the optimization software required information on delivered energy of the whole building, and not any specifics concerning the various building zones, the models could be significantly simplified in terms of zones, and still reproduce the correct yearly energy demand.

The original building models were treated in the following manner:

- Internal windows were removed
- External windows facing in the same direction were combined, preserving the total window area
- Internal doors were removed, with the exception of stairwell doors (to preserve the stack effect)
- External doors were combined, preserving the total door area
- Air handling units were combined, where possible (i.e. in zones where they were operating by the same schedule)
- Zones with the same usage profile were joined together, averaging the relevant characteristics (e.g. heating, cooling, ventilation) of each zone
- Hot water radiators and cooling beams were combined where possible, preserving the total heating and cooling power and also radiator area, where wall geometry allowed

The model simplification was in many respects a matter of trial and error, and because the initial simulation times were long, it was a time-consuming task. Model modification was carried on until all feasible simplifications were performed, or until the error in the yearly energy consumption exceeded 5%. In all but one case, this brought the model running times in the realm of minutes rather than hours (see Table 8). The differences in the energy results between the simplified and the original models were in the end 1–4 %. This was deemed acceptable, and the optimization tasks were performed with the simplified models.

As the next step, solar PV panels were introduced into the building models, with the help of the ESBO plant extension in IDA ICE. The specifications of the solar PV panel used in the simulations were given in Table 7, but in fact the only relevant technical specification in the model is the panel efficiency (17,21%).

Panel area and panel inclination were chosen as decision variables, and they were passed on to the building simulation model by the optimization software MOBO. Panel inclination varied in all optimization cases between 30° and 60°, with a step of 1°. Panel area varied from 1,6 m^2 (the area of one panel) to the maximum allowed area, in steps of 1,6 m^2. Panel area A=0 was not allowed, because it could have led to division by zero in the optimization algorithm. Maximum values for the panel area were estimated separately for each building, from the building drawings and other available documents, as explained earlier.

Table 8. Comparison between the original and the simplified building models for the case study buildings.

Building model	Number of zones in the original model	Number of zones in the simplified model	Running time of the original model	Running time of the simplified model	Difference in total annual energy consumption between the models
Luhtaa day-care centre, GSHP	13	6	1 h 19 min	22 min	-1%
Luhtaa day-care centre, DH	13	6	34 min	9 min	-1%
Jukola old people's home, A2WHP	31	23	3 h 49 min	49 min	-1%
Jukola old people's home, DH	31	23	1 h 31 min	19 min	-4%
Vehmainen school, GSHP	39	26	6 h 6 min	1 h 42 min	-2%
Vehmainen school, DH	39	26	3 h 6 min	35 min	1%

In each building model, the panels were placed in the most suitable roof plane; these faced south (Vehmainen), south-east (Jukola) or south-west (Luhtaa). The sizing and the placing of the solar PV was therefore roughly realistic. However, the IDA ICE programme does not allow for multiple rows of panels or panels facing multiple directions, so the solar PV installation was not considered in full architectural detail. The aim of the study was not to design the best possible solar PV installation for the case study buildings, but rather to find out how large a PV installation would be feasible with the building electricity consumption in each case.

For each building simulation, MOBO optimization software chose the values of the decision variables and passed them on to the IDA ICE building model (see Figure 9 in Chapter 6.4). The numerical values for the decision variables were chosen according to the optimization algorithm NSGA-II. When running the Luhtaa models, the algorithm was performed with a population of 12, for 100 generations, totalling 1200 simulations in a perfect run. Typically, in each run, 1–2 of the individual simulations came to a halt due to technical problems. This did not have a negative effect on the overall optimization task, except in one occasion where a faulty solution caused the final population of solutions to be poorly dispersed on the Pareto front. This is documented more closely in Chapter 9.

From the Luhtaa optimization runs, and from initial testing with the Jukola and Vehmainen models, it became clear that all 100 generations (1200 simulations) were not needed to find the Pareto front of the optimal solutions. After this finding, 50 generations were used for Jukola and Vehmainen and for the sensitivity analysis cases, totalling 600 building simulations in a perfect run.

8 Optimization cases

The optimization cases take the basic form

Minimize

$LCC_{20a}=\sum I_{0,tot}+\sum R_{tot}-\sum Res_{tot}-\sum E_{used,tot}-\sum E_{sold,tot}$

PE=primary energy use = $1{,}2*Q_{electricity}+0{,}5*Q_{DH}$

with decision variables

A=solar panel area [m^2]

β=panel inclination angle [°]

subject to

$1{,}6\ m^2 \leq$ panel area $\leq A_{max}$

$30° \leq$ panel inclination $\leq 60°$

$Q_{electricity}$ is the annual consumption of delivered electricity per building area

Q_{DH} is the annual consumption of district heating per building area (if any is consumed)

A_{max} is defined according to the building geometry

PE is primary energy use according to the energy carrier factors, which are defined by the legislator

1,2 and 0,5 are the suggested energy carrier factors for electricity and district heating, respectively (see Table 5)

Terms in the LCC_{20a} equation are explained in Chapter 6.5.1. (Equations 1 and 2).

The optimization cases that were set up for this study are listed in Table 9, and shown in a schematic way in Figure 23. In all these base cases 1–8, the real interest rate is chosen as r=3%, and energy price escalation is e=2%. The actual electricity price for Luhtaa is 92,2 €/MWh, and for Jukola and Vehmainen it is 81,2 €/MWh. For the sake of comparison, all Jukola and Vehmainen optimization cases were also tried with electricity price 92,2 €/MWh (cases 3b, 4b, 5b, and 6b). The maximum panel area A_{max} is 600 m^2 for Luhtaa, 1500 m^2 for Vehmainen and initially was chosen as 200 m^2 for Jukola, although this constraint was relaxed during the research.

After the results from the base cases were found, some additional sensitivity analysis for the calculation parameters was performed by setting up more optimization cases (cases 9–16). These are discussed in Chapter 9.4.

Table 9. Basic optimization cases (1–8).

Identifier	Building	Heating solution	Electricity use	Electricity price
Case 1	Luhtaa	DH	Modelled	92,2 €/MWh
Case 2	Luhtaa	GSHP	Modelled	92,2 €/MWh
Case 3a	Jukola	DH	Modelled	81,2 €/MWh
Case 3b	Jukola	DH	Modelled	92,2 €/MWh
Case 4a	Jukola	A2WHP	Modelled	81,2 €/MWh
Case 4b	Jukola	A2WHP	Modelled	92,2 €/MWh
Case 5a	Vehmainen	DH	Modelled	81,2 €/MWh
Case 5b	Vehmainen	DH	Modelled	92,2 €/MWh
Case 6a	Vehmainen	GSHP	Modelled	81,2 €/MWh
Case 6b	Vehmainen	GSHP	Modelled	92,2 €/MWh
Case 7	Luhtaa	DH	Measured	92,2 €/MWh
Case 8	Luhtaa	GSHP	Measured	92,2 €/MWh

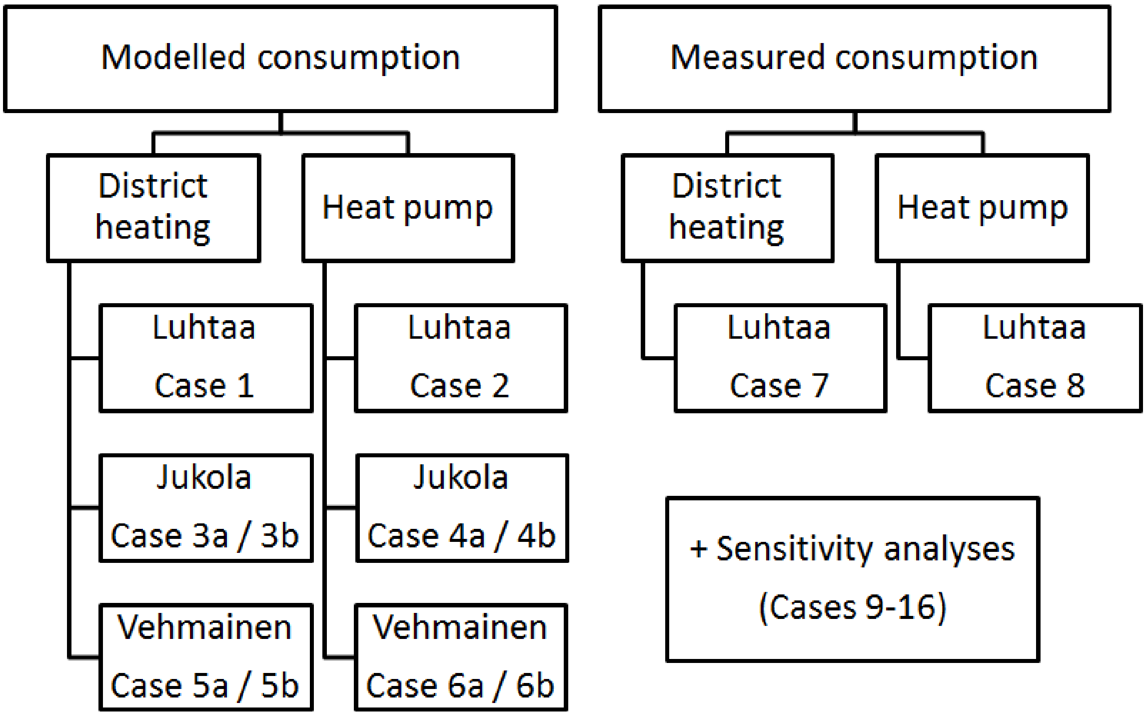

Figure 23. A schematic view of the optimization cases.

The distinction between modelled and measured electricity use for Luhtaa day-care centre is discussed in detail in Chapter 9.2. In short, electricity consumption data exists for Luhtaa, and it shows that the actual Luhtaa electricity consumption is larger than in the building models. This actual electricity consumption data for Luhtaa is utilized in Case 7 and Case 8, to find out if it affects the optimal solutions. Unfortunately, the same investigation cannot be done for the

Vehmainen and Jukola buildings. Vehmainen school started operation in August 2016, so a representative period of measured electricity consumption is not yet available. Jukola shares electricity meter with several other buildings, and thus the electricity consumption from Jukola itself is not known.

Before proceeding to the results of the energy simulations with solar PV, Table 10 lists the primary energy consumptions yielded by the building models for the optimization cases 1–6, when no solar PV production is considered (PV area = 0). These values provide the comparison with the optimization cases of PV installed. The total primary energy consumption includes both heat and electricity for the DH cases; for heat pump cases, all the delivered energy is in the form of electricity. Building primary energy consumption is not given for cases 7–8, because the measured electricity consumption from Luhtaa includes consumption from all the day-care property (outdoor lighting etc.) and not just the building itself. This is also more closely discussed in Chapter 9.2.

Table 10 demonstrates the effect from the chosen energy carrier factors. In these case-study buildings, the suggested revision of the numerical energy carrier factors already lowers the building primary energy use by several tens of kWh/m^{2}a. For all the results in Chapter 9, the primary energy consumptions are calculated with the suggested new energy carrier factors.

The nZEB legislation draft suggests E-value limit of 160 kWh/m^{2}a for a new old people's home, and 100 kWh/m^{2}a for a new school or a day-care building. These suggested upper limits provide some comparison with the primary energy consumptions listed in Table 10. With the current energy carrier factors, none of these modelled case study buildings would reach the nZEB target. By switching into the suggested new energy carrier factors, all the case study buildings would fulfil the nZEB target. Note, however, that in these cases the modelled building use is not performed exactly according to the specified E-value calculation, because design values and actual usage of the building is used as input data of the simulation. The primary energy consumptions listed here are therefore *not* the same as the building E-values; they are approximately 15–20 % larger (Juha Jokisalo, personal communication). Also old buildings such as Jukola are not expected to fulfil the nZEB E-value targets in any case. This comparison mainly illustrates the significant effect that arises from the energy carrier factor revision.

Table 10. Delivered energy and primary energy consumption for the case study buildings, according to the energy simulations without solar PV production. Numerical values for current and suggested new energy carrier factors are listed in Table 5 (Chapter 3.4).

Case ID	Building	Heating solution	Delivered energy [kWh/m^{2}a]	Primary energy use with suggested energy carrier factors [kWh/m^{2}a]	Primary energy use with current energy carrier factors [kWh/m^{2}a]
Case 1	Luhtaa	DH	117	92	127
Case 2	Luhtaa	GSHP	66	79	112
Case 3 (a&b)	Jukola	DH	182	140	198
Case 4 (a&b)	Jukola	A2WHP	106	127	180
Case 5 (a&b)	Vehmainen	DH	118	92	129
Case 6 (a&b)	Vehmainen	GSHP	63	76	108

9 Results and discussion

9.1 Optimal solutions: modelled building energy consumption

9.1.1 Case 1: Luhtaa day-care centre with DH

Figure 24 shows the optimization results for case 1, Luhtaa day-care centre with district heating as the main heating option. This is the heating option actually used in the building.

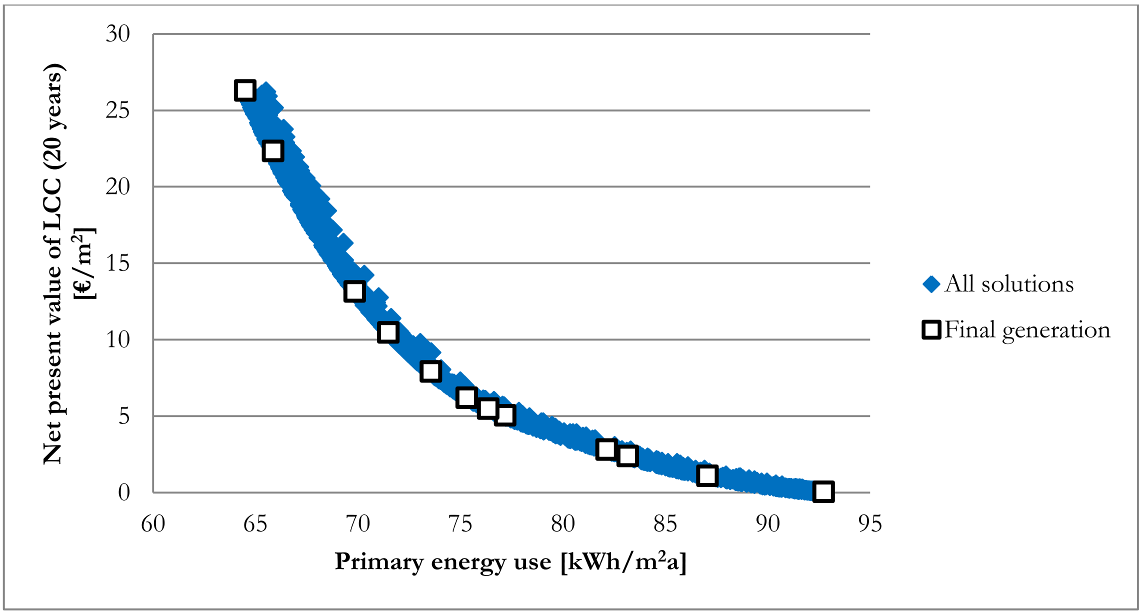

Figure 24. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m^2.

In Figure 24, as in most other figures in this chapter, Y-axis shows the net present value (NPV) of system life-cycle cost (LCC). This is the amount of cost (or profit) that installing the system will create during its life-time of 20 years, compared with the alternative of no PV installation. The life-cycle cost is normalized by the building area and expressed as €/m^2, so that the results are comparable between different case studies. X-axis shows the annual primary energy use of the building, calculated with the suggested new energy carrier factors, and also normalized by the building area.

In the figures of this chapter, the colourful markers show the solutions of all the individual simulations. The final generation of solutions produced by the optimization algorithm, in this case generation 100, is plotted separately. This final generation is the actual optimization result: the final generation reveals the Pareto front, where the optimal solutions lay. All the solutions on the Pareto front are equally good in minimizing the two objective functions, LCC and primary energy use.

In fact all the points on the Pareto front are equally good: here a population of 12 was used to find the Pareto front, but choosing a larger population size would have yielded more points in the final Pareto front. In this sense, the solutions plotted with the white square markers are not the only best solutions, they just reveal the shape of the front where all the best solutions lay. It is up to the decision maker, designer, or other end user, which point from this Pareto front is chosen to solve a design problem. It is noteworthy than in this case, the shape of the Pareto front is rather clear even without plotting the final generation separately. This is not the case with all optimization problems, and the less so, the more complicated the problem is.

The Pareto front yields information about the trade-offs inherent in the system. Does lowering the primary energy use always increase the life-cycle cost? In case 1, shown in Figure 24, this is true. All the LCC values shown on the y-axis are above zero, so the installing solar PV always incurs a life-cycle cost. The lowest lice-cycle cost occurs when no solar PV is installed (right side of the figure), and the highest LCC occurs when the maximum allowed area (600 m^2) is filled with solar panels (left side of the figure). The two objectives are always in conflict. With no solar PV installed, the need for delivered energy approaches 92 kWh/m^{2}a, as it should (see Table 10). With the maximum installation area of 600 m^2, solar PV can lower the primary energy consumption to 65 kWh/m^{2}a, a decrease of 27 kWh/m^{2}a (29%). This has a life-cycle cost of 26 €/m^2.

The optimization algorithm had two decision variables: solar panel area and panel inclination. The angle for maximizing the year-round solar PV production in Tampere is 42° [83], but the angle that maximizes the overall production is not necessarily the same as the angle that minimizes the LCC (or maximizes the profit). With inclination angles lower than 42°, more direct sunlight is captured in the summer months, but it is not usually financially profitable to produce much extra electricity in mid-summer. The optimal angle depends on the electricity usage profile of the building throughout the year.

From the optimization results, it turns out that the solar panel area is the dominating decision variable: it has a greater effect on both the LCC and primary energy use than the installation angle. This is illustrated by Figure 25 and Figure 26. Figure 25 shows both the life-cycle cost and the primary energy use plotted as the function of the panel area. The plots are shown in the same figure, because this reveals the conflicting nature of the two objectives. Blue curve shows the LCC, which approaches zero as the panel area approaches zero, and reaches its maximum of 26 €/m^2 as the panel area approaches 600 m^2. The scale for the LCC is shown on the left y-axis. The red curve shows the primary energy use of the building, which approaches 92 kWh/m^{2}a when the panel area approaches zero, and 65 kWh/m^{2}a as the panel area approaches 600 m^2. The scale for the primary energy use is shown on the right y-axis. In this way, Figure 25 reveals much the same information as Figure 24, but here the role of the panel area is made explicit.

Note that the final generation of solutions shown for both curves are in fact the same final generation. Each solution in the final generation has a numerical value for both decision variables (panel area, panel inclination) and a numerical value for both objective functions (LCC, primary energy use). Visualizing the results for multiple-objective optimization problems, having multiple decision variables, can be very challenging, and cannot be done in traditional 2D plots. In this study this is not a problem, because the effect arising from the panel inclination is largely dominated by the panel area, and here it is more important to discuss the effect of the panel area.

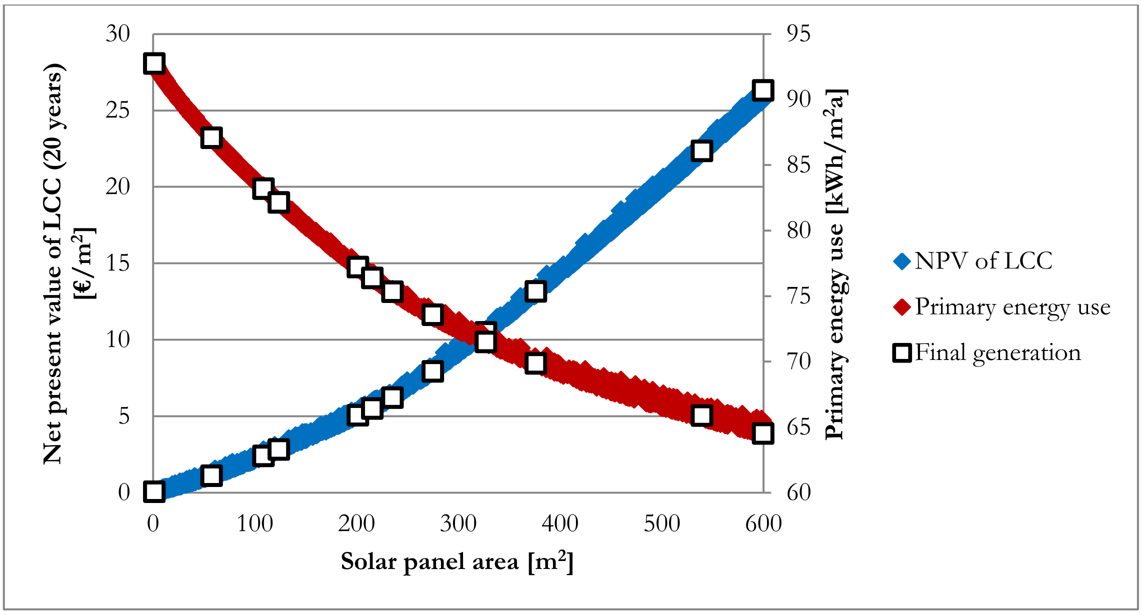

Figure 25. Luhtaa day-care centre with DH and solar PV, net present value of LCC [blue marker, €/m²] and primary energy use [red marker, kWh/m²a] as a function of solar panel area [m²]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

Figure 26 demonstrates the effect from the panel installation angle by showing the LCC plotted as the function of the panel inclination.

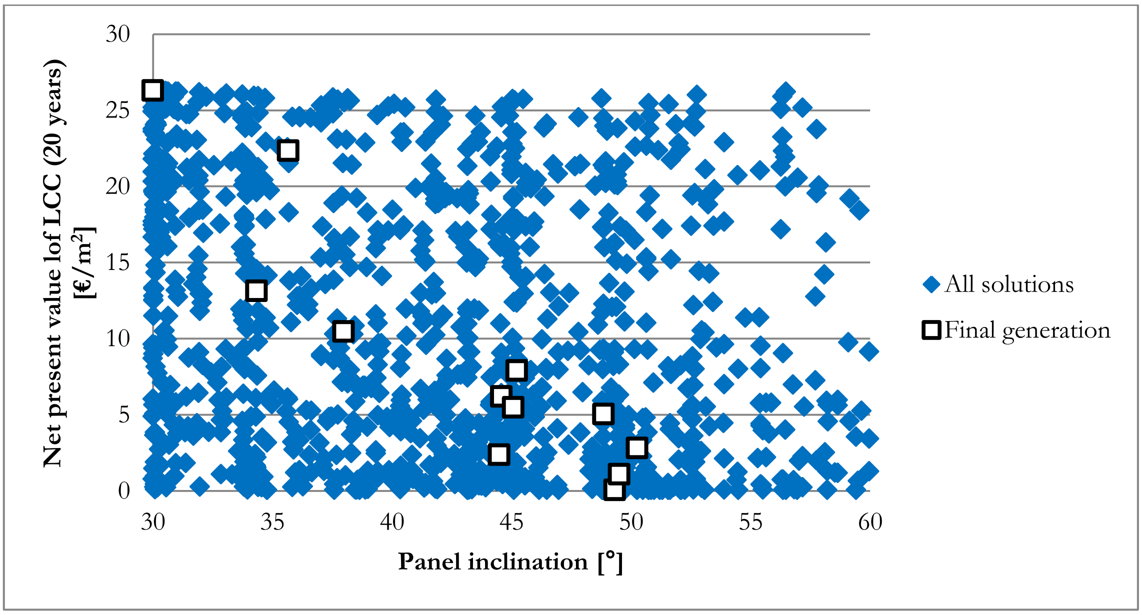

Figure 26. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m²] as a function of solar panel inclination [°]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

This time, the solutions are scattered all across the allowed region from 30° to 60°. Some regions have more dots than others, indicating that the optimization algorithm has been "searching" them more thoroughly, but even the final generation of solutions does not reveal a clear preference for the installation angle. Some clustering of the final population members is shown approximately around the angles 45° and 50°. Primary energy use as a function of the panel inclination is not shown here, because it reveals exactly the same (scarcity of) information as the LCC plot. In case of Luhtaa day-care centre with DH, it appears that the solar panel area is the dominating variable that determines the cost, and solar panel inclination does not have a clear "winning" solution.

9.1.2 Case 2: Luhtaa day-care centre with GSHP

Next case, case 2, is Luhtaa day-care with the optimal heating system, which is the ground-source heat pump (GSHP). Figure 27 shows again LCC (y-axis) as the function of the annual primary energy use (x-axis). Again the final population is plotted separately, but the shape of the Pareto front is recognizable even without showing the final population. When the panel area approaches zero, primary energy consumption approaches 79 kWh/m²a (this is correct, see Table 10). Again, the life-cycle cost LCC is positive in all cases, indicating the panels incur a net cost over their life-time. Also for GSHP heating solution, self-generation of solar PV does not appear profitable for any solar PV area, at least not profitable in the sense of creating income.

The greatest life-cycle costs occur with the largest panel area (600 m²). With the maximum panel area occupied, the building primary energy use is lowered to 49 kWh/m²a, a decrease of 30 kWh/m²a (38%) compared with the case of no PV. This decrease comes with a life-cycle cost of 27 €/m².

One important result to note from both case 1 (Figure 24) and case 2 (Figure 27) is the shape of the Pareto front, describing the relationship between money spent and energy performance improved. For both the DH and the GSHP cases, installing solar panels brings much greater energy improvements at first, and the cost gets steeper when trying to reach for even better energy performance. In these cases there is always a trade-off between cost and building energy efficiency, but the nature of the trade-off is specific for the panel area region.

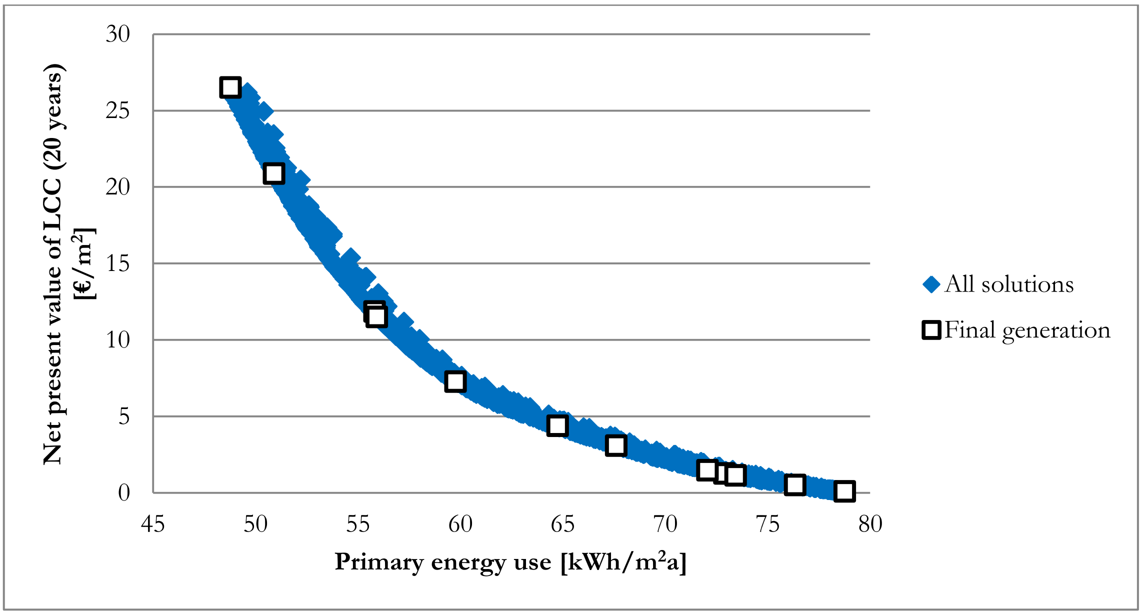

Figure 27. Luhtaa day-care centre with GSHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

For example, in case 2 shown in Figure 27, lowering the building primary energy use from 79 to 69 kWh/m²a incurs a total life-time cost of 3700€. Lowering the primary energy use from 69 to 59 kWh/m²a has a cost of 8000€, or more than twice as much as the previous 10 kWh/m²a. And lowering the primary energy use by one more 10 kWh/m²a, from 59 to 49 kWh/m²a, costs 25 700€, or more than three times as much as the previous 10 kWh/m²a. Such information can be gleaned from the Pareto front, and it is valuable for decision makers and system designers.

Figure 28 shows both LCC (blue marker) and primary energy use (red marker) as a function of the panel area. In the Luhtaa GSHP case, both LCC and primary energy use depend on the panel area in a manner very similar to the Luhtaa DH case. Again, increasing the installed panel area increases the life-cycle cost, and decreases the primary energy use. This is true for the whole panel area region, up to the maximum panel area of 600 m².

LCC as the function of the panel inclination is shown in Figure 29. Again the result is similar to the Luhtaa DH case. The optimization algorithm has explored the whole area between 30° and 60°, with perhaps more tries in the region below 45°. However, no clearly preferred panel installation angle emerges. Again the panel area is the dominating decision variable.

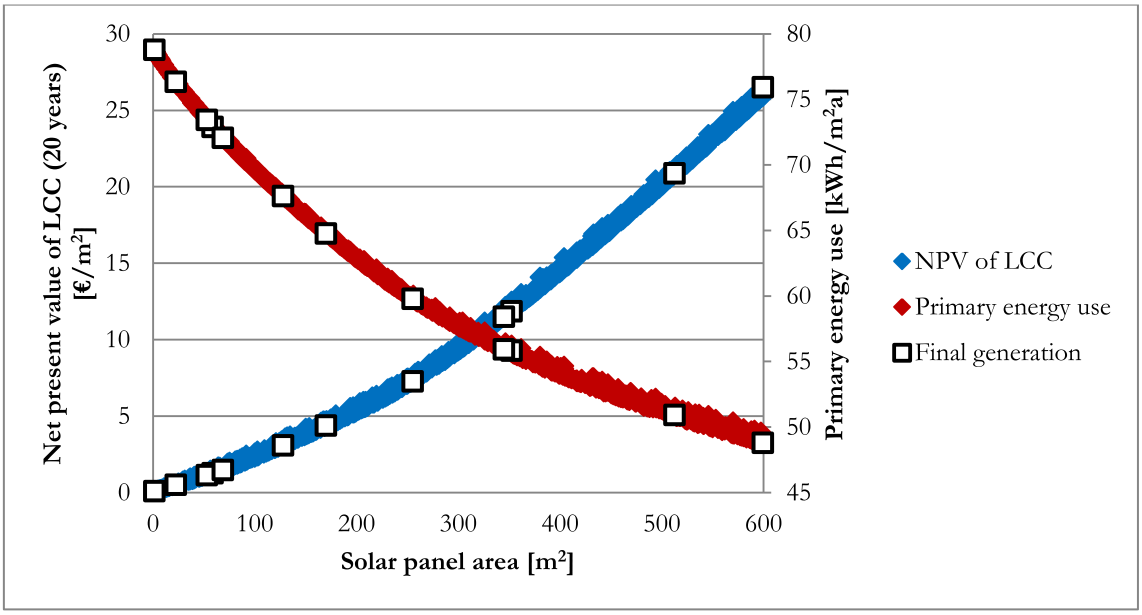

Figure 28. Luhtaa day-care centre with GSHP and solar PV, net present value of LCC [blue marker, €/m²] and primary energy use [red marker, kWh/m²a] as a function of solar panel area [m²]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

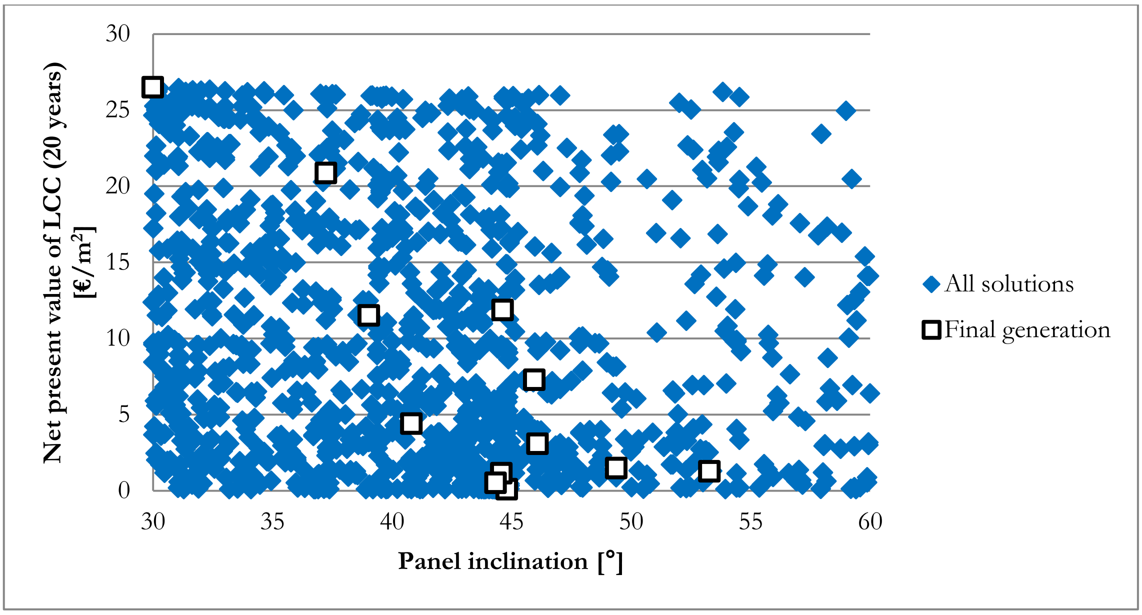

Figure 29. Luhtaa day-care centre with GSHP and solar PV, net present value of LCC [€/m²] as a function of solar panel inclination [°]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

9.1.3 Cases 3a and 3b: Jukola old people's home with DH

In optimization case 3a and 3b, Jukola old people's home is set up to have district heating, just like it does in real life. The original constraint on the available roof area for Jukola panel installation was 200 m². With some initial optimization test runs, it soon became evident that for such a tight roof-area constraint, this was not a true multi-objective optimization problem. This is illustrated by Figure 30, which shows an incomplete optimization case with a panel area constraint of 200 m².

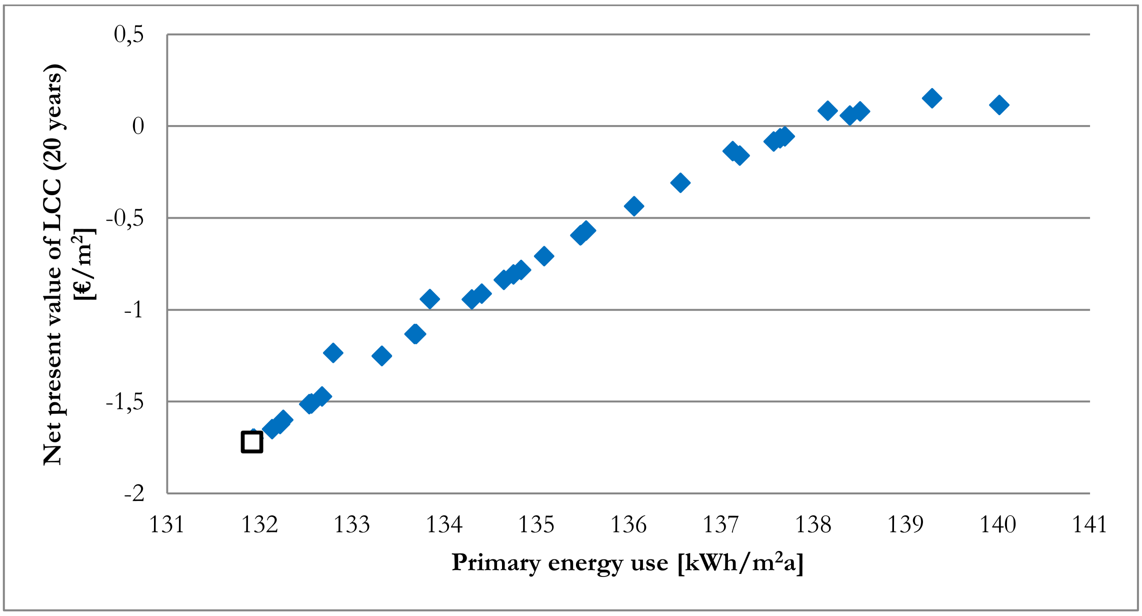

Figure 30. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2%. An example of solutions reached for the Jukola DH case with a panel area constraint of 200 m².

In this case, all the optimal results converge at the maximum panel area 200 m², because this provides both smallest LCC and lowest primary energy use. No Pareto front is formed, because a single solution emerges as the overall winner.

To learn more about the profitability of solar PV production in the Jukola old people's home, the maximum panel area constraint was relaxed. With some test simulations, it was decided that the new maximum panel area should be 600 m², which is enough to contain the region of the maximum (financial) profitability in the DH case. Figure 31 shows the optimization results for case 3, Jukola with DH and maximum solar panel area of 600 m².

The first important finding is that for this case, almost all the LCC values shown on the y-axis are negative. This means that the PV installation in most cases brings a life-cycle profit. The situation is almost opposite to the Luhtaa day-care centre, where solar PV was had no financial profitability at any panel area.

Starting from zero and installing more solar panels incurs costs only for small PV areas (< 54 m²), and creates profit (negative LCC) for larger panel areas (54…600 m²). The largest attainable profit is 2,7 €/m², totalling a profit of 12 600€ in 20 years. This profit occurs at panel area 360 m². At this point, the primary energy consumption is lowered from 140 kWh/m²a to 126 kWh/m²a, a reduction of 10%. With no solar PV, the primary energy use approaches 140 kWh/m²a, as it should (see Table 10).

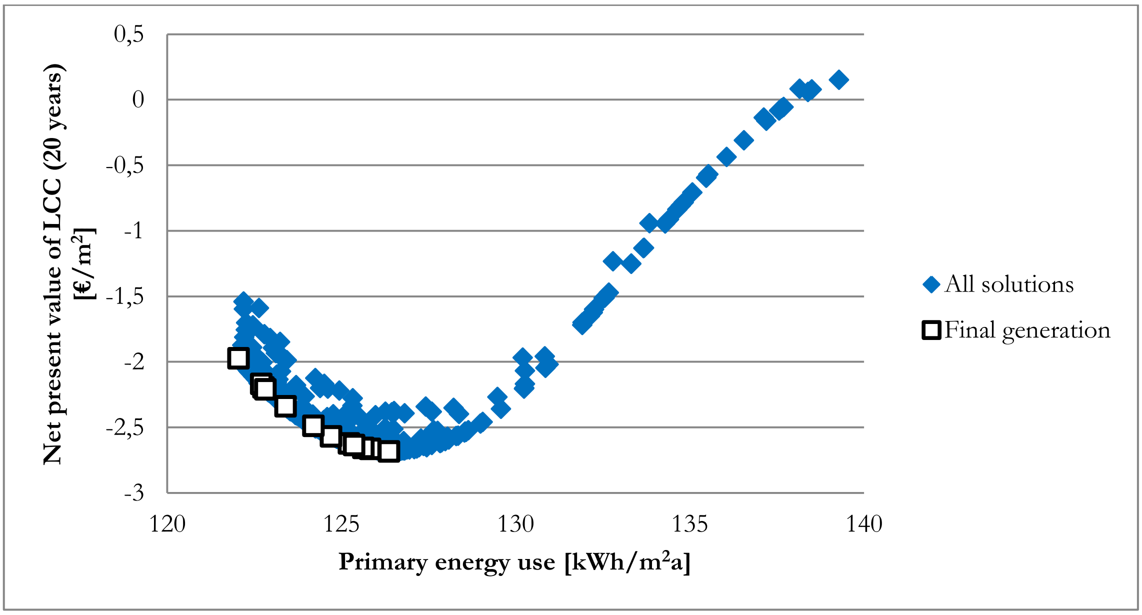

Figure 31. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

In Figure 31, the separate plotting of the final generation becomes more meaningful than in the Luhtaa cases (case 1 and case 2). Now the final generation reveals that the Pareto front lies only on the left side of the minimum LCC solution (126 kWh/m²a, -2,7 €/m²). If the objective is to minimize both LCC and primary energy use, there is no reason to install less than 360 m² of solar panels: by installing 360 m² or more, better energy efficiency can be reached with the same cost. Even installing the maximum allowed amount of 600 m² solar PV, the system still has a life-cycle profit of 2 €/m², totalling 9300 € in 20 years, or 465 €/year. At this point of maximum PV installation, the primary energy use is lowered to 122 kWh/m²a.

In retrospect, it would have been interesting to choose even a larger solar PV area, to find out how large solar PV installation finally becomes financially unprofitable. Clearly Jukola could profitably use even more solar PV generation than 600 m². The problem is the scarcity of available roof area: the generation should take place for example on the roof of the neighbouring buildings. In case of Jukola, this could be a real possibility, because Jukola belongs to the Koukkuniemi nursing home complex, with several municipally-owned service buildings on the same property. Jukola itself is attached to a newer building that could possibly house solar PV. However, the same reasoning cannot be generalized for all buildings on the property. If every building needed to rely on its neighbours for solar PV installation, then the end result becomes the same; there is not enough installation space available.

Figure 32 and Figure 33 illustrate the effect of the solar panel area on the results. Figure 32 shows the LCC as the function of the panel area, and Figure 33 shows the primary energy use as the function of the panel area. This time they are plotted separately, because the shape of the curves is such that they look unclear plotted together. Similar to the Luhtaa cases (case 1 and case 2), the effect of the solar panel area on both optimization targets is very clear. Also from these plots it is easily comprehended that the optimal panel areas occur in the region between 360 m² and 600 m².

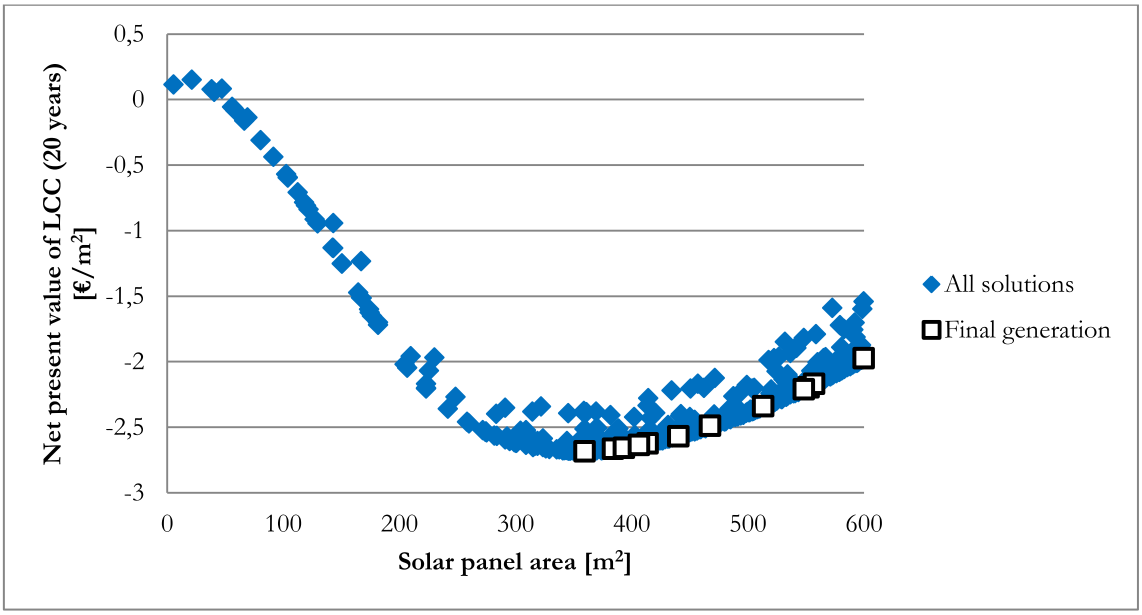

Figure 32. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of solar panel area [m²]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

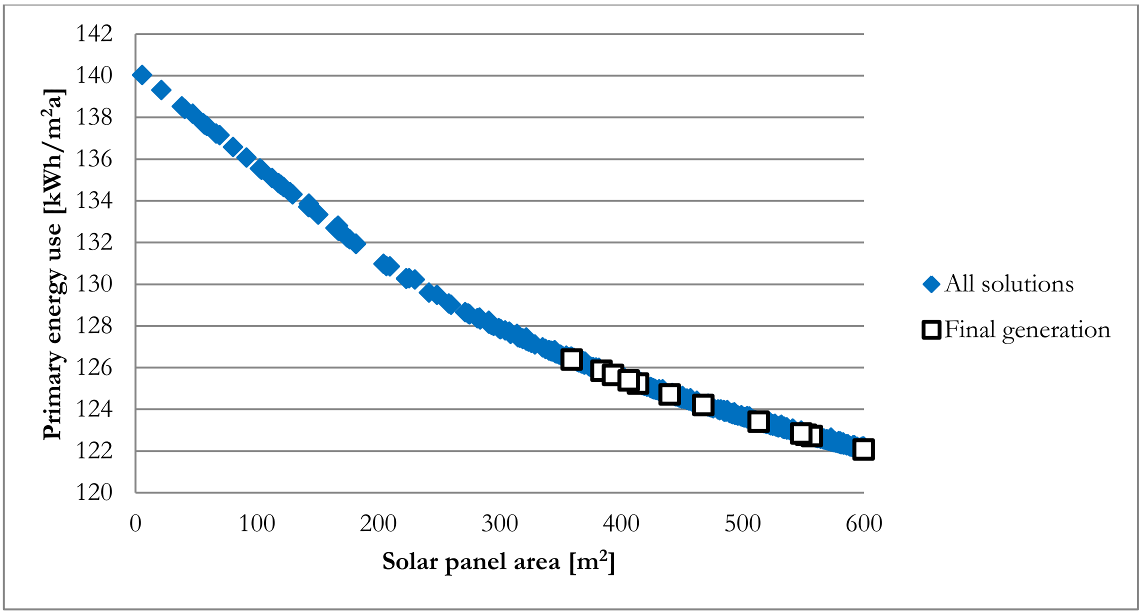

Figure 33. Jukola old people's home with DH and solar PV, primary energy use [kWh/m²a] as a function of solar panel area [m²]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

Figure 34 shows LCC as the function of the solar panel inclination. Again the optimization algorithm has searched widely for the optimal angle, although the area most explored is around 45° to 49°. This time the final generation shows a congregation of results at panel inclination angles 47°– 48°. For optimization case 3a, Jukola with DH, a preferred inclination angle is thus found, and it is larger than the angle that maximizes yearly production (42°). The largest financial profit occurs in this case with inclination angle 47°.

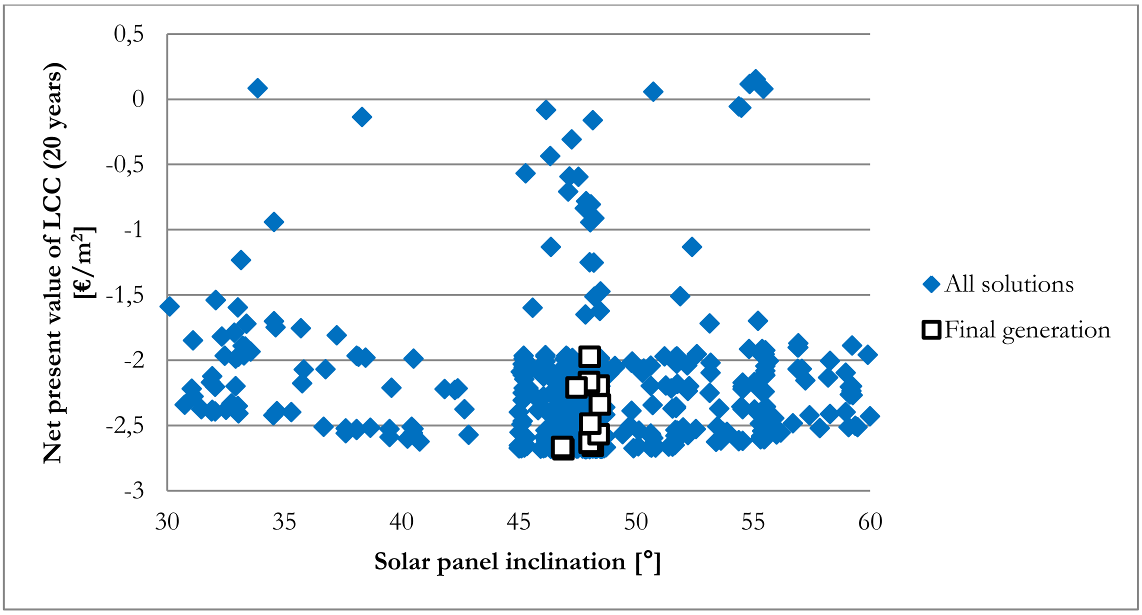

Figure 34. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of solar panel inclination [°]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

In optimization case 3a, solar PV in Jukola was found to be financially profitable, unlike in Luhtaa day-care centre (cases 1 and 2). The main reason for the difference is the different usage profile of the buildings: day-care building is closed during the summer holiday and other holidays, whereas the old people's home houses its residents throughout the year. However, there is also one calculation parameter that differs between cases 1–2 and case 3a: the electricity purchase price.

In order to investigate solar PV production in the actual case-study buildings, it was decided that the actual electricity price should be used. For Luhtaa, the electricity price (transmission included) is 92,2 €/MWh, whereas the electricity price for the larger buildings Jukola and Vehmainen is 81,2 €/MWh. While comparing results from case 3a with cases 1–2, it should be kept in mind that the different electricity price also affects the results.

To investigate the effect of the electricity purchase price, optimization case 3b for the Jukola DH system was set up. Case 3b is identical to 3a, except that the electricity purchase price is now 92,2 €/MWh, similar to the Luhtaa day-care centre. This also serves as a partial sensitivity analysis: how sensitive is the result to the electricity price? Will the Pareto front look the same with different electricity purchase prices?

Figure 35 shows the optimization results for case 3b. It reveals that with the electricity price assumed 14% higher, solar PV in Jukola is even more profitable. Now the maximum financial profit is 5,2 €/m², totalling a profit of 24 300 € in 20 years, or 1215 € every year. This is attained with a panel area of 469 m². At this point of maximum profit, the building primary energy use is lowered from 140 to 124 kWh/m²a, a decrease of 11%.

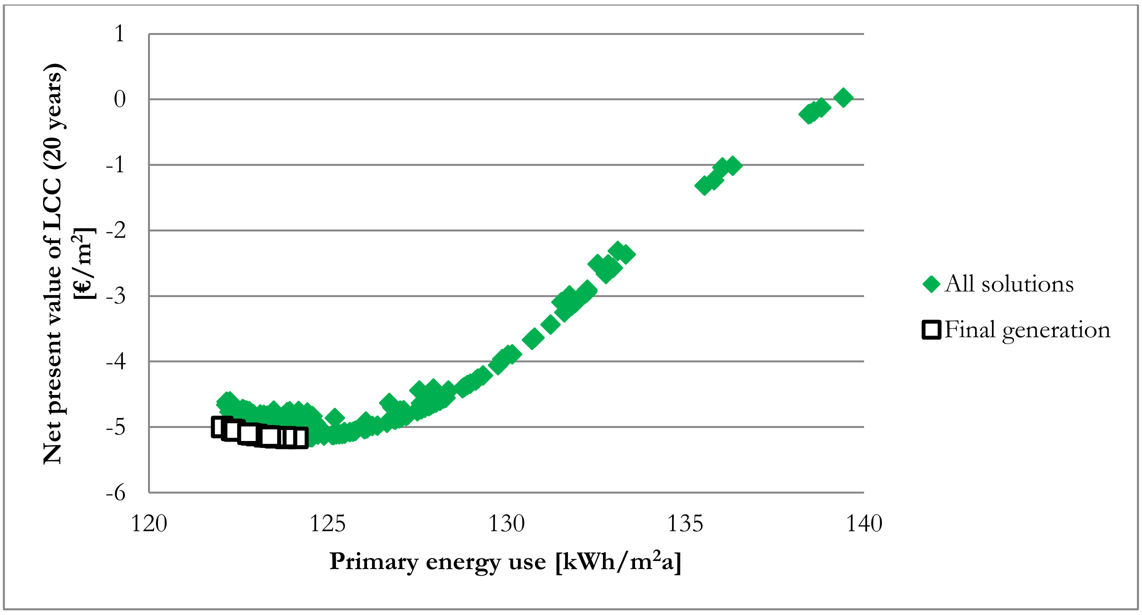

Figure 35. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. Electricity purchase price is assumed to be 92,2 €/MWh instead of 81,2 €/MWh. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

Figure 36 shows the comparison with case 3a (blue marker, electricity price 81,2 €/MWh) and case 3b (green marker, electricity price 92,2 €/MWh). The maximum profit in case 3a is 2,7 €/m², and in case 3b it is almost doubled, 5,2 €/m². Primary energy use at the point of maximum financial profit is not as strongly affected: it is shifted from 126 kWh/m²a (case 3a) to 124 kWh/m²a (case 3b). This is a much less dramatic effect than the effect on the life-cycle cost. The panel area for the maximum financial profitability is shifted from 360 m² (case 3a) to 469 m² (case 3b). This is best observed from Figure 37, where the LCC in both cases is shown as the function of the panel area.

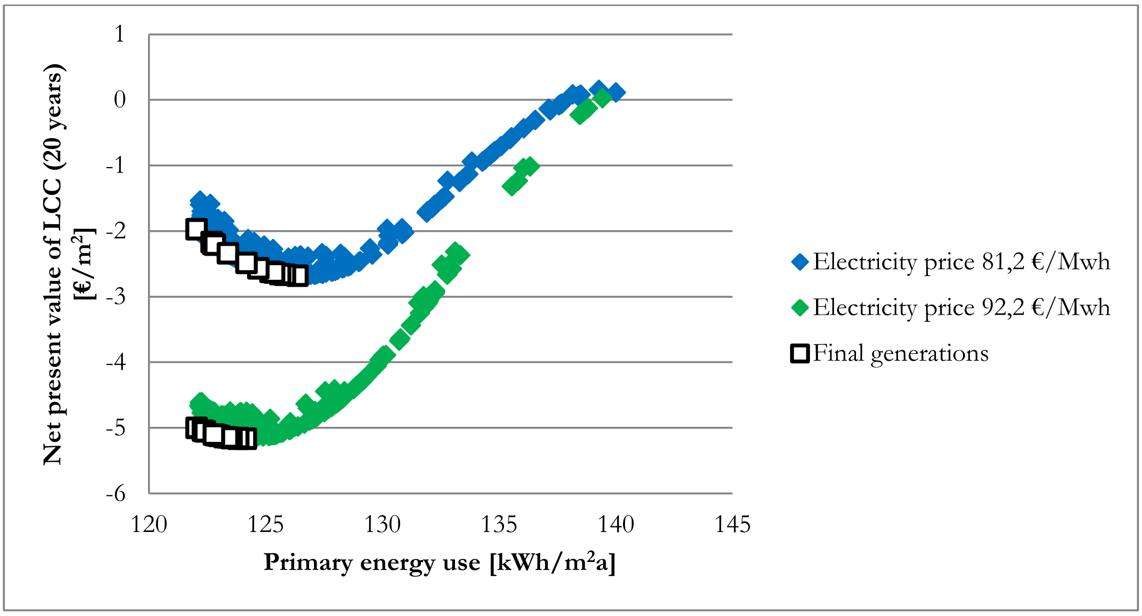

Figure 36. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. A comparison between electricity price 81,2 €/MWh [case 3a, blue marker] and 92,2 €/MWh [case 3b, green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

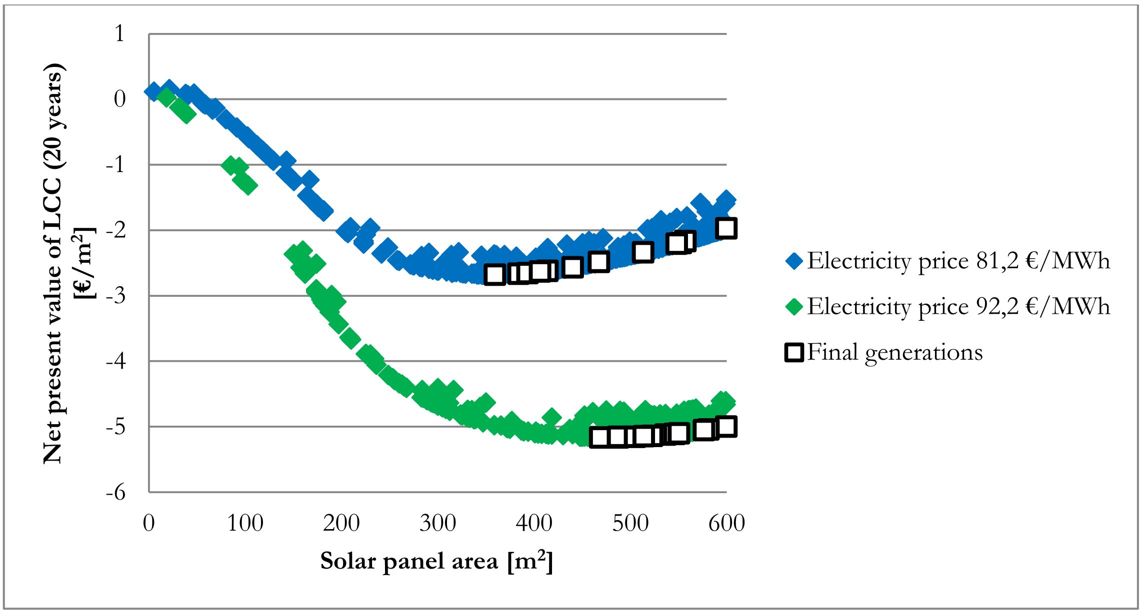

Figure 37. Jukola old people's home with DH and solar PV, net present value of LCC [€/m²] as a function of solar panel area [m²]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

In case 3b, the inclination angles for all solutions (not shown here) form a cluster between 45° and 50°, and the inclination angle that brings the lowest LCC or highest profit is 47°. This is in line with the result from 3a, where the angle of 47° was also associated with the largest profit.

It can be concluded that the 14% difference in the electricity price brings about a large difference in the system financial profitability, and a smaller effect on the primary energy use. If the electricity price were 92,2€/MWh for Jukola, as it is for Luhtaa, it would be the most advantageous to install 469 m^2 or more of solar PV. Again the problem with Jukola old people's home is the lack of the available roof space for such an installation.

This results raises an interesting question on the overall profitability of solar PV installation, for the municipality point of view. In this study, the balance is drawn around each case study building, and the financial profitability is considered from the building's point of view. In the larger scheme of things, it should be considered that all these municipal service buildings purchase their energy from the municipal energy company. The electricity price charged by the municipal energy provider strongly affects the financial profitability of own solar PV generation. As the municipality owns both the service buildings and the energy company, then what is the overall profitability of the scheme, from the whole municipality point of view? This is not a question that can be answered by the study at hand, but it should be considered more closely.

This also stresses the importance of having other optimization targets that just the financial profit. Financial profit can depend on where the balance line is drawn, but the climate benefits realized through diminished emissions do not function that way. Minimizing the primary energy use is not a zero-sum game in this sense: avoiding GHG emissions from built environment is beneficial for the climate and human health in all cases.

9.1.4 Cases 4a and 4b: Jukola old people's home with A2WHP

Optimization cases 4a and 4b model Jukola old people's home with the optimal heating solution, which is air-to-water heat pump. Similar to the Jukola DH cases, some preliminary optimization runs revealed that the panel area restriction of 200 m^2 was not enough to reveal the true nature of the multi-objective optimization problem. The maximum financial profitability, as well as the maximum energy efficiency, again occurred at a single point, which was at the maximum panel area of 200 m^2.

For the sake of more thorough investigation, the roof area constraint was again relaxed. This time the new maximum solar PV area was chosen as 800 m^2, which was estimated to accommodate the area of maximum probability. With A2WHP, the chosen maximum area is larger than with DH, because the heat pump solution can profit from more solar PV than district heating.

Figure 38 shows optimization results for case 4a, Jukola old people's home, with a maximum panel area of 800 m^2 and electricity price 81,2 €/MWh. Compared with case 3a, where the heating system was district heating, solar PV is more profitable. This is not surprising, because heat pump can utilize more of the self-generated electricity: if not in mid-summer, then at least in the spring and autumn seasons. Also the panel area is larger at the point of the maximum profit, as expected.

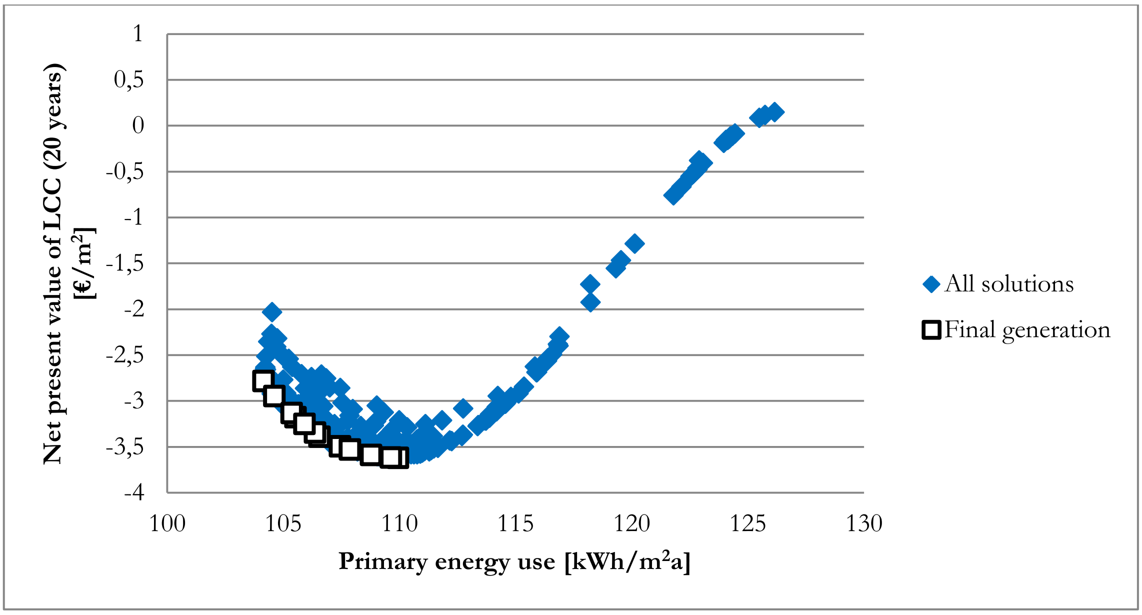

Figure 38. Jukola old people's home with A2WHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m².

With solar PV installation approaching zero, the primary energy use of the building approaches 127 kWh/m²a (see Table 10). The maximum financial profit is 3,6 €/m², which totals a profit of 17 100 € in 29 years, or 855 €/year. This maximum profit occurs at panel area 461 m². At this point the primary energy is lowered from 127 kWh/m²a to 110 kWh/m²a, a reduction of 17 kWh/m²a (13%).

In a similar manner to cases 3a and 3b, the final generation of solutions indicates that the Pareto front starts at the point of the maximum financial profitability. This is even more clearly visible from Figure 39, where LCC is plotted as the function of the panel area, or Figure 40, where primary energy is plotted as the function of the panel area. All the optimal solutions, minimizing LCC and primary energy use, occur at panel areas from 461 m² to 800 m². When considering these two objectives, it is not advisable to install solar PV systems any smaller than 461 m².

In real life, the case-study building sets the constraints for solar panel installation on the roof: the actual Jukola building cannot house 461 m² of solar panels. Solutions such as vertical solar panels integrated to the walls or a separate solar panel installation on the property, might be an interesting option, in case their cost was sufficiently low.

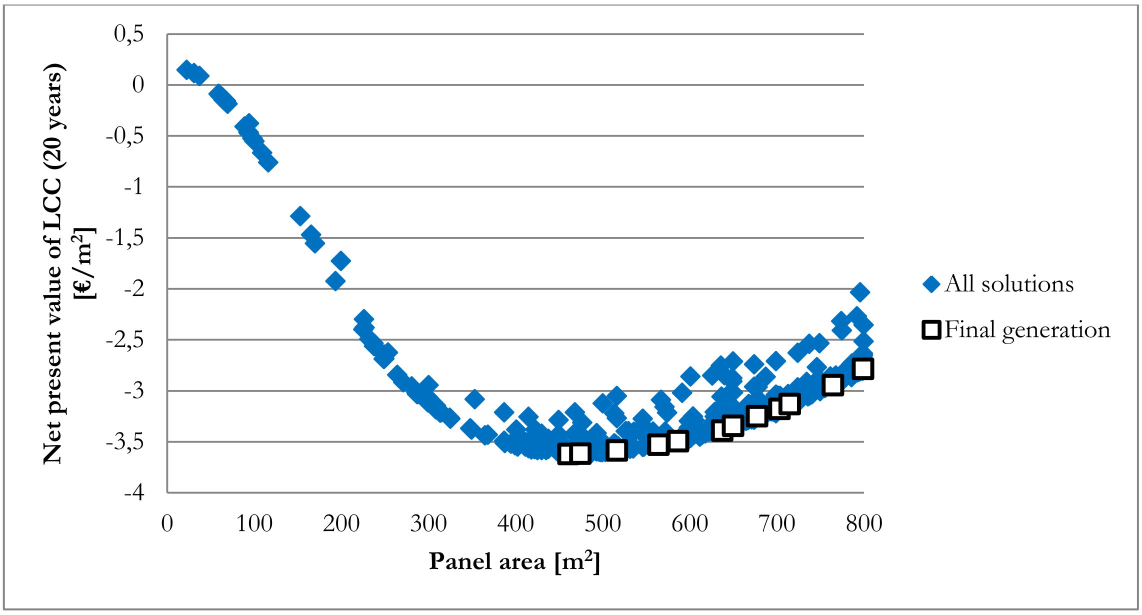

Figure 39. Jukola old people's home with A2WHP and solar PV, net present value of LCC [€/m^2] as a function of solar panel area [m^2]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m^2.

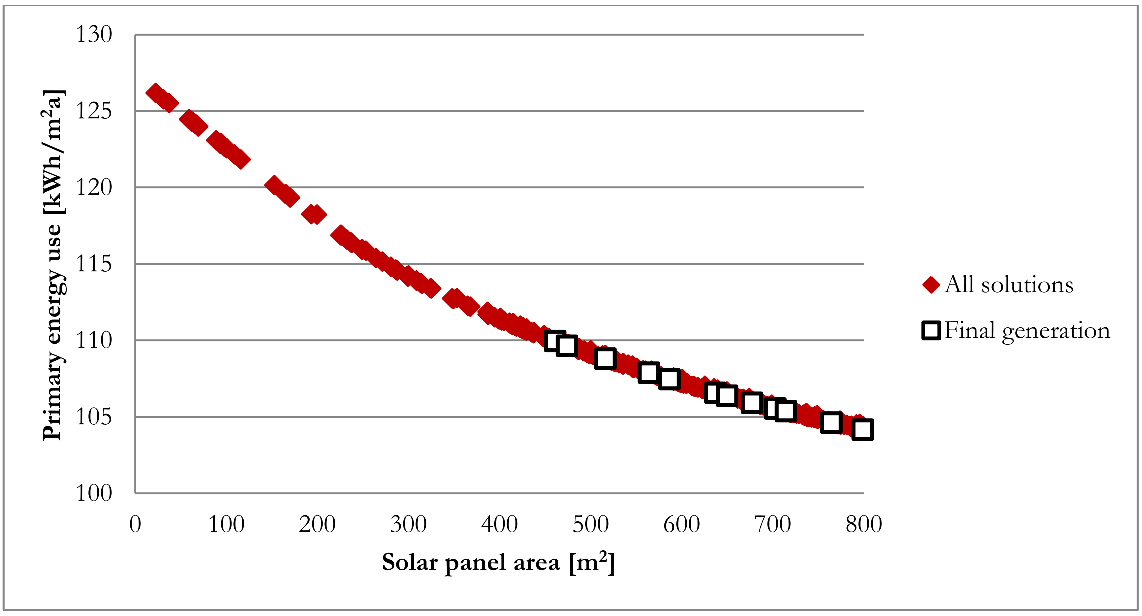

Figure 40. Jukola old people's home with A2WHP and solar PV, primary energy use [kWh/m^{2}a] as a function of solar panel area [m^2]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m^2.

The effect of the solar panel inclination angle is shown in Figure 41, where LCC is plotted as a function of the panel inclination. This time the final generation of solutions is clustered in panel angles from 47° to 52°. The inclination associated with the greatest financial profit is 48°. This result again shows a preference for solar panel inclinations somewhat larger than the 42° that maximizes the yearly production in Tampere.

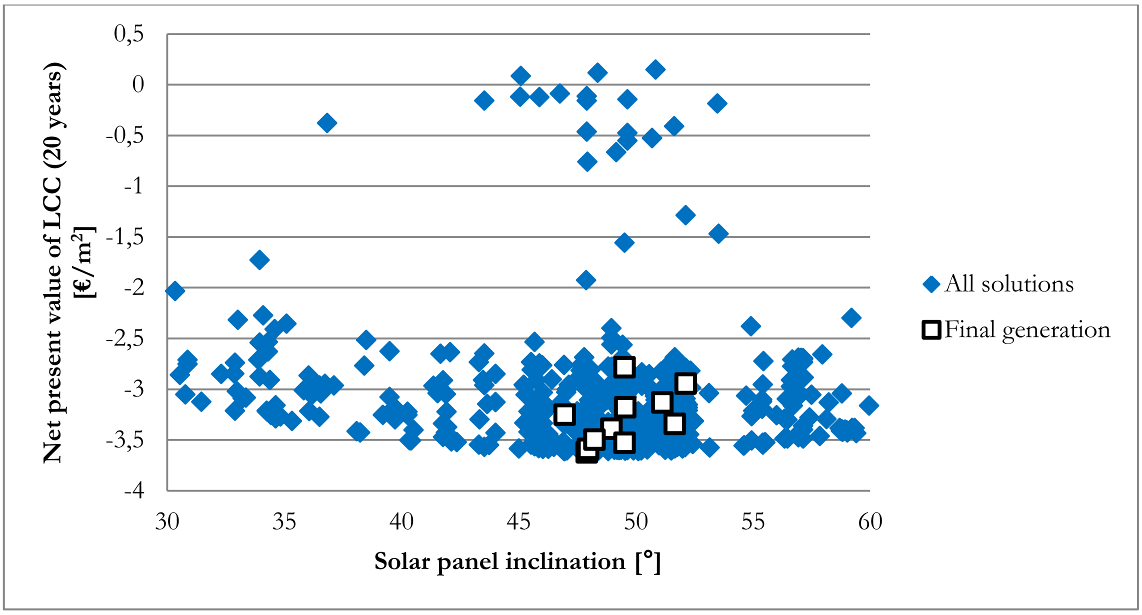

Figure 41. Jukola old people's home with A2WHP and solar PV, net present value of LCC [€/m²] as a function of solar panel inclination [°]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m².

Similarly to the Jukola DH cases, an additional optimization case 4b was set up. It is otherwise identical to case 4a, but having a larger electricity purchase price (92,2 €/MWh instead of 81,2 €/MWh). This additional optimization run reveals how the profitability of solar PV in the Jukola A2WHP case might look, in case Jukola was charged a 14% higher price for its electricity, or the same rate as Luhtaa day-care centre. This allows for a more accurate comparison with the Luhtaa day-care centre cases.

Figure 42 shows the results from the optimization case 4b. Without solar PV, primary energy use again approaches 127 kWh/m²a, just like it should in an otherwise identical system. This time the maximum financial profitability reaches 6,8 €/m², totalling 32 100 € for the whole building in 20 years, or 1605 € per year. The maximum profit is realized with panel area 626 m². At this point, the primary energy use of the building is lowered from 127 kWh/m²a to 107 kWh/m²a, a reduction of 20 kWh/m²a (or 16%).

For the sake of comparison, Figure 43 shows LCC vs. primary energy use for cases 4a (blue marker) and 4b (green marker). Similar to the DH cases (3a and 3b), the 14% increase in electricity price renders self-generation of solar PV considerably more profitable. The maximum profit shifts from 3,6 €/m² to 6,8 €/m², and the panel area creating the largest profit shifts from 461 m² to 626 m². Primary energy use at the financial optimum is lowered from 110 kWh/m²a to 107 kWh/m²a.

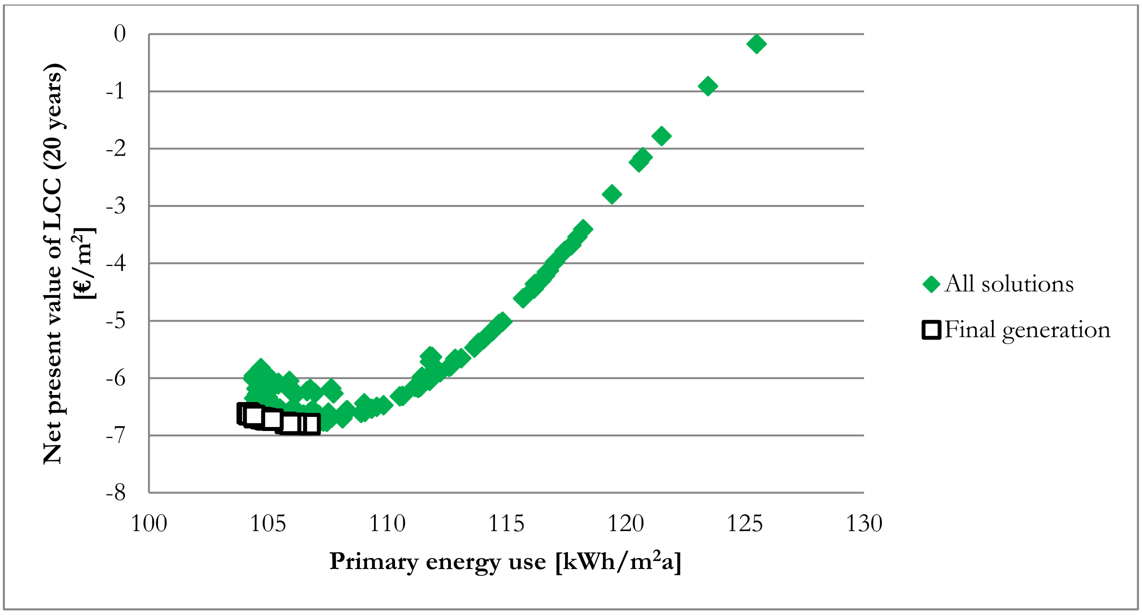

Figure 42. Jukola old people's home with A2WHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. Electricity purchase price is assumed to be 92,2 €/MWh instead of 81,2 €/MWh. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m².

The effect of the panel area on the LCC is best seen from Figure 44. The shape of the Pareto fronts after 800 m² would be valuable to know, because again it seems that primary energy use could be brought even lower while still creating a financial profit. However, time did not allow for additional optimization runs with larger maximum panel area.

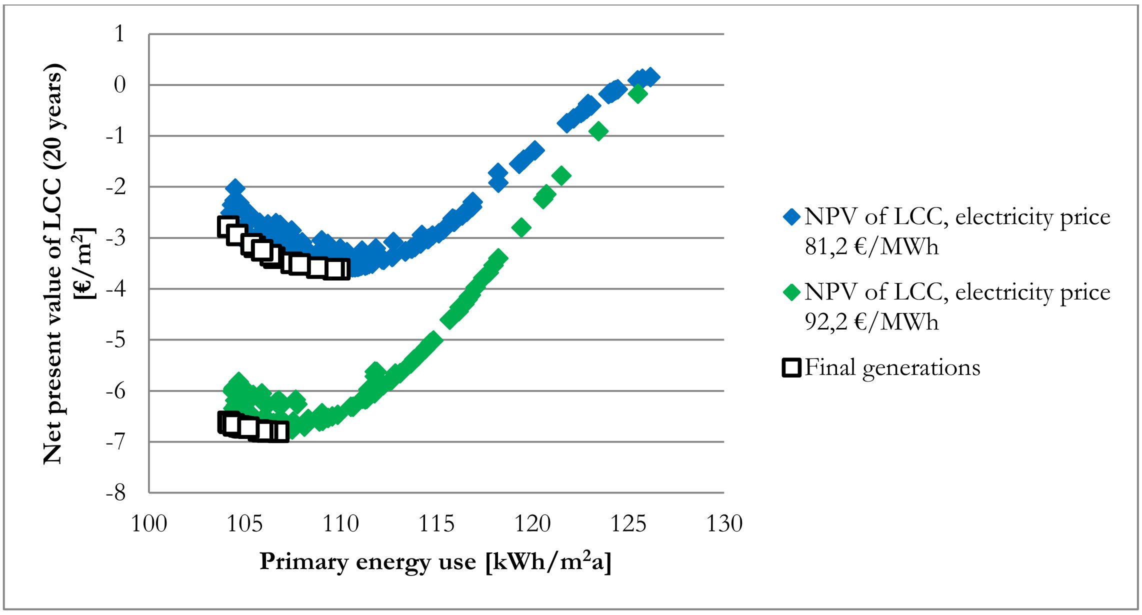

Figure 43. Jukola old people's home with A2WHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m².

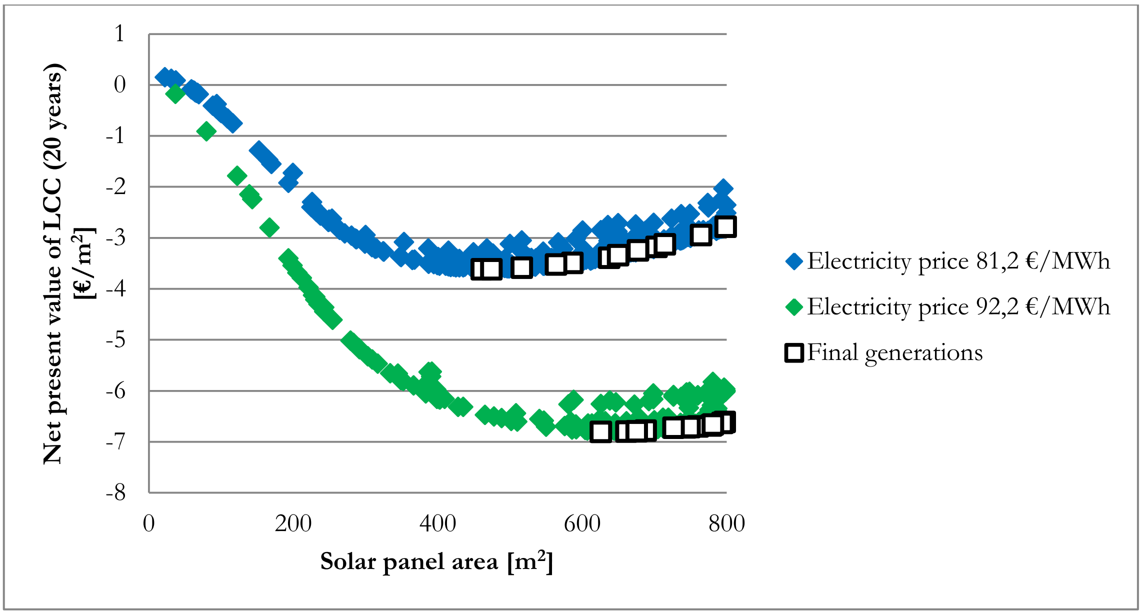

Figure 44. Jukola old people's home with A2WHP and solar PV, net present value of LCC [€/m²] as a function of solar panel area [m²]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 800 m².

9.1.5 Cases 5a and 5b: Vehmainen school with DH

The last case-study building, Vehmainen school, is the largest of the studied buildings, and also has the biggest area estimated available for solar PV production (1500 m²). In optimization cases 5a and 5b, its heating system is district heating, which is the actual heating system used in the building. Figure 45 shows the results from case 5a, where the electricity purchase price is also the actual one, 81,2 €/MWh.

The results from Vehmainen school resemble the results from Luhtaa day-care: self-generation of solar PV does now appear profitable for any solar PV area. Without any solar PV, the building primary energy use is 92 kWh/m²a (see Table 10). Utilizing the whole 1500 m² for solar panel installation lowers the primary energy consumption to 68 kWh/m²a, a reduction of 24 kWh/m²a or 26%. This has a life-cycle cost of 6,9 €/m². The cost for extra energy efficiency improvement again rises the more steeply, the more panels are already installed.

Figure 46 shows both LCC (blue marker) and primary energy use (red marker) as a function of the panel area, in case 5a. Just like in the Luhtaa day-care cases, the final generation showing the optimal solutions is dispersed all over the allowed panel area. For the whole range from 0 m² to 1500 m², the objectives are in conflict: installing more panels to improve the energy efficiency always incurs more life-cycle costs.

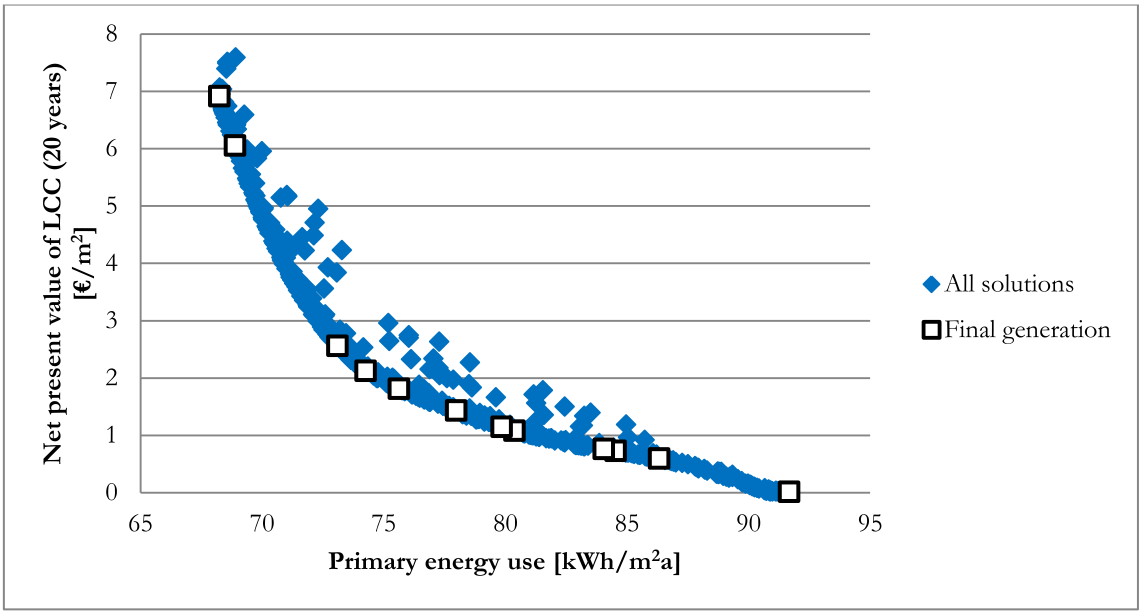

Figure 45. Vehmainen school with DH and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m^2.

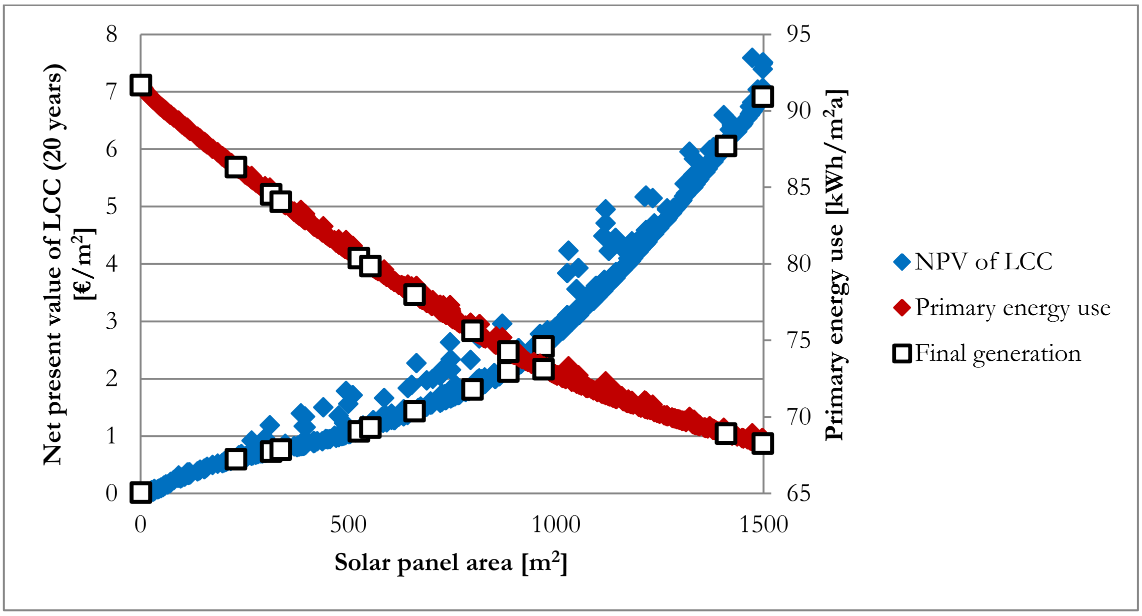

Figure 46. Vehmainen school with DH and solar PV, net present value of LCC [blue marker, €/m^2] and primary energy use [red marker, kWh/m^{2}a] as a function of solar panel area [m^2]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m^2.

To illustrate the effect of the panel inclination, Figure 47 shows LCC as a function of the inclination angle. All members of the final generation fall between inclination angles 48° and 54°. This is the region of the preferred panel inclination.

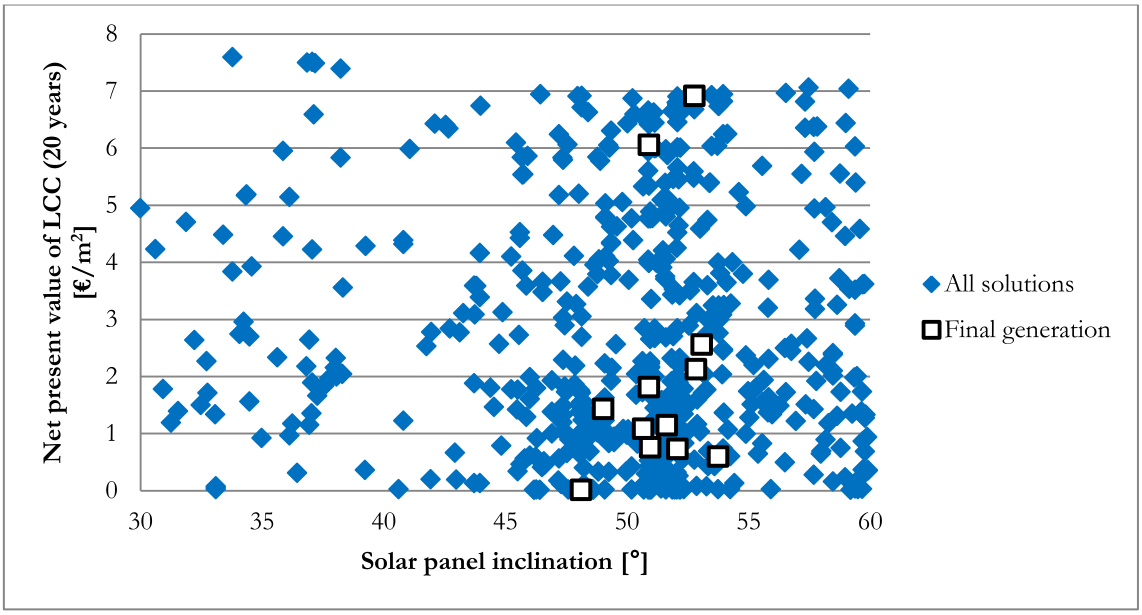

Figure 47. Vehmainen school with DH and solar PV, net present value of LCC [€/m^2] as a function of solar panel inclination [°]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m^2.

Again, an additional optimization case 5b is set up with electricity price 92,2 €/MWh. The results for this optimization run are shown in Figure 48. In this optimization run, the final generation is poorly dispersed along the Pareto front, which in fact starts from the point of minimum LCC. This was caused by one simulation failing and producing a clearly faulty solution, which survived all the way to the final generation and affected the dispersion of the final population members. This faulty member was removed from the final result and the plot in Figure 48. In all the optimization runs one or more simulations came into a halt, but this was the one occasion where a faulty simulation was found to affect the result. For the same reason, a preferred panel inclination angle for the minimum LCC point was not found.

Although the beginning of the Pareto front is not immediately evident from Figure 48, the Pareto front starts at the point of the maximum financial profitability. At this point the LCC is 0,9 €/m^2, totalling 5600 € for the building in 20 years, or 280 € per year. The assumption of a higher electricity price now renders solar PV financially profitable. The maximum profitability is attained with 749 m^2 of solar PV, which lowers the building primary energy consumption from 92 kWh/m^{2}a to 76 kWh/m^{2}a, a reduction of 16 kWh/m^{2}a (17%). It is noteworthy that the curve of the solutions is rather flat around the minimum LCC, indicating that in this panel area region, it is not expensive to improve building energy efficiency.

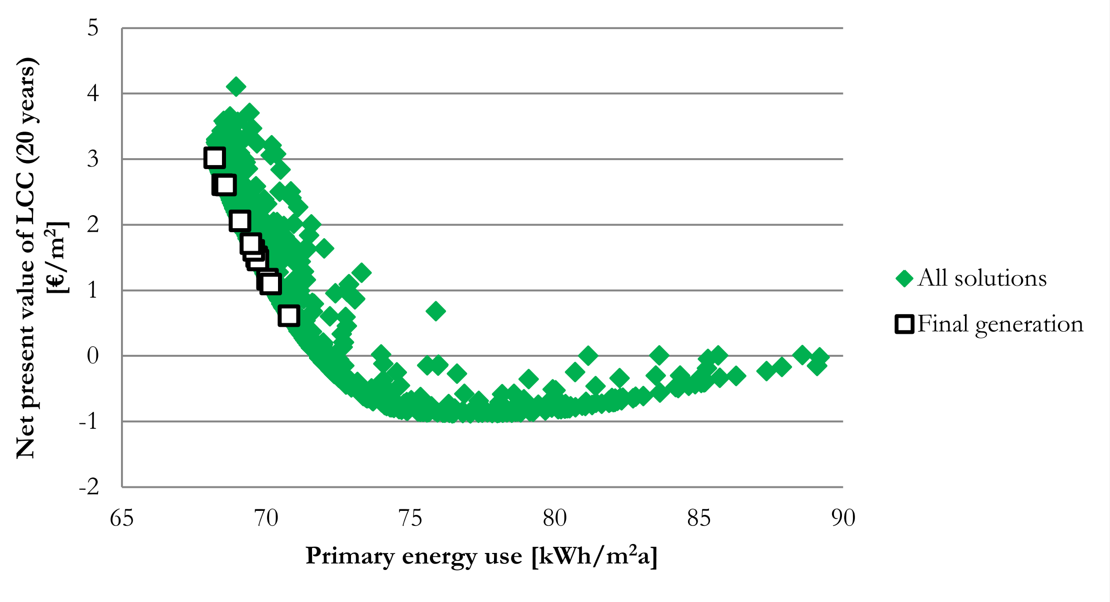

Figure 48. Vehmainen school with DH and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. Electricity purchase price is assumed to be 92,2 €/MWh instead of 81,2 €/MWh. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m^2.

Figure 49 shows the comparison between case 5a (blue marker, electricity price 81,2 €/MWh) and case 5b (green marker, electricity price 92,2 €/MWh). In case 5a, all the LCC values are above zero, indicating life-cycle cost. In case 5b, LCC values are below zero, indicating life-cycle profit, until 72 kWh/m^{2}a. This means that in such a case, the building energy efficiency could be improved by 20 kWh/m^{2}a, or 22%, while still creating financial profit.

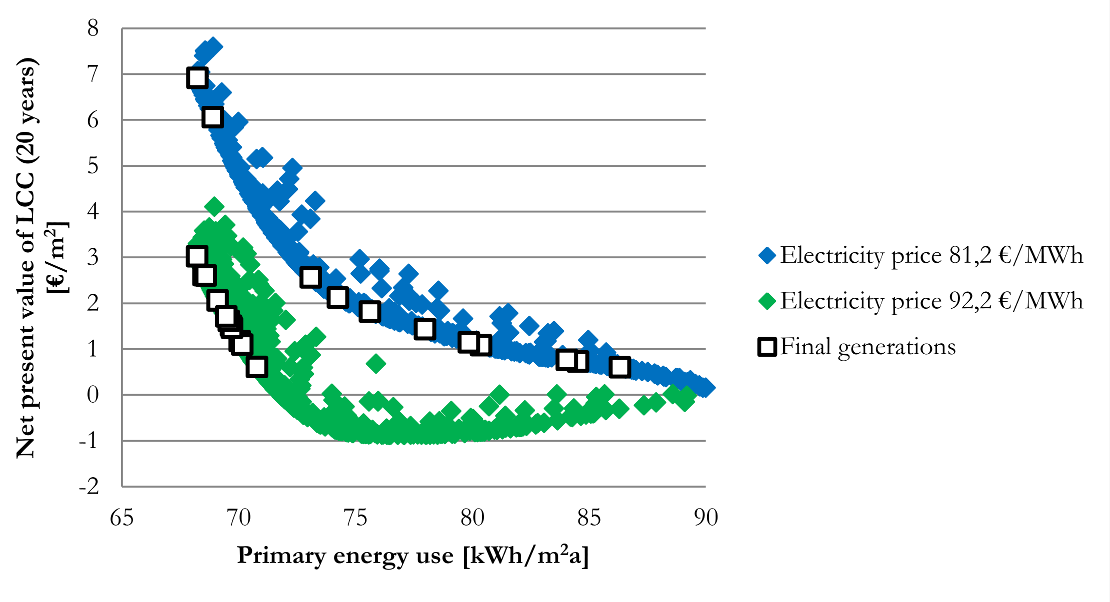

Figure 49. Vehmainen school with DH and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m^2.

Again the question arises: which is the overall best solution for the whole municipality, and not just one service building? A higher price for electricity makes solar PV financially profitable also in Vehmainen, but installing solar PV means a loss of income for the (municipal) energy company. When a municipal service building installs solar PV, does the municipality as a whole win or lose? This could be investigated in a separate optimization case, but the question is out of scope for this thesis work.

Figure 50 shows LCC as a function of panel area for case 5a (blue marker) and case 5 b (green marker). In case 5b, the final generation of the solutions should start at approximately 749 m², if it was reasonably well dispersed along the Pareto front. In case 5a the Pareto front again covers the whole range from 0 m² to 1500 m²: for the whole region, life-cycle cost is in conflict with energy efficiency improvement.

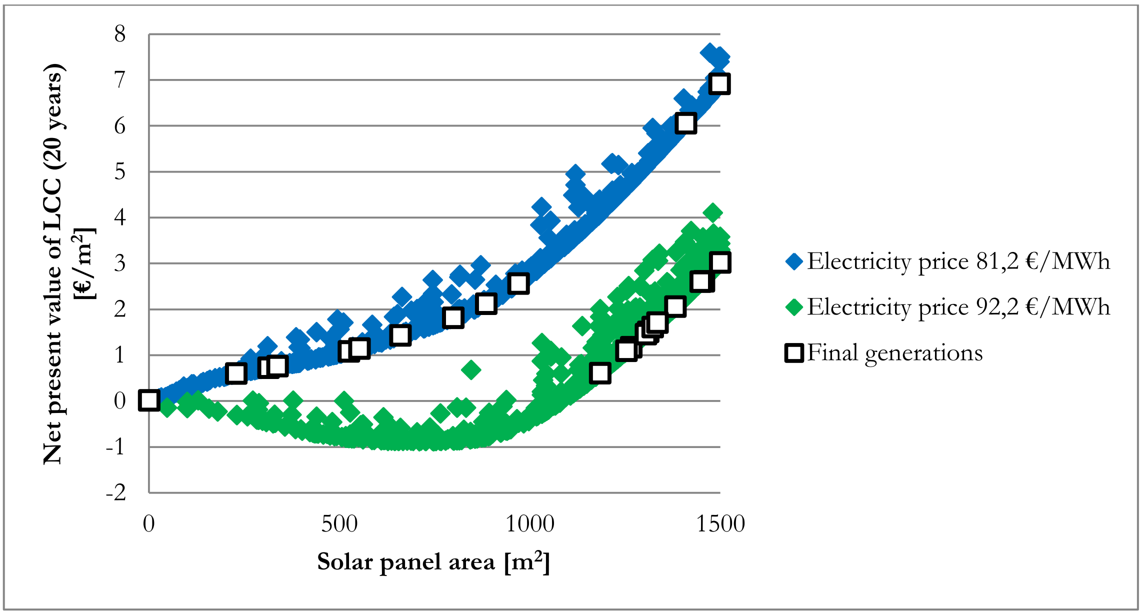

Figure 50. Vehmainen school with DH and solar PV, net present value of LCC [€/m²] as a function of solar panel area [m²]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

9.1.6 Cases 6a and 6b: Vehmainen school with GSHP

Optimization cases 6a and 6b investigate Vehmainen school with GSHP as the main heating option. GSHP is the optimal heating choice for Vehmainen, according to the previous research task [5]. In 6a, electricity price is 81,1 €/MWh, which is the actual rate charged for Vehmainen.

Figure 51 shows the result of the optimization run for case 6a. All the LCC values are again >0, meaning that installing solar PV incurs a life-cycle cost for all panel areas. The cost again gets much steeper with improving energy efficiency.

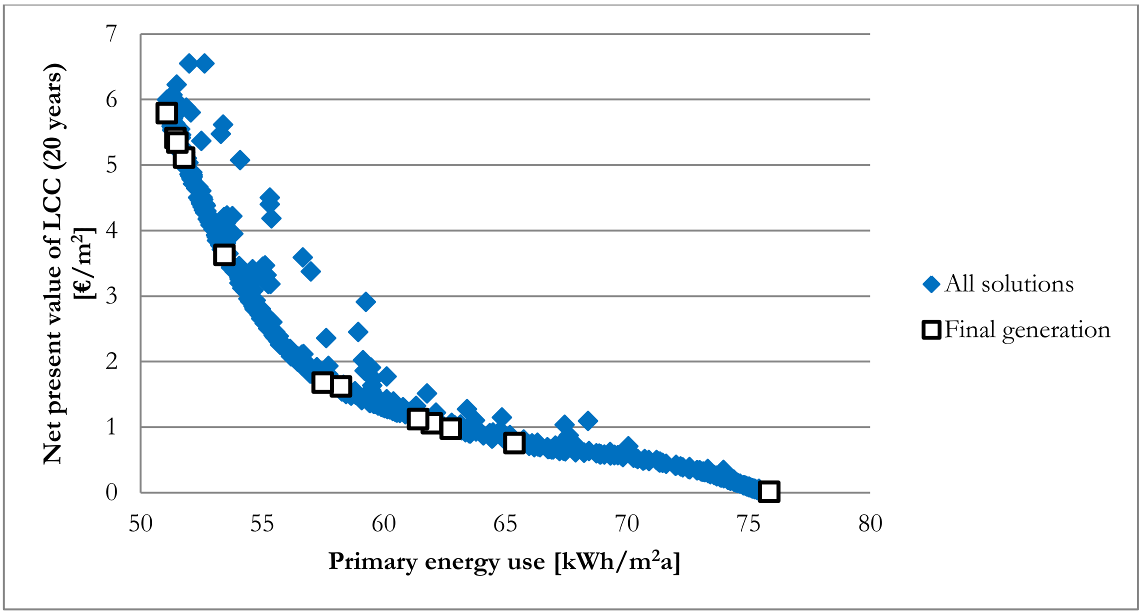

Figure 51. Vehmainen school with GSHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

Figure 52 shows both LCC and primary energy use as a function of the panel area. With no solar PV installed, the primary energy use approaches 76 kWh/m²a (see Table 10). Utilizing the entire 1500 m² for solar PV lowers the primary energy use to 51 kWh/m²a, a decrease of 25 kWh/m²a (33%). This creates a cost of 5,8 €/m².

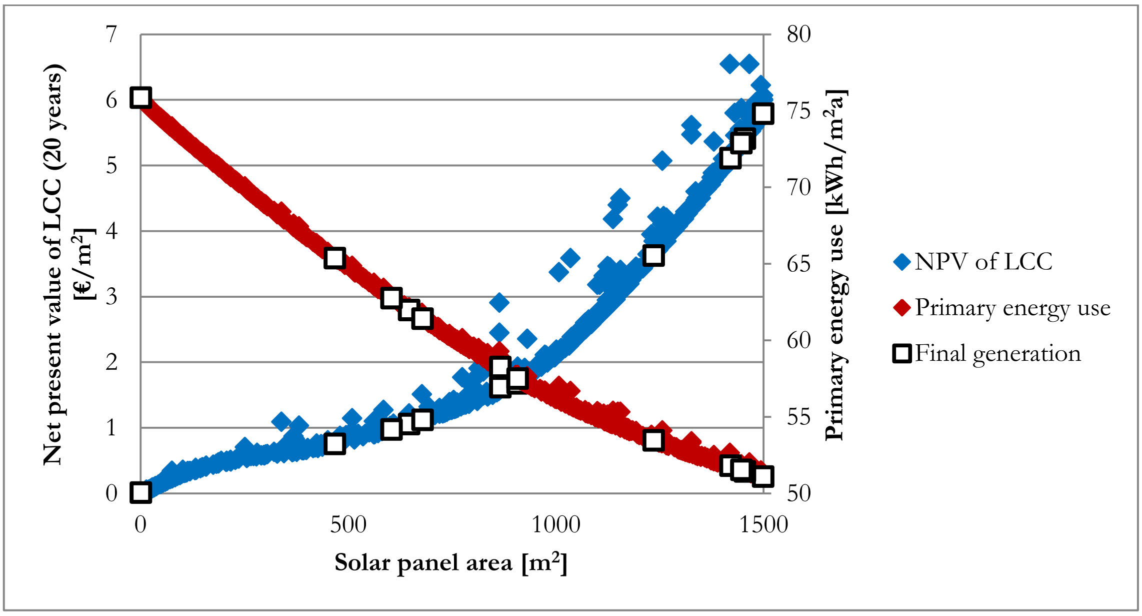

Figure 52. Vehmainen school with GSHP and solar PV, net present value of LCC [blue marker, €/m²] and primary energy use [red marker, kWh/m²a] as a function of solar panel area [m²]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

Figure 53 shows LCC as a function of the panel area. The preferred panel inclination ranges from 48° to 54°, again rather higher than the 42° maximizing the yearly production in the Tampere latitude.

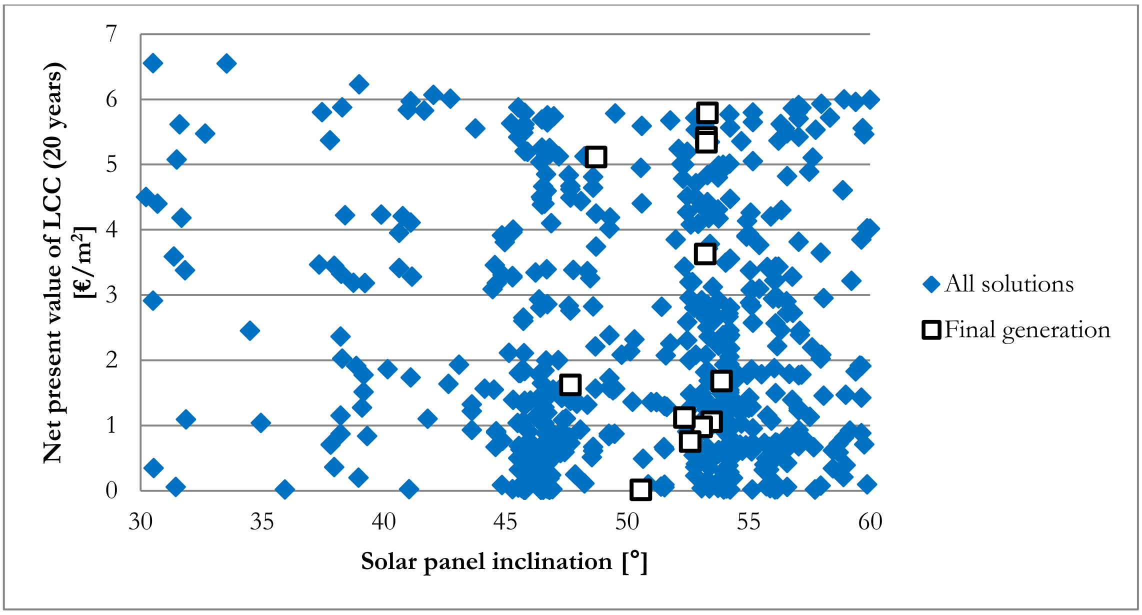

Figure 53. Vehmainen school with GSHP and solar PV, net present value of LCC [€/m²] as a function of solar panel inclination [°]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

As the final optimization case for Vehmainen, case 6b is set up with electricity price 92,2 €/MWh. The results are show in Figure 54. Similar to the Vehmainen DH cases, again the assumed higher electricity renders the solar PV profitable. Maximum profit is 1,4 €/m², totalling 8900 € in 20 years, or 445 € per year. At this point, the primary energy use is lowered from 76 kWh/m²a to 58 kWh/m²a, a reduction of 18 kWh/m²a (24%). This maximum profitability occurs at panel area of 857 m², and a panel inclination 53°. Generating solar PV remains profitable until primary energy use of 53 kWh/m²a is reached, requiring 1255 m² of solar panels.

Figure 55 shows LCC cases 6a (blue marker) and 6b (green marker) plotted together, for the sake of comparison. In case 6a, installing solar PV is not financially profitable for any panel area, but in case 6b it is profitable, or at least cost-neutral, until 53 kWh/m²a has been reached. Figure 56 shows LCC as a function of the panel area for cases 6a and 6b, so that the effect of the solar panel area can be better observed. For case 6a, there is always a conflict between energy efficiency and life-cycle cost, for all solar panel areas. For case 6b, the optimal solutions occur from panel area 857 m² upwards.

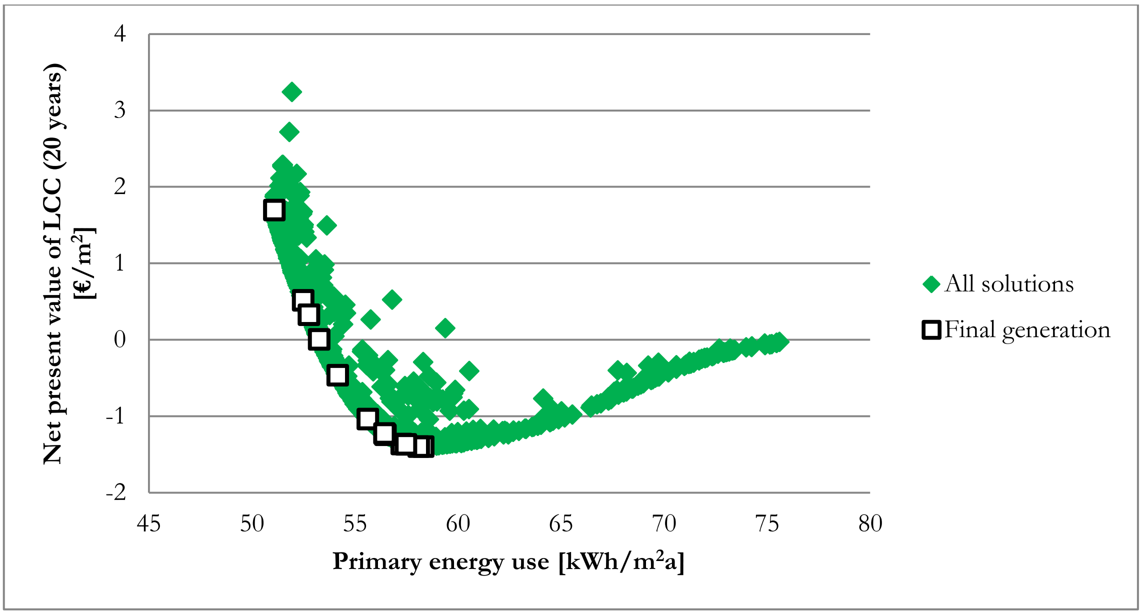

Figure 54. Vehmainen school with GSHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. Electricity purchase price is assumed to be 92,2 €/MWh instead of 81,2 €/MWh. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

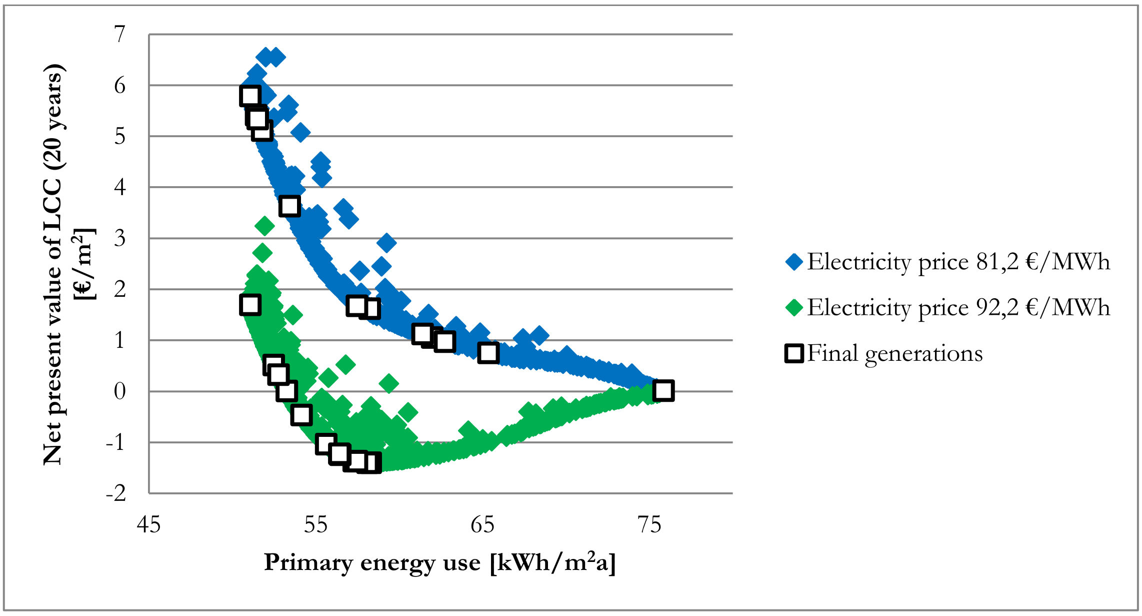

Figure 55. Vehmainen school with GSHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

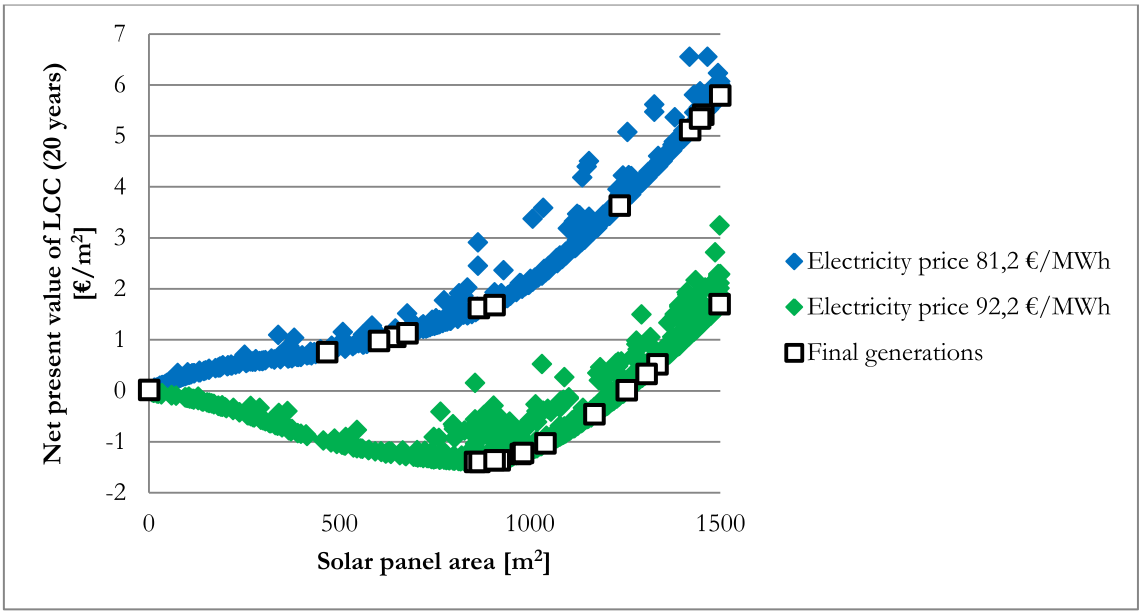

Figure 56. Vehmainen school with GSHP and solar PV, net present value of LCC [€/m²] as a function of solar panel area [m²]. A comparison between electricity price 81,2 €/MWh [blue marker] and 92,2 €/MWh [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 1500 m².

9.2 Luhtaa: measured building electricity consumption

9.2.1 Comparing the measured and the modelled electricity use in Luhtaa

In cases of Luhtaa and Vehmainen, it is already seen that a choice of electricity tariff affects the profitability of solar PV production. Both 81,2 €/MWh and 92,2 €/MWh are based on actual tariffs charged by Tampere municipal energy service provider. There are other factors that can decisively affect the PV generation profitability, and they too can be investigated by setting up additional optimization cases.

As explained earlier, the occupancy profiles for all the case study buildings were based on target values provided by FINVAC [84], with some modifications resulting from building user interviews and measured DHW data. All the results so far have been generated with these modelled building energy consumptions. In order to approximate the actual building energy consumption as closely as possible, one direction of investigation is to use measured data from these actual buildings.

How does the measured building energy consumption compare with the modelled building energy usage? For the three case study buildings, Luhtaa is the only one for which this question can be answered with some confidence. There is no energy consumption data from Vehmainen school yet, because the school was inaugurated in August 2016, and has been in operation for only few months. Energy consumption data exists for the totality of Koukkuniemi old people's housing and service building complex, but specific consumption data just for the Jukola wing (which is also connected to the new Impivaara building) is unfortunately not available.

For the Luhtaa day-care centre, hourly data exists for both electricity and district heating consumption. The day-care building was inaugurated in January 2012, so in principle the consumption data already spans 4 full years (2012–2015). By examining the hourly consumption data (available for the COMBI through Tampereen Sähkölaitos, Tampere municipal energy company) some gaps in data were detected for the year 2012. For comparison purposes, data for only the full years 2013–2015 is used.

Comparing the Luhtaa measured electricity consumption with the modelled consumption is not straightforward. There are two main complications: firstly, Luhtaa does have 143 m^2 of solar PV panels installed. Luhtaa electricity meter measures the electricity delivered to Luhtaa, but some part of Luhtaa's total electricity consumption is already covered by their own solar PV generation. This was taken into account, before the modelled consumption was compared with the measured consumption.

The second complication is that the Luhtaa electricity meter measures electricity delivered to the whole property, and not just to the building itself. Outdoor lighting and heater units outside the building (pavement and gutter heating) add some consumption to the electricity meter reading. This in itself is not a problem for PV utilization. On the contrary, with "extra" electricity consumed on the property, solar PV may be even more profitable than for the building alone – but only in case the "extra" consumption matches the hours of likely PV generation. For example, outdoor lighting is an especially poor match with PV production: outdoor lights are required precisely when the sun does not shine.

The first complication, which is the existing solar PV panels in Luhtaa, is handled by incorporating the existing solar panels into the building model before the comparison takes place. Luhtaa has 56 TopSun model 390 panels, with a total area of 143 m^2 and efficiency of 15,25%. The measured electricity consumption of Luhtaa was compared against a building model with the existing PV included into the model. This way, own generation was accounted for, and the amount of the "extra" consumption could be found out from the data. The second complication – the fact that some of this extra consumption results from electrical fixtures on the property – is not problematic as such, as long as it is kept in mind that the measured consumption from the property is not the same as building consumption.

The situation is clarified in Table 11. First row presents the yearly energy consumption acquired from the Luhtaa model with district heating and no solar PV in place. This information was also presented in Table 10 in Chapter 8, but here the heat and electricity use are reported separately, because the electricity use is of interest. Next row shows the energy use results from otherwise identical simulations, but this time with the actual solar PV plant incorporated into the building model. As can be expected, the amount of heat consumption is not affected by the solar PV, but the total yearly delivered energy consumption is lowered from 49 kWh/m^{2}a to 40 kWh/m^{2}a (18%). Note that these results still arise from the model, and not from the measurement.

Third row in Table 11 presents the measured delivered energy use, averaged for the years 2013–2015. The modelled delivered electricity consumption of the building is only 44% of the measured electricity consumption (40 kWh/m^{2}a vs. 71 kWh/m^{2}a). As noted above, part of this difference originates from electricity use on the property, outside the building itself. On a yearly level, then, there is a substantial difference between the measured and the modelled electricity use. Whether or not this affects the profitability of solar PV production depends much on when this "extra" consumption occurs.

It appears from Table 11 that the modelled heating energy use is also lower than the measured one (67 kWh/m^{2}a vs. 84 kWh/m^{2}a). The figures for heating are not directly comparable, because the modelled result arises from a test reference year [62]. In order to compare it against measured data from actual years, normalization should be performed according to the weather conditions of those years. This is not done here, because the main interest lies in the electricity consumption. A more thorough investigation could also take the difference in the heat consumption into account, especially when considering the GSHP heating option.

Table 11. Comparisons of Luhtaa day-care centre modelled and measured energy consumption.

District heat use [kWh/m²a]	Delivered electricity use [kWh/m²a]	Total delivered energy use [kWh/m²a]	Primary energy use [kWh/m²a] (suggested energy carrier factors)
Luhtaa with DH and no PV, modelled energy consumption			
67	49	117	92
Luhtaa with DH and existing PV, modelled energy consumption			
67	40	107	82
Luhtaa with DH and existing PV, measured energy consumption (average 2013–2015)			
84	71	155	127

When the measured electricity consumption is examined in detail for the year 2014 (the simulation year), it emerges that although the overall measured electricity use is higher than the modelled use, the time-pattern of varying consumption is described by the model fairly well. Over the whole year, the correlation coefficient between the modelled and the measured electricity use is as high as 0,73. For 27 of the 51 full weeks in the year 2014, the correlation between the measured and the modelled use is 0,8 or greater.

As the worst-case example, Figure 57 shows the least well matching full week for the year 2014. This is week 27, occurring in mid-summer. Measured electricity consumption is plotted with red, and modelled consumption with blue. The correlation between the measured and the modelled consumption is only 0,08. During mid-summer there should be no outdoor lighting or other outdoor electrical equipment in use, so this mismatch is not easily explained. Even in mid-summer there seems to be approximately 5 kW of base load. The effect of the solar panels is visible in both measured and modelled data; they lower the delivered electricity need in the day-time.

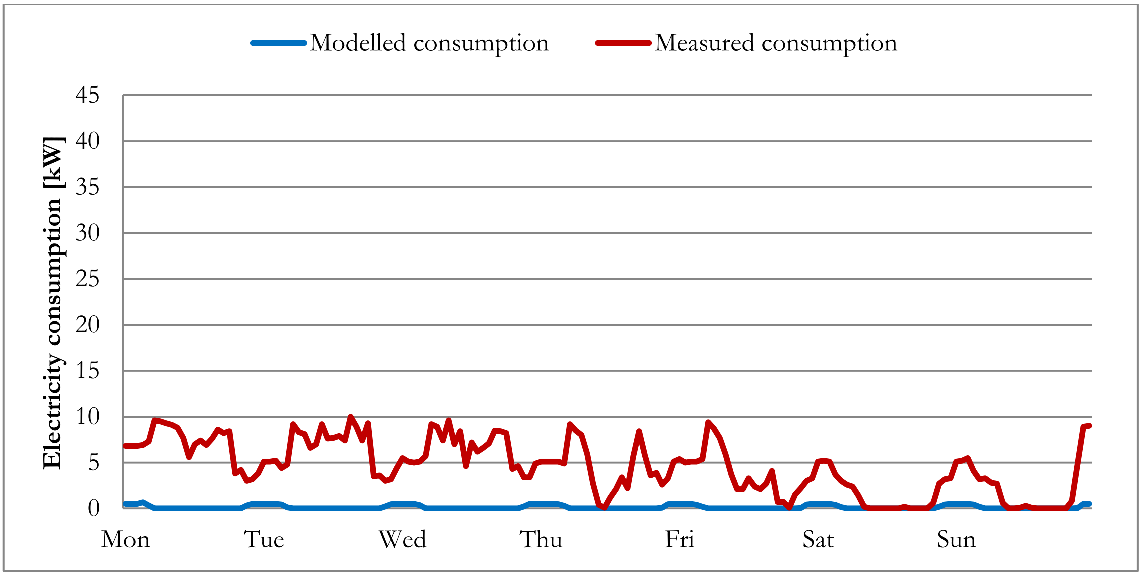

Figure 57: Measured and modelled delivered electricity consumption for Luhtaa day-care centre, week 27, 2014.

Figure 58 shows the best matching week, week 51, where the correlation between measured and modelled electricity consumption is 0,91. The best matching week occurs in mid-winter. The time-pattern of consumption is captured well, and hence the high correlation. However, there is an underlying base consumption of more than 10 kW, not described by the model. In mid-winter, the outdoor heating units and outdoor lighting likely explain this “extra” consumption.

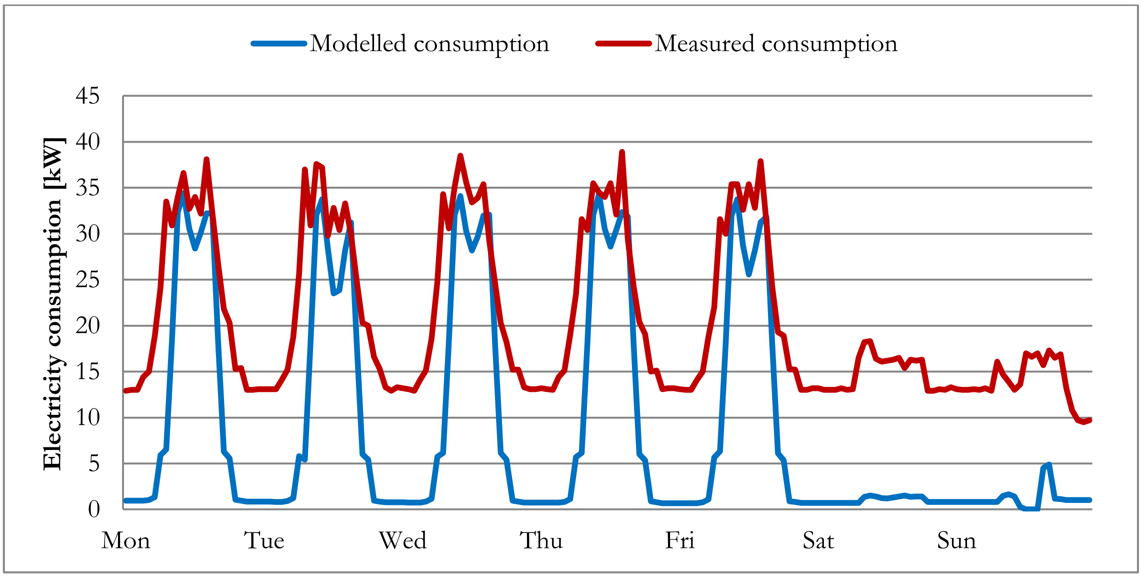

Figure 58: Measured and modelled delivered electricity consumption for Luhtaa day-care centre, week 51, 2014.

Figure 59 and Figure 60 show the comparison of modelled and measured electricity consumption for a spring week and an autumn week, respectively. Here the matching of the measured and the modelled electricity consumption is intermediate: not as good as in mid-winter, but not as poor as in mid-summer.

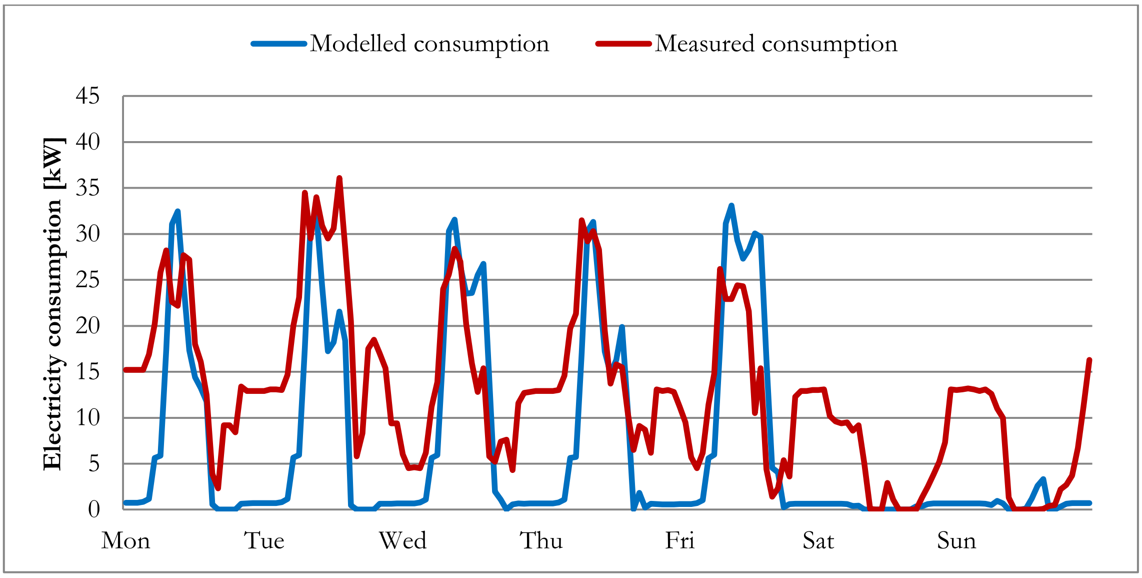

Figure 59: Measured and modelled delivered electricity consumption for Luhtaa day-care centre, week 14, 2014.

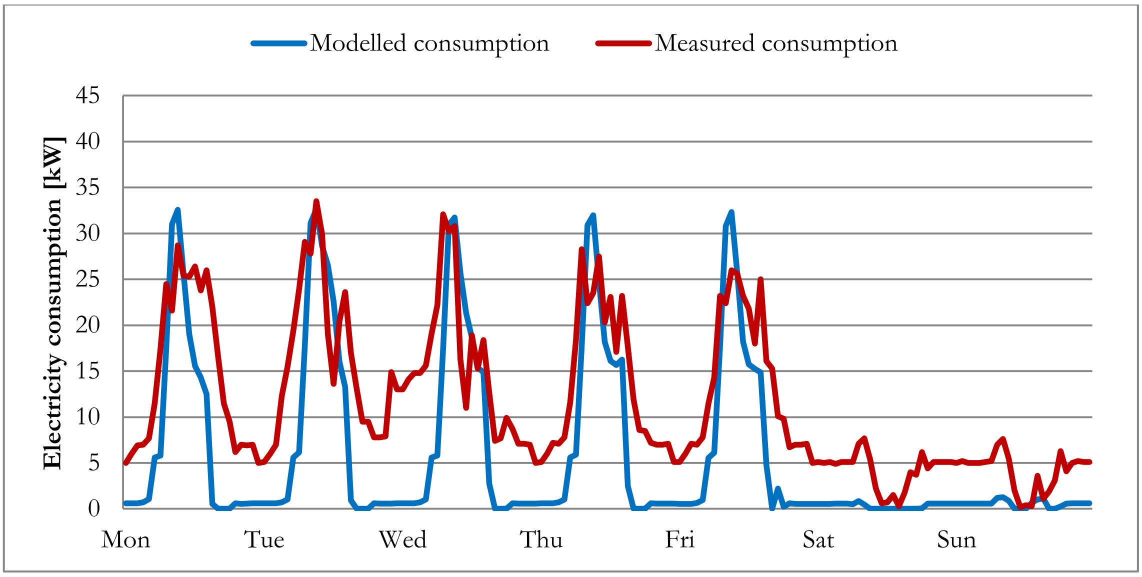

Figure 60: Measured and modelled delivered electricity consumption for Luhtaa day-care centre, week 39, 2014.

In order to create a more realistic building model for Luhtaa, one that better captures the actual electricity usage on the whole property, some modifications were performed on the building model. Electricity consumption was increased by adding generic electrical equipment, consuming electricity at a time schedule determined to provide a good fit with the measurements.

For modelling purposes, it was necessary to introduce a separate building for the extra consumption. Locating the extra electricity consumption inside the day-care building model would have created significant amount of extra heat gain inside the building, and thus affected the heating and cooling demand of the building. The separate little building keeps this simulated load outside the actual day-care building. No heating, cooling, lighting, air conditioning or occupancy is assumed in the separate little building model: it resembles a dark and empty sauna, located on the day-care centre premises.

Figure 61 shows this model with the little “sauna” building outside the day-care, incorporating the additional electricity usage. Note that the model of the day-care building itself also differs from the original model shown in Figure 13. Here the building model is simplified, and the modelled solar panels are also visible on the roof.

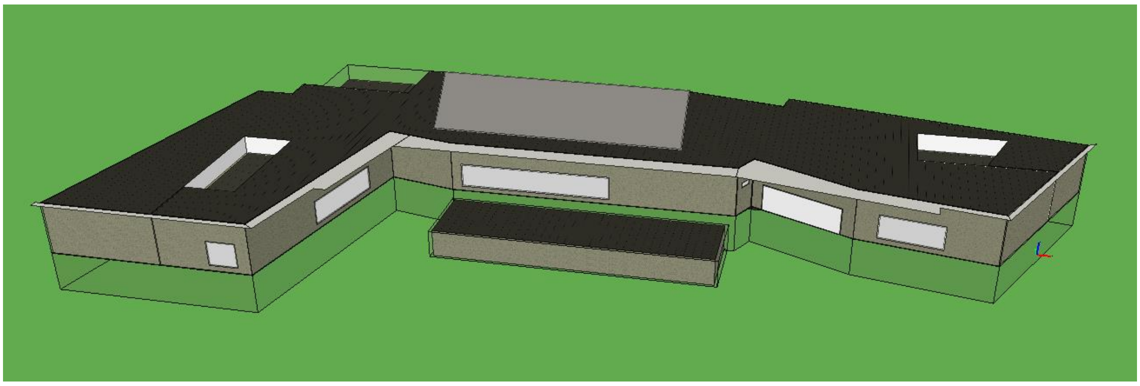

Figure 61. Luhtaa day-care IDA ICE model, with extra building outside to simulate the additional electricity usage.

For the modelled electricity consumption to match the measured consumption, consumption patterns were examined week for week, and corrections were introduced based on the weekly profiles. The differences between the measured and the modelled consumption varied from season to season, as illustrated by Figures 57–60. By carefully examining these weekly profiles throughout the year, and through a method of trial and error, the following modifications were performed for the electricity consumption model:

- A base load of 5 kW was added at all times throughout the year except on Monday-Friday 8–16 during weeks 2-5, 19-26 and 32-42.
- Additional base load of 10 kW was introduced during weeks 1 and 53.
- Yet additional 6 kW was added during weeks 6-10 and 47-51, occurring all times during those weeks except Mon-Fri 8–16.
- Additional 10 kW was introduced for weekend day-time (Saturday-Sunday 8–16) during weeks 6-9, 12-14, 16-17 and 46-51.
- Additional 5 kW was introduced on Wednesday-Sunday 8–16, during week 52.

After these operations, the delivered electricity use in the Luhtaa modified building model was 72 kWh/m^{2}a, falling between measured delivered electricity consumption during years 2013–2015 (71 kWh/m^{2}a) and the consumption in year 2014 (73 kWh/m^{2}a). This was deemed accurate enough for the optimization task: adding more detailed modifications would have introduced longer calculation times.

To illustrate the modified consumption, Figure 62 shows the best matching week after the corrections, which was again week 51 in mid-winter. The correlation coefficient between the modelled and the measured time series is the same as before, R=0,91, but now the initial off-set between the modelled and the measured use is removed with the above modifications. The modelled consumption now matches the measured consumption fairly well throughout the year, and the modified model was utilized for the next optimization task.

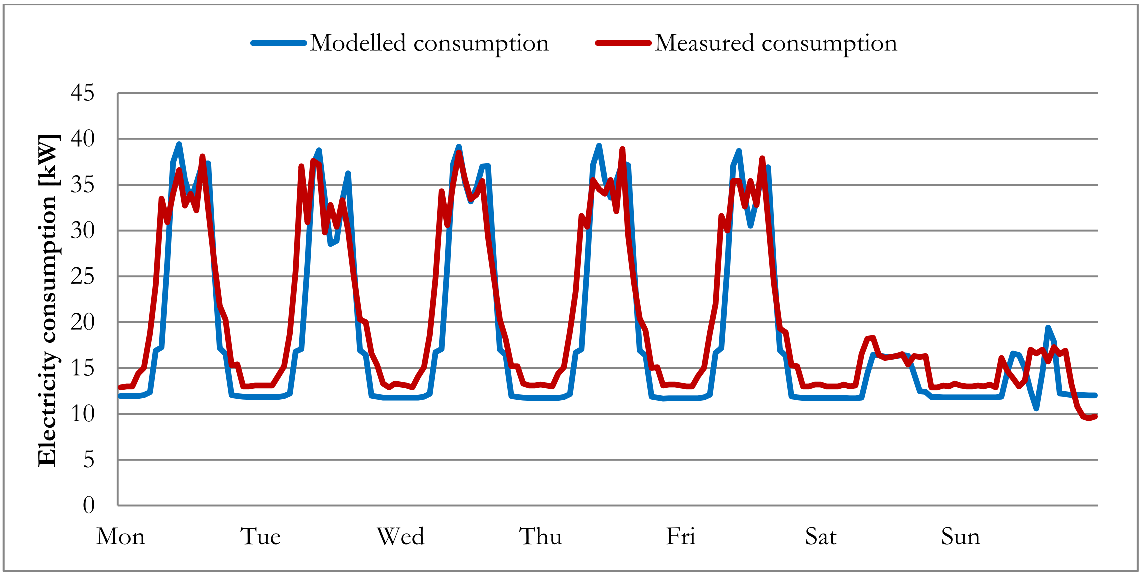

Figure 62. Measured and modelled delivered electricity consumption for Luhtaa day-care centre, week 51, 2014 (corrected building model).

9.2.2 Case 7: Luhtaa day-care centre with DH and measured electricity consumption

As the next optimization task, case 7, Luhtaa DH model was run with the "extra" electricity consumption added. This was done to find out if self-generation of PV becomes more profitable, when the model is switched from modelled electricity consumption to measured electricity consumption. The existing solar PV at Luhtaa was removed from the model at this stage, and the optimization was performed with the same kind of PV modules as in all the previous optimization tasks, disregarding the older and less efficient PV panels that are already installed.

Figure 63 shows the result from case 7, Luhtaa DH with measured electricity use. Now the profitability of solar PV indeed looks different from case 1, Luhtaa DH with modelled electricity use (Figure 24). Solar PV installation is now financially profitable, or at least cost-neutral, until panel area has reached approximately 235 m², After 235 m², more panel installation incurs a net cost instead of net profit. The maximum profitability is 1,6 €/m², totalling 2300 € in 20 years, or 115 € per year. This is reached with solar panel area of 114 m² and panel inclination of 48° (inclination plot not shown here).

With the panel model used in this study, panel area of 114 m² corresponds to 20 kW$_p$. This is close to the real-life situation at Luhtaa day-care centre, where the actual installed panel area of 143 m² has a capacity of 21,8 kW$_p$. One immediate conclusion from case 7 is that Luhtaa day-care already has a solar PV installation that well matches their needs. One difference that remains with the real-life case is that Luhtaa day-care does not currently receive profit from the excess electricity fed into the grid.

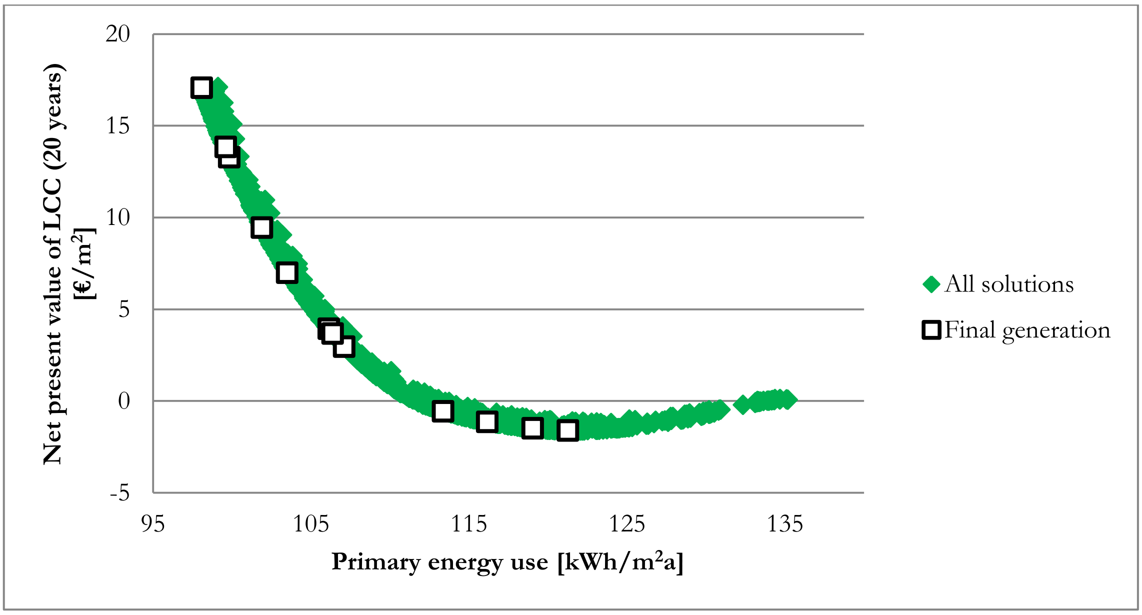

Figure 63. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. Building model is modified to approximate the measured electricity consumption. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

Figure 64 shows both LCC and primary energy use as a function of the panel area. Note that this time, as the panel area approaches zero, the primary energy use approaches 135 kWh/m²a. The primary energy use in this model no longer describes the primary energy use of the building itself:

now the model includes "extra" electricity from the property, and not just from the building. Also 135 kWh/m²a obtained with zero PV area is higher than the primary energy use according to the measured data (127 kWh/m²a, see Table 11). This is because in real life, the solar PV area at Luhtaa is not zero. As the final difference, no corrections or modifications have been attempted on the district heating use, because the main interest here is the electricity production and consumption. For all these reasons, the primary energy use shown here is something specific to this model, and should not be regarded as actual building primary energy use.

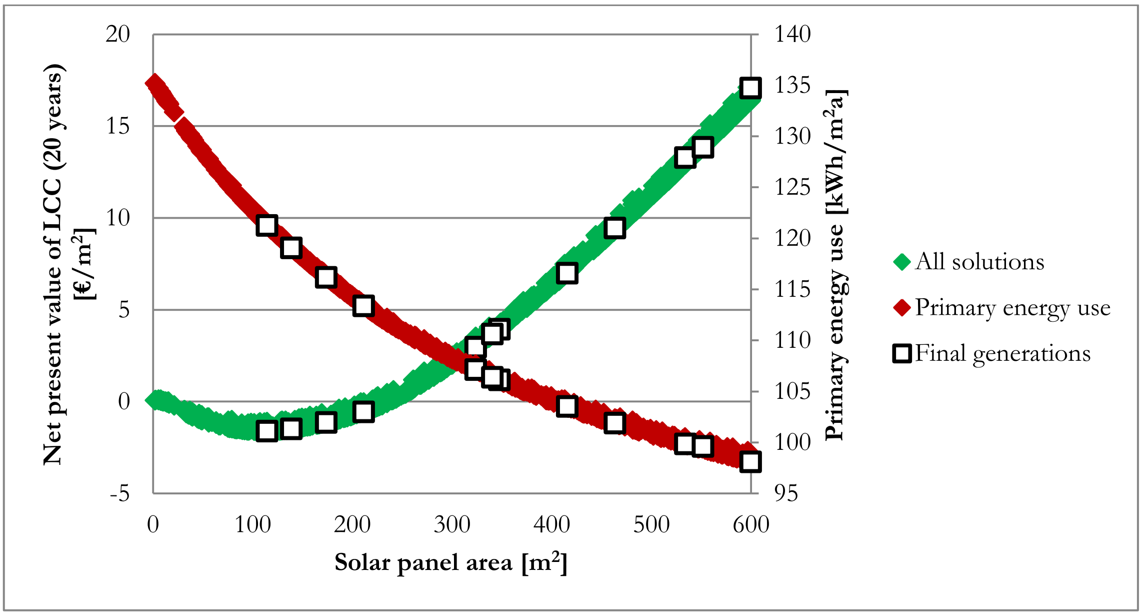

Figure 64. Luhtaa day-care centre with DH and solar PV, net present value of LCC [green marker, €/m²] and primary energy use [red marker, kWh/m²a] as a function of solar panel area [m²]. Building model is modified to approximate the measured electricity consumption. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

The distinction becomes clearer in Figure 65, which shows both case 1 (modelled electricity consumption, blue marker) and case 7 (measured electricity consumption, green marker) together. As is evident from the figure, the primary energy use in the model used in case 7 differs much from the primary energy use in case 1, and they should not be directly compared. Optimization case 7 is a hybrid between measured and modelled energy consumption. Its purpose is to illustrate that if electricity use is actually greater than the modelled one, then solar PV can become more profitable, no matter if the extra electricity is consumed inside the building or outside on the property. What matters is how well the production and the consumption can be matched. In case 7, there is a good enough matching for solar PV to become financially profitable, although it was not profitable in the modelled case 1.

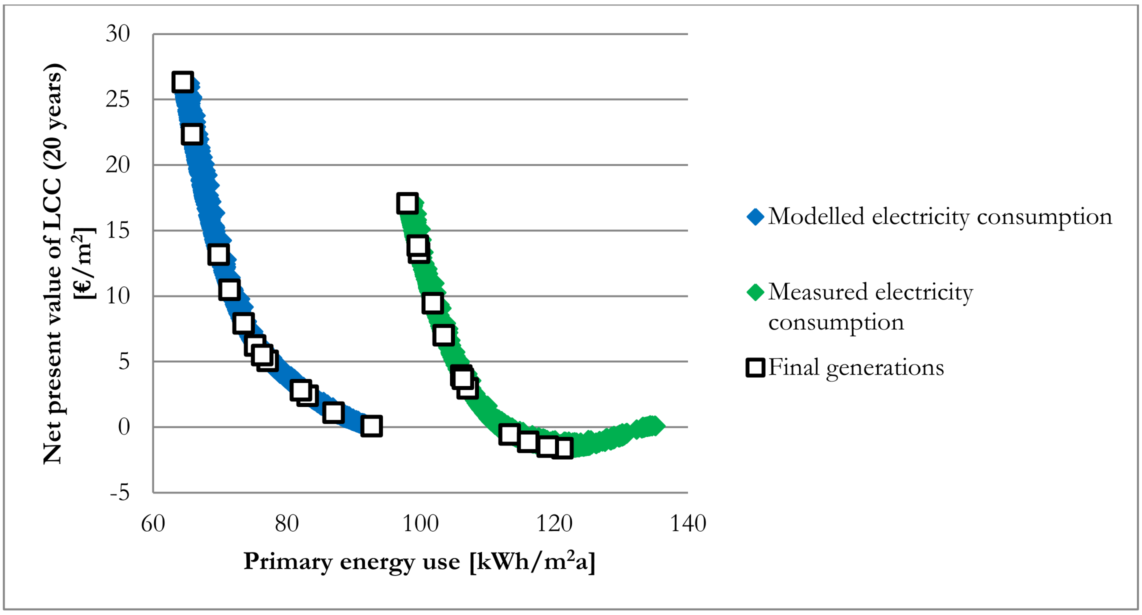

Figure 65. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. A comparison between the original building model [blue marker] and the modified building model which approximates the measured electricity consumption [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m^2.

9.2.3 Case 8: Luhtaa day-care centre with GSHP and measured electricity consumption

Luhtaa GSHP model was also altered to include the extra electricity use approximated from the measured data. The assumption was that if solar PV is profitable with the actual electricity use, it would be even more profitable with the GSHP heating solution. However, this modified model for case 8 is not a fully realistic one either: the heating consumption has not been modified according to the measured data.

With GSHP model plus the extra electricity consumption, the optimization case 8 is even more of a hybrid between the model and the reality, and should be taken as such. It can give an indication whether solar PV might be profitable also in the GSHP heating case, with the measured electricity use. If the building actually consumes more heat than it does in the model, then it would require more heat from the GSHP as well. This extra heat consumption would lead to even greater electricity consumption, and likely even better profitability of solar PV. Thus a more accurate picture of the profitability would require the heating consumption also to be in accordance with the measured data. It would have been too time-consuming to alter the entire model for such an analysis, so this was not attempted.

Figure 66 shows the optimization results for case 8, Luhtaa with GSHP and measured electricity consumption. The maximum profitability is better than in case 7, but only slightly so. Now the maximum profit is 1,8 €/m^2, totalling 2600 € in 20 years, or 130 € per year. This is not far from case 7, where the maximum profit was 1,6 €/m^2, totalling 2300 € in 20 years. With GHSP, the maximum profitability is reached with panel area 126 m^2, at which point the primary energy consumption of the model is 106 kWh/m^{2}a (see Figure 67). The inclination angle of the maximally profitable solution is 50° (inclination plot not shown here).

As the panel area approaches zero, primary energy use for optimization Case 8 approaches 122 kWh/m²a. As with Case 7, this primary energy consumption does not reflect the primary energy consumption of the building, but is specific to the model used here, describing the whole property.

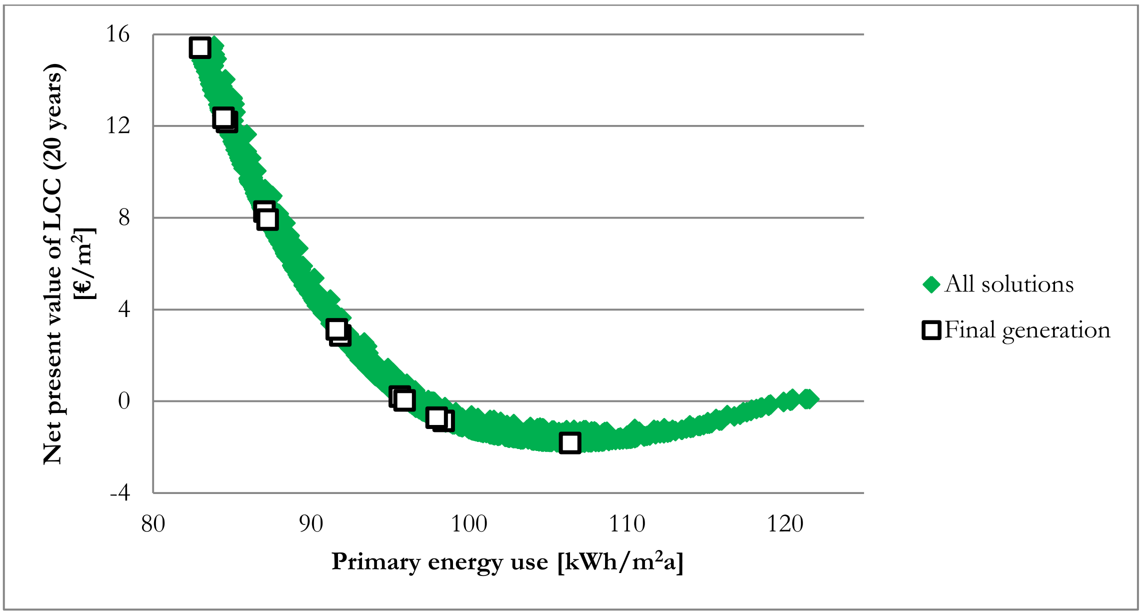

Figure 66. Luhtaa day-care centre with GSHP and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. Building model is modified to approximate the measured electricity consumption. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

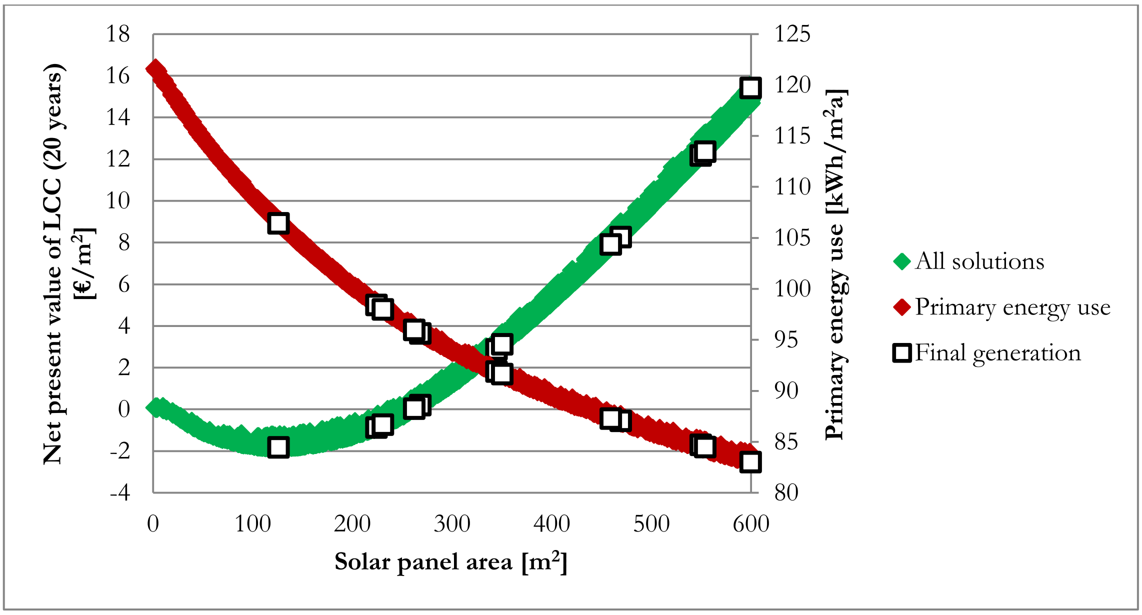

Figure 67. Luhtaa day-care centre with GSHP and solar PV, net present value of LCC [green marker, €/m²] and primary energy use [red marker, kWh/m²a] as a function of solar panel area [m²]. Building model is modified to approximate the measured electricity consumption. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m².

In Figure 68, case 2 (Luhtaa day-care with GSHP and modelled electricity consumption, blue marker) is plotted together with case 8 (Luhtaa day-care with GSHP and measured electricity consumption, green marker). Primary energy use is higher in case 8, because it includes consumption from the whole property. Solar PV can be financially profitable in case 8 (LCC dips below zero), whereas it was not financially profitable for any panel area in case 2.

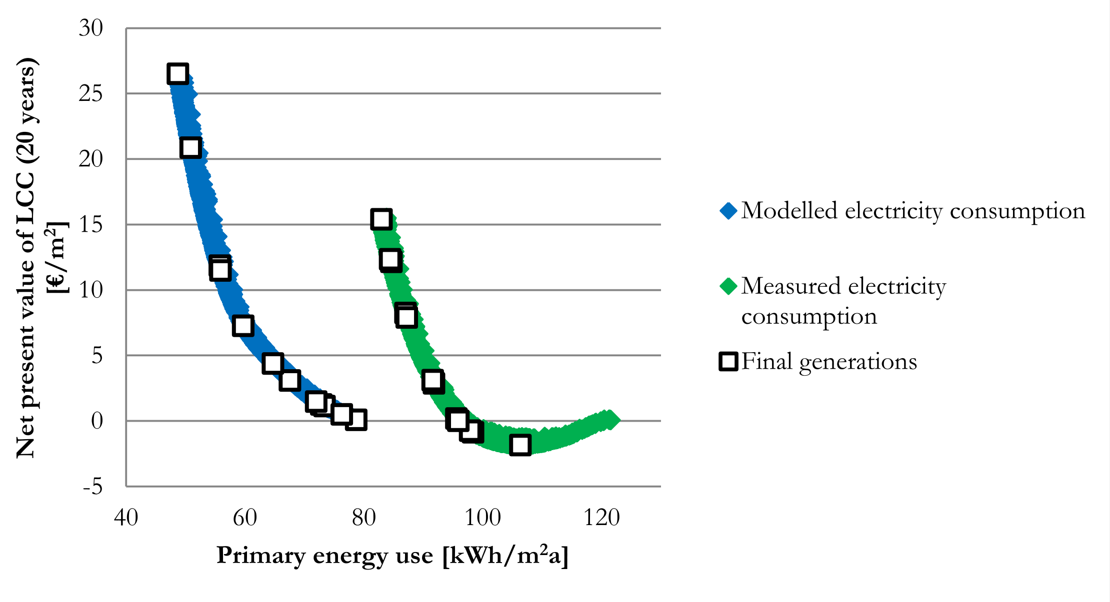

Figure 68. Luhtaa day-care centre with GSHP and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. A comparison between the original building model [blue marker] and the modified building model which approximates the measured electricity consumption [green marker]. System life-time is 20 years, real interest rate 3%, energy price escalation 2% and maximum panel area 600 m^2.

9.3 Discussion and summary of cases 1-8

Tables 12 and 13 summarize the main findings discussed previously in this chapter. Table 12 presents the financial characteristics of the optimal solutions, and Table 13 reviews the energy use characteristics. Other financial parameters than just the maximal profit can be extracted from the results, if desired. For example, internal rate of return (IRR) is a common way of assessing the feasibility of investments. It is the (assumed) real interest rate, at which the NPV of an investment becomes zero. Here IRR at minimum LCC is calculated for those cases where maximum profit occurs, and it is presented in Table 12. IRR for the cases in this study ranges from 3,4% to 5,6%. This agrees well with a current estimate from the Finnish Smart Energy Transition project, placing the IRR from municipal investments usually within 4–8% [85].

Another parameter that is calculated from the energy use results is the fraction of PV used on-site (see Table 13). The majority of the solar electricity generated in all the modelled cases is consumed on-site. Perhaps surprisingly, in Vehmainen cases 5b and 6b, the fraction of the energy used on-site is no higher than 57% and 58%, respectively. For all other (financially) profitable cases, the fraction of electricity utilized on-site ranges from 71% to 85%. In Vehmainen cases 5b and 6b, the optimal solution calls for large panel areas (749 m^2 / 857 m^2) and nearly half of the produced electricity ends up being sold into the grid. A large portion of this extra electricity is generated in the summer, precisely when the school is closed. In case the building had any summer usage, the profitability of the PV generation would improve further, because the electricity consumed on-site is approximately three times as valuable as the electricity sold into the grid.

Tables 12 and 13 are the most informative in those cases where a financially profitable solution is found. However, results from the optimization cases can be utilized to assess and compare even those cases where financial profit does not occur. An additional Table 14 is put together to illustrate this.

One way of comparing the study cases is to assume they should undergo major renovations. In a renovation, the E-value requirement in the current national building code is that the E-value of an educational building must diminish by 20%. For old people's home, the requirement states that the E-value must diminish by 30% (see Table 1). The primary energy use in the building models of this study is not strictly the same as E-value, and the E-value requirement is not the only way to fulfil the building renovation energy requirements. For the sake of comparison, however, it is now assumed that the primary energy use in cases 1–6 should be diminished by 20%, and this is to be done by solar PV installation. How much panels are needed, and do they incur a cost or a profit?

Table 14 answers this question for cases 1, 2, 5a/5b and 6a/6b. Cases 3a/3b and 4a/4ba are missing, because there is not enough data, at least not without performing additional simulations. For Jukola old people's home with DH, the -30% target means that primary energy use should diminish from 140 kWh/m^{2}a to 98 kWh/m^{2}a. This is not attainable with the chosen maximum panel area of 600 m^2 (see Figure 31, 35 or 36). For Jukola with GHSP, primary energy use should diminish from 127 kWh/m^{2}a to 89 kWh/m^{2}a. Again, this is not attainable with the chosen maximum panel area of 800 m^2 (see Figure 38, 42 or 43). In retrospect, it can once again be said that it would have been wise to choose even a larger maximum panel area for these cases. As this was not done, the Jukola cases are missing from Table 14. Luhtaa cases with the measured electricity use (cases 7 and 8) are also missing, because the primary energy use in these cases does not represent the primary energy use of the building.

For both Luhtaa and Vehmainen, improving the building energy performance by 20% is possible with the chosen maximum PV areas. As seen from Table 14, lowering the primary energy use of these buildings by 20% is the most costly for Luhtaa with DH, incurring a cost of 8,0 €/m^2 and requiring 274 m^2 of solar panels. For Luhtaa with GHSP, the cost would be 5,2 €/m^2, requiring 196 m^2 of panels. For Vehmainen, assuming actual electricity pricing (cases 5a and 6a), the costs would be 2,6 €/m^2 (DH) and 1,2 €/m^2 (GSHP). The cost difference between the least costly and the most costly solution is almost sevenfold (1,2 €/m^2 vs. 8,0 €/m^2). Assuming the higher electricity purchase price for Vehmainen (cases 5b and 6b), improving the building energy efficiency by 20% would create profit instead of a cost. For the DH case (5b) the profit would be 0,5 €/m^2, and for the GSHP case it would be more than double, 1,2 €/m^2.

Note that the panel areas needed for the 20% reduction should be exactly the same for Vehmainen cases 5a/5b, as well as for Vehmainen cases 6a/6b. The system is the same, only the electricity price differs, so the panel area needed for the energy efficiency improvement should be identical. In Table 14 the required panel area is 944/942 m^2 for cases 5a/5b, and 716/718 m^2 for cases 6a/6b. This is a reflection of the uncertainties present in the simulation and optimization phase. The simulations are numerical, and slight variations occur in the simulation results. The differing panel areas given in Table 14 do not differ much: the difference is in the order of 1‰. Uncertainty is discussed in more detail in the next chapter.

Table 12. Summary of the main results from cases 1–8. Comparing the financial and PV system characteristics of the maximum profitability panel area for cases 1–8.

Maximum profit [€/m^2]	Maximum profit [€, total]	Maximum profit [€, year]	Internal rate of return, IRR [%]	Panel area at minimum LCC [m^2]	System capacity at minimum LCC [kW$_p$]	Preferred inclination [°]	Inclination at minimum LCC [°]
Case 1:Luhtaa DH with modelled energy consumption							
0	0	0	N/A	0	0	30–50	N/A
Case 2: Luhtaa GSHP with modelled energy consumption							
0	0	0	N/A	0	0	30–53	N/A
Case 3a: Jukola DH with modelled energy consumption							
2,7	12 600	630	4,7	360	62	47–48	47°
Case 3b: Jukola DH with modelled energy consumption (electricity price +14%)							
5,2	24 300	1215	5,6	469	81	45–50	47°
Case 4a: Jukola A2WHP with modelled energy consumption							
3,6	17 100	855	4,9	461	79	47–52	48°
Case 4b: Jukola A2WHP with modelled energy consumption (electricity price +14%)							
6,8	32 100	1605	5,6	626	108	48–51	49°
Case 5a: Vehmainen DH with modelled energy consumption							
0	0	0	N/A	0	0	48–54	N/A
Case 5b: Vehmainen DH with modelled energy consumption (electricity price +14%)							
0,9	5600	280	3,4	749	129	44–54	N/A
Case 6a: Vehmainen GSHP with modelled energy consumption							
0	0	0	N/A	0	0	48–54	N/A
Case 6b: Vehmainen GSHP with modelled energy consumption (electricity price +14%)							
1,4	8900	445	3,5	857	147	51–55	53
Case 7: Luhtaa DH with measured electricity consumption and modelled heat consumption							
1,6	2300	115	3,8	114	20	30–48	48
Case 8: Luhtaa GSHP with measured electricity consumption and modelled heat consumption							
1,8	2600	130	3,9	126	22	31–50	50

Table 13. Summary of the main results from cases 1–8 continues. Comparing the energy use characteristics of the maximum profitability panel area for cases 1–8.

Primary energy use with no PV installation [kWh/m^{2}a]	Primary energy use at minimum LCC [kWh/m^{2}a]	Decrease in primary energy use at minimum LCC [kWh/m^{2}a]	Decrease in primary energy use at minimum LCC [%]	PV generated at minimum LCC [MWh/a]	PV sold at minimum LCC [MWh/a]	Fraction of PV used on-site at minimum LCC [%]
Case 1: Luhtaa DH with modelled energy consumption						
92	92 (no PV)	0	0	0	0	N/A
Case 2: Luhtaa GSHP with modelled energy consumption						
79	79 (no PV)	0	0	0	0	N/A
Case 3a: Jukola DH with modelled energy consumption						
140	126	14	10	65	11	83
Case 3b: Jukola DH with modelled energy consumption (electricity price +14%)						
140	124	16	11	85	22	74
Case 4a: Jukola A2WHP with modelled energy consumption						
127	110	17	13	84	16	81
Case 4b: Jukola A2WHP with modelled energy consumption (electricity price +14%)						
127	107	20	16	114	33	71
Case 5a: Vehmainen DH with modelled energy consumption						
92	92 (no PV)	0	0	0	0	N/A
Case 5b: Vehmainen DH with modelled energy consumption (electricity price +14%)						
92	76	16	17	143	61	57
Case 6a: Vehmainen GSHP with modelled energy consumption						
76	76 (no PV)	0	0	0	0	N/A
Case 6b: Vehmainen GSHP with modelled energy consumption (electricity price +14%)						
76	58	18	24	163	69	58
Case 7: Luhtaa DH with measured electricity consumption and modelled heat consumption						
135	121	14	10	20	3	85
Case 8: Luhtaa GSHP with measured electricity consumption and modelled heat consumption						
122	106	16	13	22	3	82

Table 14. Effects of lowering the building primary energy use by 20%, for cases 1–2 (Luhtaa day-care centre) and 5–6 (Vehmainen school).

Primary energy use with no PV installation [kWh/m²a]	Primary energy use -20% [kWh/m²a]	Panel area needed for the -20% reduction [m²]	Cost / profit of the PV installation (values > 0 indicate cost) [€/m²]	Total cost / profit of the PV installation (values > 0 indicate cost) [€]
Case 1: Luhtaa DH with modelled energy consumption				
92	73,6	274	8,0	11 500
Case 2: Luhtaa GSHP with modelled energy consumption				
79	63,2	196	5,2	7530
Case 5a: Vehmainen DH with modelled energy consumption				
92	73,6	944	2,6	16 400
Case 5b: Vehmainen DH with modelled energy consumption (electricity price +14%)				
92	73,6	942	-0,5	-3200
Case 6a: Vehmainen GSHP with modelled energy consumption				
76	60,8	716	1,2	7900
Case 6b: Vehmainen GSHP with modelled energy consumption (electricity price +14%)				
76	60,8	718	-1,2	-7800

9.4 Uncertainty and sensitivity analysis (Cases 9–16)

Uncertainties affecting the results of the optimization tasks arise from e.g. following factors:

- The operation of the building simulation programme: do the simulation results vary from one simulation to another?
- The accuracy of the original building models themselves: how accurately do they model the energy use of the buildings in question?
- Simplifying the building models for this optimization task: have the modified models preserved the relevant energy use characteristics?
- Switching from one version of IDA ICE programme to another: models were created with IDA ICE 4.62, but modified and run with IDA ICE 4.7, did this introduce errors?
- Modelling the solar PV installation: was it realistic enough?

Some of the sources of uncertainty can be quantified, and have been assessed during the research work. Simplification of the original building models caused a difference of 1–4% in the total annual delivered energy consumption between the original and the simplified model. Switching between IDA ICE model 4.62 and 4.7 caused a 2–3% difference in the building energy results. Comparisons with measured building energy use were not possible; in Luhtaa case, the comparison was made with consumption from the whole day-care property, and for Jukola and Vehmainen the measured building energy use was not available. Without enough measured data for comparison, it is not possible to say which of the IDA ICE building models produced the more accurate result. Also without measured building energy use it is not possible to quantify the accuracy of the original building models in reproducing the energy use of the building. The error arising from the employed solar PV geometry is difficult to quantify, but uncertainty is present there as well.

The building IDA ICE programme was very accurate in its workings, and the variation of the energy results between repeated simulation runs was small. This is reflected in Table 14, where the panel areas needed for a 20% energy performance improvement were within 0,11% and 0,14% of each other, although they were obtained from different optimization runs. The variations between the simulations were so small that this can be neglected as a source of error. (This will be further confirmed in Table 16.)

All in all, a realistic error margin for the results presented here must be at least in the order of 5%, when it comes to the technical optimization task. However, the errors and uncertainties arising from the method and the performance of the calculations are probably not the main causes of uncertainty. As has been discussed already, assumptions concerning the various calculation parameters are major source of uncertainty. The time period for the LCC is 20 years, and it is impossible to know how e.g. the real interest rate or the energy price escalation behave in the future.

To some extent, this matter has been investigated in the optimization tasks performed so far. Cases 3b, 4b, 5b and 6b were set up to find out how the results from Jukola and Vehmainen would change, if the same electricity price was assumed for them as was used for Luhtaa. The effect of the 14% change in the electricity price was considerable, especially in the LCC. Also including the measured electricity consumption from Luhtaa day-care centre property into the Luhtaa model made the difference between financial profitability and non-profitability.

In order to further quantify the sensitivity of the results to some key calculation parameters, 8 more optimization cases are set up for sensitivity analysis. These cases are presented in Table 15. They are all variations on case 1, Luhtaa with DH and modelled electricity consumption, which serves as the base case. The model for the sensitivity cases was chosen for practical reasons: it has the shortest simulation times, making the additional optimization tasks fastest to perform with this model.

Table 15. Description of the optimization cases for the sensitivity analysis.

Case #	Building	Heating solution	Electricity use	Varied parameter (shown with **boldface**)
Base case	Luhtaa	DH	Modelled	r=3%, e=2%
Case 9	Luhtaa	DH	Modelled	**r=1%** (e=2%)
Case 10	Luhtaa	DH	Modelled	**r=5%** (e=2%)
Case 11	Luhtaa	DH	Modelled	**e=0%** (r=3%)
Case 12	Luhtaa	DH	Modelled	**e=4%** (r=3%)
Case 13	Luhtaa	DH	Modelled	**Electricity purchase price +10%** (r=3%, e=2%)
Case 14	Luhtaa	DH	Modelled	**Electricity purchase price -10%** (r=3%, e=2%)
Case 15	Luhtaa	DH	Modelled	**PV investment cost -10%** (r=3%, e=2%)
Case 16	Luhtaa	DH	Modelled	**PV investment cost -20%** (r=3%, e=2%)

Results from the sensitivity analysis cases 9–16 are presented in Figures 69–72. Figure 69 shows base case (blue marker) with case 9 (green marker, r=1%) and case 10 (red marker, r=5%). Assuming a real interest rate of 5% makes it even more expensive to install solar PV the Luhtaa DH case, whereas assuming a real interest rate of r=1% brings the case into the realm of financial profitability. In this case LCC is below zero until primary energy use of approximately 73 kWh/m²a is reached. Maximum profit is 1,3 €/m², totalling 1870 € in 20 years, and realized with 45 m² of solar panels.

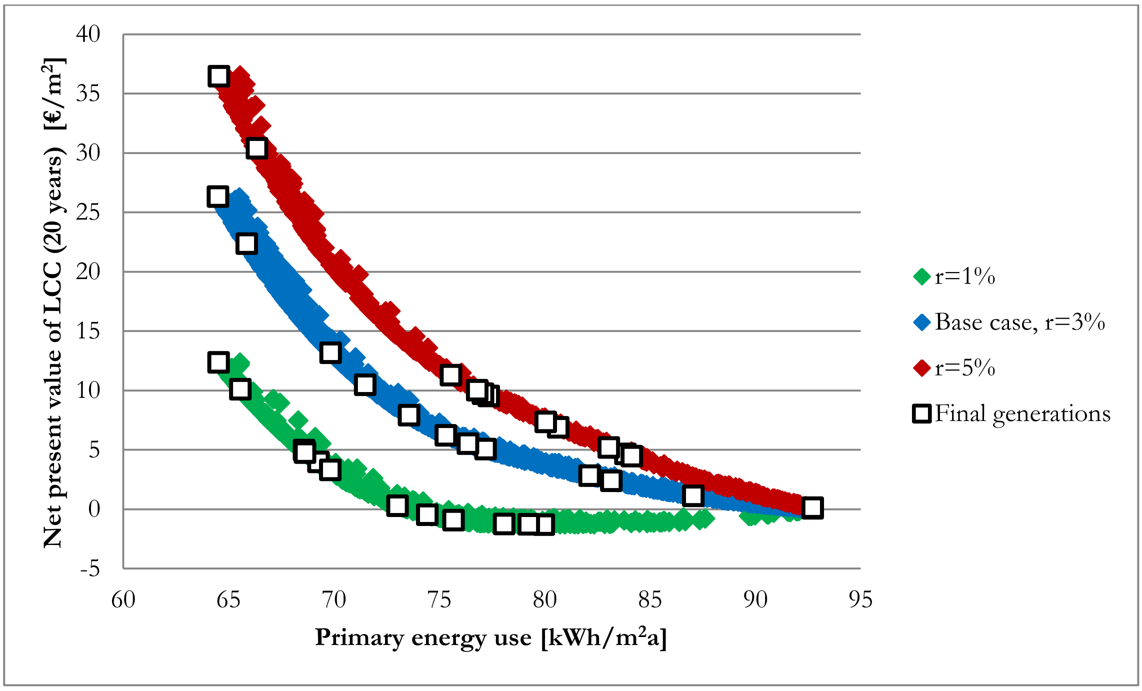

Figure 69. Sensitivity to real interest rate. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, energy price escalation 2% and maximum panel area 600 m². Real interest rates r=1% (case 9, green marker), r=3% (base case, blue marker) and r=5% (case 10, red marker).

Figure 70 shows base case (blue marker) with case 11 (red marker, e=0%) and case 12 (green marker, e=4%). The results are almost identical with Figure 69: assuming the energy escalation to increase or decrease by 2% has almost the same effect as increasing or decreasing r by 2%. Assuming energy escalation of 4% makes installing solar PV financially profitable until approximately 73 kWh/m²a is reached. The maximum profit in this case is 1,2 €/m², totalling 1790 € in 20 years, and requires 45 m² of solar panels.

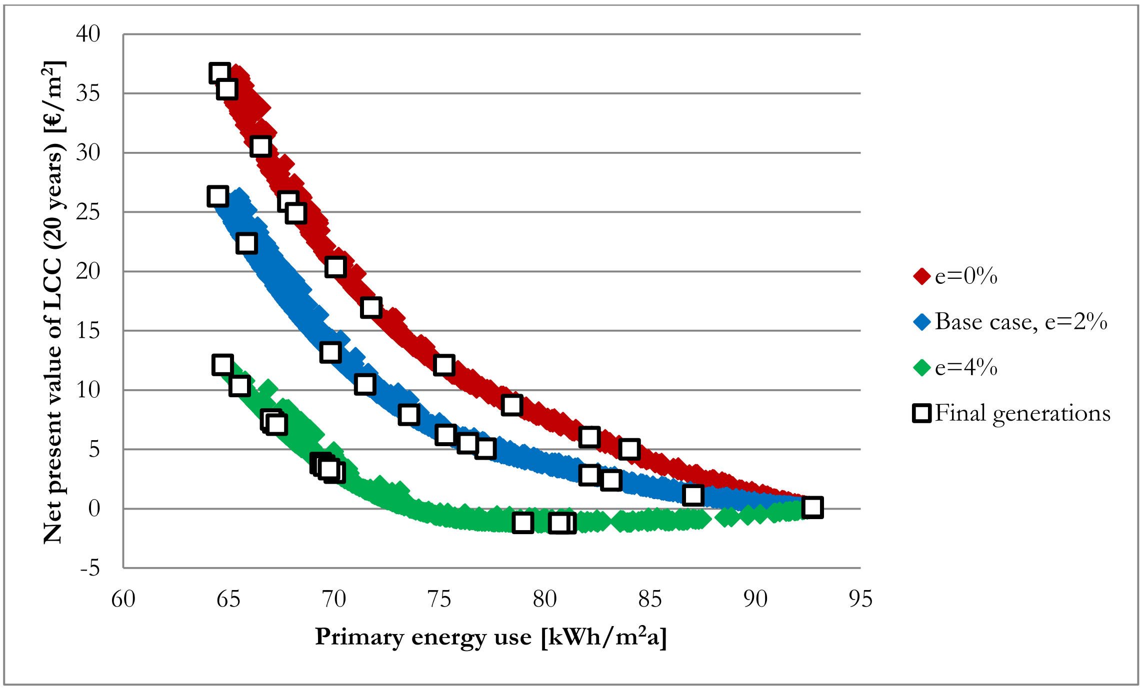

Figure 70. Sensitivity to energy price escalation. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3% and maximum panel area 600 m². Energy price escalation e=0% (case 11, red marker), e=2% (base case, blue marker) and e=4% (case 12, green marker).

Figure 71 shows base case (blue marker) with case 13 (green marker, electricity price +10%) and case 14 (red marker, electricity price -10%). Altering the electricity price does affect the LCC, but the effect is not nearly as pronounced as it was in the earlier Vehmainen and Jukola cases where electricity price was increased by 14%. Here increasing the electricity price by 10% does not make the Luhtaa DH case financially profitable.

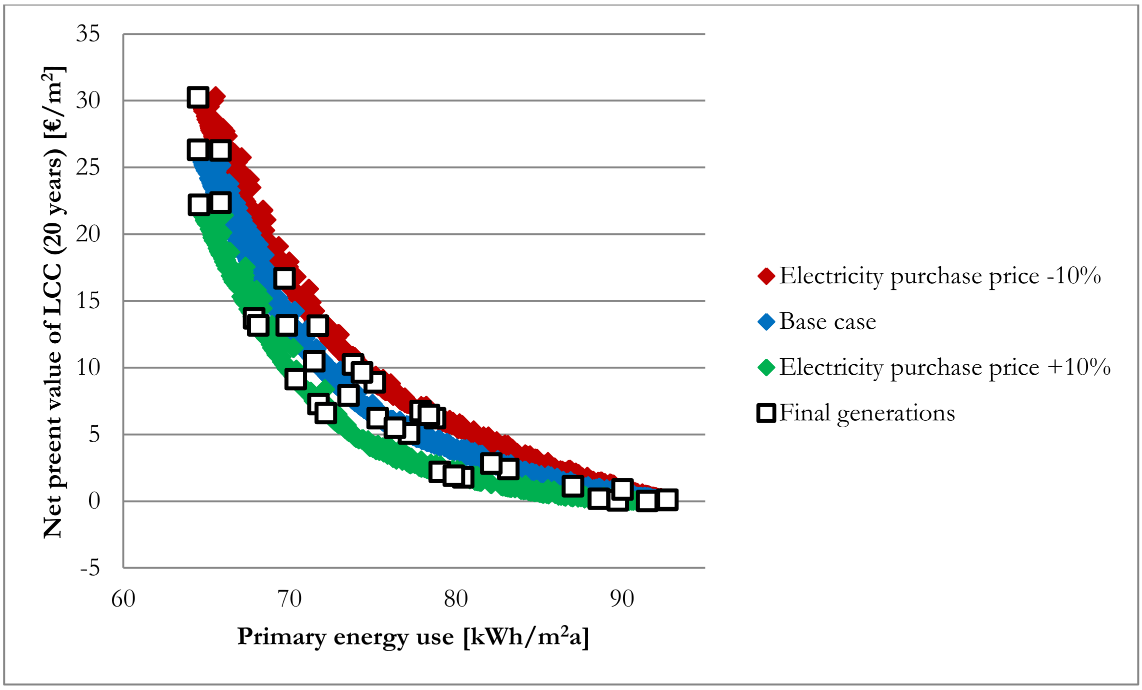

Figure 71. Sensitivity to electricity purchase price. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m²] as a function of primary energy use [kWh/m²a]. System life-time is 20 years, real interest rate 3% and maximum panel area 600 m². Energy purchase price +10% (case 13, green marker), base case (blue marker) and energy purchase price -10% (case 14, red marker).

Lastly, Figure 72 shows base case (blue marker) with case 15 (red marker, solar panel cost -10%) and case 16 (green marker, solar panel cost -20%). The solar panel cost is not varied upwards, because it is not likely that the panel prices will increase in the future. Decreasing the panel price by 10% does not quite make solar PV profitable in the Luhtaa DH case, although the LCC is close to zero until primary energy use of approximately 86 kWh/m²a has been reached. Decreasing the panel price by 20% makes the case financially profitable, bringing a maximum profit of 1,4 €/m², totalling 2050 € in 20 years. This is, once again, realized with a panel area of 45 m². Interestingly, all three sensitivity cases that showed a financial profitability (lowering r to 1%, increasing e to 4%, or decreasing the panel price by 20%) resulted in an optimal panel area that can be rounded up to 45m².

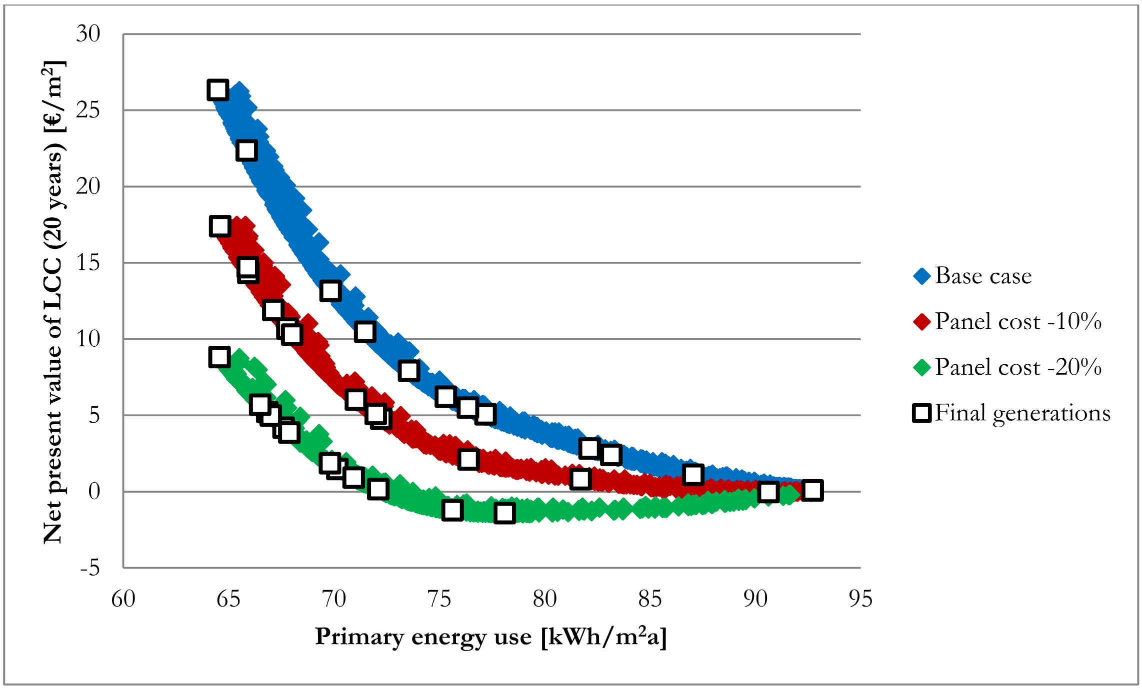

Figure 72. Sensitivity to solar panel investment cost. Luhtaa day-care centre with DH and solar PV, net present value of LCC [€/m^2] as a function of primary energy use [kWh/m^{2}a]. System life-time is 20 years, real interest rate 3% and maximum panel area 600 m^2. Solar panel investment cost base case (blue marker), -10% (red marker) and -20% (green marker).

The discussion on the sensitivity is rather qualitative, because the base case (Luhtaa DH) did not have a panel area of maximum financial profitability. Had there been more time available for simulations, a preferred method would have been to perform the full sensitivity analysis on one of the cases that do have a panel area of maximum financial profitability. One of the Jukola cases would have been a good candidate for the base case. In that manner, the effect on the optimal panel area could have been quantified for each of the sensitivity cases. However, time did not allow for this.

Table 16 presents some comparisons between the sensitivity analysis cases 9–16. In Table 14, it was shown how much it cost and how much panel area was needed to decrease the primary energy use of the model by 20%. Here the same comparison is performed on the sensitivity analysis cases. Because the building model itself is the same for all the sensitivity cases 9–16, the panel area needed for the 20% energy efficiency improvement is in fact the same. The slightly differing values obtained from each of the sensitivity cases are shown in Table 16, because they demonstrate how little the energy results vary between the different building simulation runs.

It can be seen from Table 16 that the costs for decreasing primary energy by 20% vary greatly between the sensitivity cases. In the last case, where the solar panel initial cost is decreased by 20%, the energy efficiency improvement creates a profit of 0,5 €/m^2. Table 16 also indicates the cases where a maximum financial profit is found. Because the maximum profit, or minimum LCC, is not found for all the sensitivity cases, a full sensitivity analysis cannot be performed on this end result. Table 16 gives a general indication, however, how varying the different parameters affects the profitability of each case.

Table 16. Comparisons between the sensitivity analysis cases 9-16.

Cost to decrease primary energy use -20% (values > 0 indicate cost) [€/m^2]	Total cost, 20 years (values > 0 indicate cost) [€]	Panel area needed to decrease primary energy use -20% [m^2]	Maximum profit (values> 0 indicate profit) [€/m^2]	Maximum total profit (values > 0 indicate profit [€]	Panel area creating the maximum profit [m^2]	Primary energy use at maximum profit [kWh/m^{2}a]
Base case: r=3%, e=2%						
8,0	11 500	273,7	0	0	N/A	N/A
Case 9: r=1%, e=2%						
0,1	183	274,2	1,3	1870	45	80
Case 10: r=5%, e=2%						
8,3	11 945	274,9	0	0	N/A	N/A
Case 11: r=3%, e=0%						
14,1	20 230	273,3	0	0	N/A	N/A
Case 12: r=3%, e=4%						
0,1	189	273,8	1,2	1790	45	81
Case 13: r=3%, e=2%, electricity price +10%						
5,3	7605	273,6	0	0	N/A	N/A
Case 14: r=3%, e=2%, electricity price -10%						
10,7	15 391	274,2	0	0	N/A	N/A
Case 15: r=3%, e=2%, panel cost -10%						
3,8	5429	274,3	0	0	N/A	N/A
Case 16: r=3%, e=2%, panel cost -20%						
-0,5	-761	274,0	1,4	2050	45	78

10 Conclusions and recommendations

The purpose of this research was to investigate how self-generation of solar PV can help lower the primary energy use of municipal service buildings, and what is the cost-optimal way to achieve the energy efficiency improvement. The findings underline the fact that building occupation profile matters very much in the profitability of own solar PV generation. This is especially true in countries such as Finland, where the seasonality of solar PV production is strong. Without storage, solar PV generation cannot cover the electricity need in mid-winter, so the profitability must arise from the generation that takes place in spring, summer and autumn. Service buildings that do not close for the summer are the best candidates for profitable solar PV production.

For the case study buildings examined in this work, assuming current electricity prices, self-generation of solar PV is financially profitable only in Jukola old people's home. In Jukola, installing solar PV could create a profit of 2,7–3, 6 €/m^2, depending on the main heating solution. In Luhtaa day-care centre and Vehmainen school solar PV does not appear profitable in the financial sense. The difference is explained by the differing occupation profiles of the service buildings. School and day-care are not normally occupied in the evenings or during the weekends and holidays, but the old people's home is occupied around the clock and throughout the year. It is therefore the most suited for self-generation of solar PV, which brings the greatest profit when utilized on-site.

One clear recommendation arising from the study is that when considering solar PV installations for currently existing municipal service buildings, old people's homes and other nursery or care homes inhabited throughout the year should take precedence over educational buildings. Some day-care centres do stay open in the summer, and it would be sensible to keep those day-care centres open that have the best roof direction and available roof area for solar PV installation. For such day-care centres, solar PV is more profitable than for those that close during the summer.

For all cases where solar PV production was financially profitable, the profit was greater with a heat pump than with district heating. Heat pumps use electricity, and therefore buildings with a heat pump can utilize more of the self-generated solar electricity. Producing electricity that cannot be utilized on-site is generally not profitable, because the selling prices of own excess generation are low, and likely to remain so in the future.

All new municipal care-housing buildings, and especially those with a heat pump as the main heating solution, should be designed with abundant roof area for solar panel installation. Available roof area, facing as close to south as possible, should extend to several hundreds of square meters. In case of Jukola old people's home with district heating, 360 m^2 (equalling 62 kW$_p$) of solar panels was needed to realize the maximum profit of 2,7 €/m^2, and Jukola old people's home with A2WHP required 461 m^2 of panels (79 kW$_p$) to reach the maximum profit of 3,6 €/m^2. The optimal panel area depends on e.g. electricity pricing, main heating solution and building usage profile. It is wise to plan for a large panel area, and to allow this to characterize the building architecture from the beginning.

In addition to the panel area, different panel inclinations were also tested. The results indicate that the panel area was the dominant decision variable, playing a much bigger role in the profitability than the panel inclination. Where preferred inclination angles were found, they were in the region of 47°–55°. Such angles bias the solar PV production away from the mid-summer, and towards autumn and spring. The finding is expected for the day-care and school buildings, which are closed during the summer. It was somewhat surprising that the cases for the old people's home also favour shifting the production away from mid-summer.

The exact inclination findings are specific to the Tampere latitude. When solar PV is considered for municipal service buildings elsewhere, it is not possible to use the Tampere results as absolute guide. However, the seasonal usage profile of the building, and the matching of electricity production and consumption, should be carefully considered. Inclination angles that produce the greatest yearly production do not necessarily yield the largest financial profit. In Finland the summer season is short, and it may be necessary to shift the production away from the mid-summer. However, one simplification of this research work was that all installation angles from 30° to 60° were considered equally costly to install. In case the larger inclination angle creates substantial added costs, the profitability must considered with taking the added cost into account.

A study such as this one, which utilizes current prices and interest rates, is necessarily based on a snap-shot in time. It assumes current-day electricity rate and panel installation costs, and estimates the future energy prices and interest rates based on today's knowledge. The future is uncertain and difficult to predict, but qualitatively it can be said that many of the global mega-trends at work today are likely to further improve the profitability of solar PV self-generation.

Perhaps the most important mega-trend, global warming, increases the summer temperatures and creates more space cooling need in the summer, also in Finland (e.g. [86]). This increases the electricity demand for cooling, and at precisely the times when solar irradiation is best available. Heat pumps are becoming more common, and solar electricity combines well with heat pumps. Prices for solar panels are still declining, which lowers the initial panel installation cost. Electricity storage technologies will likely also become cheaper, which will assist in utilizing more of the on-site PV generation. Although energy prices for electricity may decline in the future, it is possible that the transmission costs rise, because of the need to modernize the grid. Producing own electricity helps to avoid the transmission costs. Finally, one rising trend is to utilize service buildings in more diverse purposes, and generally increase their occupation hours: this also improves the profitability of solar PV generation in those buildings.

Even based on today's panel costs and electricity pricing, solar PV installation is on the verge of profitability in Luhtaa day-care centre and Vehmainen school. Indeed, when considering the actual measured use of electricity in the Luhtaa day-care centre and on its property, solar PV production becomes profitable in Luhtaa, even at today's electricity prices. Another recommendation for the municipalities is that when considering solar PV installation, all the electricity usage from the whole property should be taken into account, as long as it is situated behind the same electricity meter.

As for improving building energy efficiency, installing solar PV lowers the building primary energy use in every case. In those optimization cases where a solution with maximal profit was found, primary energy use was lowered by 10–24%, with the maximally profitable installation. Even larger energy efficiency improvements can be profitable, or at least cost-neutral. The need for lowering new service building primary energy use will depend on the final form of the nZEB legislation, which is still not known as this work is concluded. It seems likely, however, that solar PV will be valuable technology for fulfilling the future nZEB targets.

Lastly, the conclusions and recommendations are compacted in a nut-shell summary for municipalities and decision-makers:

When choosing the service buildings for solar PV production, occupation profile matters. Consider care housing first.

When choosing the panel area, bigger can be better. Plan for enough roof installation space in new service buildings.

When choosing the panel inclination, less (energy) can be more (money). Investigate a range of installation angles, not just the one that maximizes the yearly production.

When assessing the electricity use, everything counts. Remember to include the electricity use from the whole property.

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